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2019
MCM/ICM
Summary Sheet

Time to leave the Louvre

Summary

France is a famous tourist country, but the recent turmoil has increased. In order to ensure the safety of tourists, we have established the Louvre evacuation optimization model, hoping to improve current situation.

First of all, we searched a large amount of information and obtained the research methods of other people. We analyzed these methods and found their advantages and disadvantages to lay a solid foundation for our model.

Secondly, we built a model of speed, describing the relationship between the speed and the density of visitors in a room. After that,we determined the relevant coefficients. Then we model the museum with various numerical parameters. We also analyzed the evacuation process and modeled this. Based on these models and simulated annealing,we calculate an optimal solution for personnel evacuation.

Thirdly,In order to make the model more widely applicable, we considered how small exports can be reflected in the model, and also considered small accidents. Besides, the application of this model to other large-scale buildings is proposed, which makes our model more widely used.

Finally, we evaluated the model by sensitivity testing and pros and cons analysis so that users can quickly understand its characteristics.The evacuated route calculated by the model allows visitors to leave the Louvre safely in the shortest possible time. The scope of adaptation is large and can be targeted at different types of events. We select one parameter :rate for sensitivity testing,which also confirms the usefulness of our model.

Keywords: Louvre; Evacuation; Simulated annealing algorithm;

Contents

1 Introduction

1.1 ProblemBackground

France is one of the most popular tourism countries in the world. It has many popular destinations, but the increasing number of terror attacks in France pose a threat to the safety of people. Given these social effects, our team reviewed the previous safe evacuation models and optimized them, in order to provide better solution for emptying the building as soon as possible under the emergency situation. In the paper, we have been asked to answer the following questions:

1. When the circumstance is given,the plan to evacuate tourists most quickly.
2. When a terrorist attack occurs,where should emergency personnel go to?And how can they get there?

1.2 PreviousResearch

Scholars have been studying the evacuation model for a long time. The developed and applied simulation models are all proposed from a certain perspective or a certain kind of accident under the building safety evacuation. Currently, the following models are popular internationally:
EVACNET: EVACNET was developed by Francis and Kisko at the university of Florida in 1984. The software describes the structure of the building in the form of a network, simulating the flow of personnel in this network, until all personnel finally arrived at the designated safe location. The key to the simulation of evacuation is to set up the network model of the building which can reflect the internal structure of the building.
SIMULEX: Simulex was developed by Dr Peter Thompson of Integrated Environmental Solutions Ltd in Scotland to simulate the evacuation of large Numbers of people in multi-storey buildings.Simulex's mobility features are based on precise simulations of each person as they move through the space of a building.
FDS+Evac: FDS+Evac software is an escape model developed by VTT technology research center in Finland on the basis of NIST fire dynamics simulation software (FDS), which can simultaneously simulate fire development and evacuation of people in the fire field. The simulation results can be animated by the visual software in the FDS as well as the area view. The model adopts grid computing method, and the basic algorithm is to simulate everyone's behavior through motion equation. The social force model proposed by He1bing, a Hungarian traffic expert, is adopted as the model of motion calculation.

1.3 Our Assumptions

Because visitors in the Louvre come from all over the world and have different languages, some of them belong to the same tour group, and considering that there may be disabled people among tourists, in order to solve the problem of how to evacuate the Louvre visitors more quickly in an emergency situation, we will arrange some security personnel and set up some warning signs to guide the evacuation of tourists, and we have made some reasonable assumptions as follows.

- Assume that the evacuation of tourists is effective enough to ensure that the flow of visitors evacuated and the entry of rescue workers do not interfere with each other.
- Assume that the maximum number of people that each pavilion can accommodate is known and proportional to the pavilion area.
- In principle, the number of people in each pavilion is proportional to the area. A few famous pavilions, such as the Mona Lisa Pavilion, are set to be 10 times larger than the number of other pavilions.
- The proportion of visitors in each exhibition hall remains unchanged every week.
- The direction of tourist evacuation remains unchanged during the evacuation process.
- The evacuation of tourists is effective enough to enable tourists to move completely along the evacuation route.

2 Analysis of the Problem

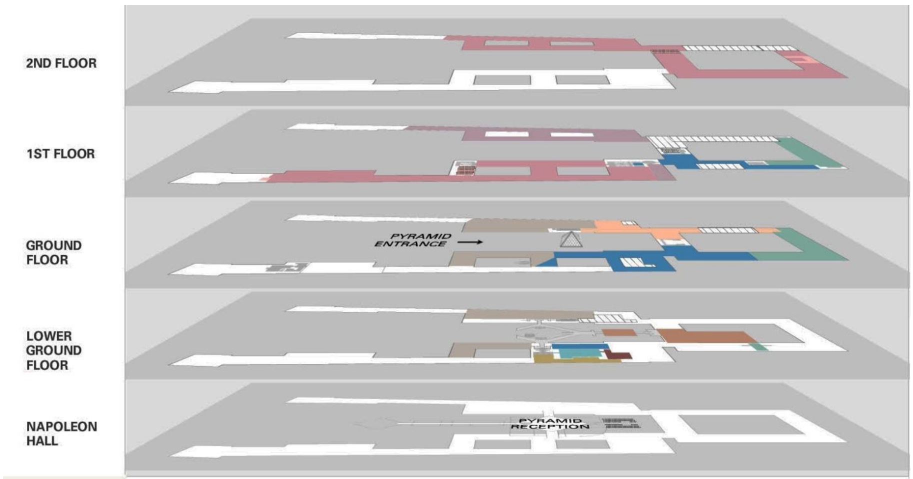


Figure 1: Floor Plan Of Louvre

We set a premise for the problem in the third and fourth parts. Accidents caused by terrorists are large-scale incidents such as fires and landslides, rather than small-scale incidents of killing people with swords. Therefore, people's goal is to escape from the building as soon as possible, without considering factors such as avoiding suspects.

3 Description of Symbols

Here is a description of the symbols used in our model.

- mP:The maximum number of people that a pavilion can accommodate.

- P:The actual number of visitors to a pavilion.
- $rate$:P/mP in general pavilions ($P = mP * (10 * rate)$ in some famous pavilions).
- $\beta rate$:When the $P*$ rate of a pavilion exceeds the $mP * \beta rate$ during the simulated evacuation, the room becomes the bottleneck.

4 Calculating and Simplifying the Model

4.1 The assumption of population in each room

4.1.1 The maximum capacity of each room

In the Louvre, there are many rooms of different sizes and shapes on each floor, which are connected by passageways. We simplified each different room into an area with a certain area, and the number of visitors in most rooms is proportional to the area of the room.

We used data from the Internet to find the average density of people in public places. Then, we estimated the size of each room by comparing the scale of the Louvre map of Google with the internal structure of the Louvre, and thus estimated the number of people in each room.

Figure 2: The Google map

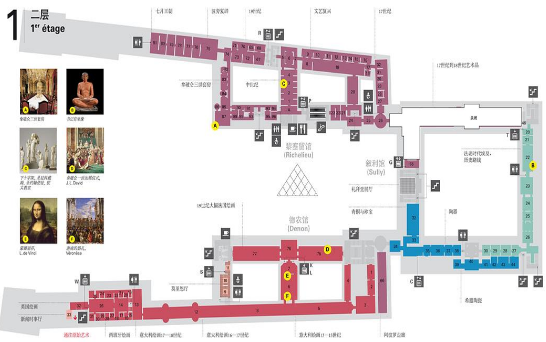


Figure 3: The first floor of the Louvre

4.1.2 The number of visitors in each room

It is assumed that the number of visitors will increase sharply except for a few rooms, and the tourists are evenly distributed in most rooms.

Among them, some special exhibition halls, such as the Mona Lisa exhibition hall, the population density will increase moderately.

4.2 The Model of Crowd Moving Speed

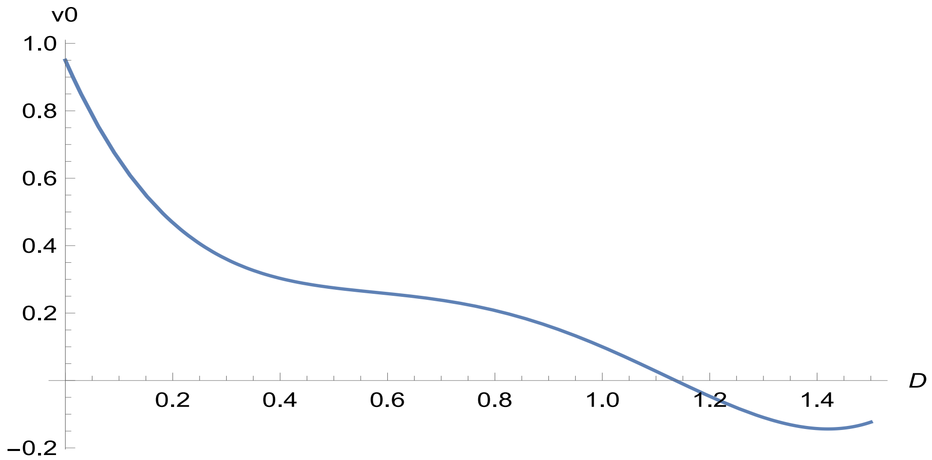
By consulting a large number of data, we refer to many different functional relationships between crowd movement speed and population density in crowded environment. Finally, we decide to use the Predtechenskii and Milinskii's velocity model($P\&M'sModel$)(we assume that the velocity will plunge to 0 if the next room is full):

We classify the velocity model into the following four types ,where the evacuation speed is defined as the number of people passing through the doors or stairs per second :

4.2.1 Evacuation speed on a straight passage

We assume that the velocity is determined by the following equation:

$$v_0(D) = 1.867D^4 - 6.333D^3 + 7.233D^2 - 3.617D + 0.95$$



where $D = 1.248P/mP$, and the P is the number of the people waiting to go to the next room, the mP is the maximum number of people that can be accommodated in the room. Here, we need to notice that the P is related to the time t, that is to say P can be expressed as $P(t)$.

4.2.2 Evacuation speed of descending stairs

In this model, the speed of ascending or descending stairs is obtained by modifying the coefficient of the moving speed along the horizontal passage.

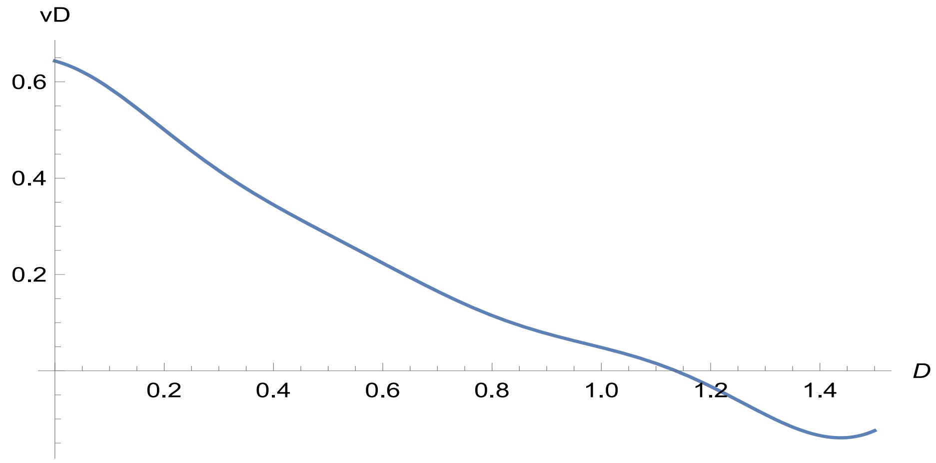
The speed of descending stairs can be obtained by the following formula:

$$v_D(D) = K_{down}v_0$$

where K_{down} can be expressed as:

$$K_{down} = 0.775 + 0.44e^{-0.39D}sin(5.16D - 0.224)$$

We can see the function image of $v_D - D$:



4.2.3 Evacuation speed of ascending stairs

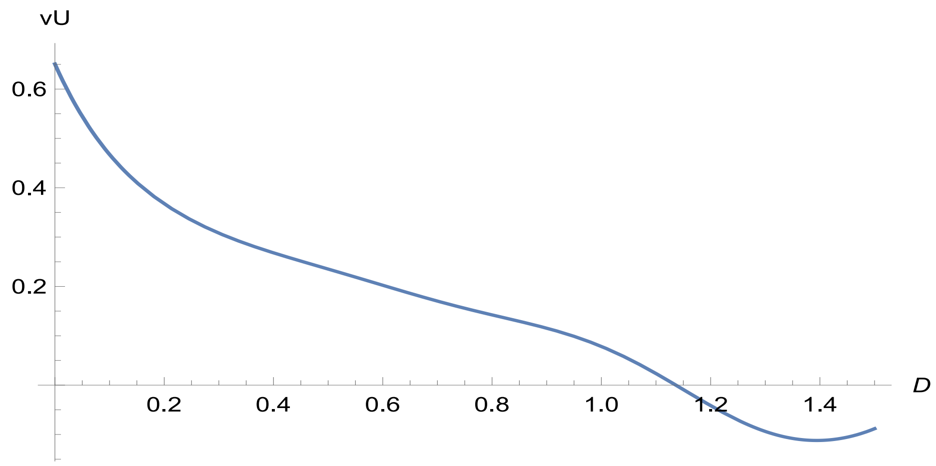
Similarly, the speed of ascending stairs can be obtained by the following formula:

$$v_U(D) = K_{up}v_0$$

where K_{up} can be expressed as:

$$K_{up} = 0.785 - 0.1sin(7.85d + 1.57)$$

We can see the function image of $v_U - D$:

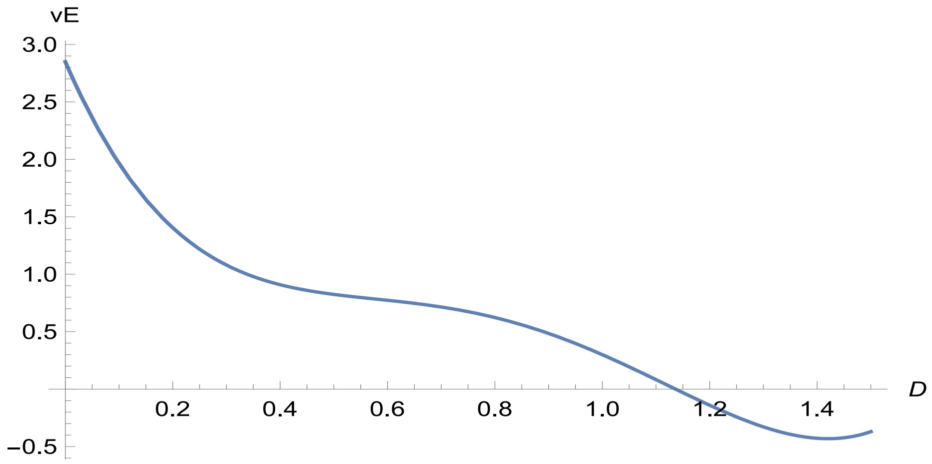


4.2.4 Evacuation speed passing through the exit

In our model, the velocity is related to the crowd density in the previous room. So we may put forward a reasonable hypothesis that the visitors flowrate v is propotional to the width of doors.

Assume that the width of the exit is three times as wide as the passage in Louvre. So the evacuation speed passing through the exit is three times as large as the evacuation speed on a straight passage in Louvre.

$$v_E(D) = 3v_0$$



5 Establishment of Model

In order to describe our model in the program, we present some elements as follows:

1. (a) The node (room) :
      i. number each room
      ii. property(O: ordinary room, T: particularly crowded room, E: exit)
      E: abstraction of outer space
      T: the abstractions representing the Mona Lisa and so on often accumulate in the rooms of a large number of visitors
      O: other ordinary rooms
      iii. mP:Maximum capacity of the room
      iv. code of adjacent room
   (b) passenger :
      i. the code which connect next room
      ii. property(O common door, L stairs, E connecting exit)
2. We show a evacuation scheme in this way:
   Each room contains the following information
   (a) current number of tourists P
   In order to calculate the initial number of people, the management will input the parameter rate according to the crowded degree of the venue in case of an accident. And P is decided by the following formulas:
   O: $P = mP * rate$,
   T: $P = mP * rate * 10$, if the P exceeds mP, then mP.
   E:initial :$P = 0$.
   (b) Target exit(value $1 - 6$)
      i. pyramid 1
      ii. richelieu channel 2
      iii. caluces 3

iv. lions gate 4
v. art gate 5
vi. the subway 6

(c) The direction of action, which guide the tourists to this room.

(d) Border
If the target exit of a room adjacent to the room and its own target exit are different, the border value is true, otherwise border value is false.

6 The Procedure of the Program Calculation

1. input the map and initialize border to false

2. Using the weightless graph shortest path algorithm to calculate the shortest path from each room to each exit, that is, the shortest path from each room to each exit, store the path information from each room to each exit and the number of rooms that this path passes through.

3. Travel through each room to find the outlet with the smallest path length, and change its direct and exit members to the corresponding value of the outlet.

4. Travel through each room and mark the border as true if the target exit of its adjacent room is different from its corresponding target exit.

5. Input the current crowding coefficient of the parameter, and decide the P(current number of people in the room) of each room through this ratio.

6. Calculate the evacuation time under this scheme and write it into Tmin.

7. Optimize the scheme by Simulated Annealing.

   "Simulated Annealing (SA) is a probabilistic technique for approximating the global optimum of a given function. Specifically, it is a metaheuristic to approximate global optimization in a large search space for an optimization problem. It is often used when the search space is discrete (e.g., all tours that visit a given set of cities). For problems where finding an approximate global optimum is more important than finding a precise local optimum in a fixed amount of time, simulated annealing may be preferable to alternatives such as gradient descent. "

   (a) At each temperature, randomly change the target exit at the boundary. Then, simulate the process of the metal cooling and decide whether to accept or not according to the time calculated by simulation.

   (b) Re-calculate border members of each node. Cycle until the temperature is low enough.

8. Output the final evacuation route.

We can roughly show the flow chart of the program as follows.

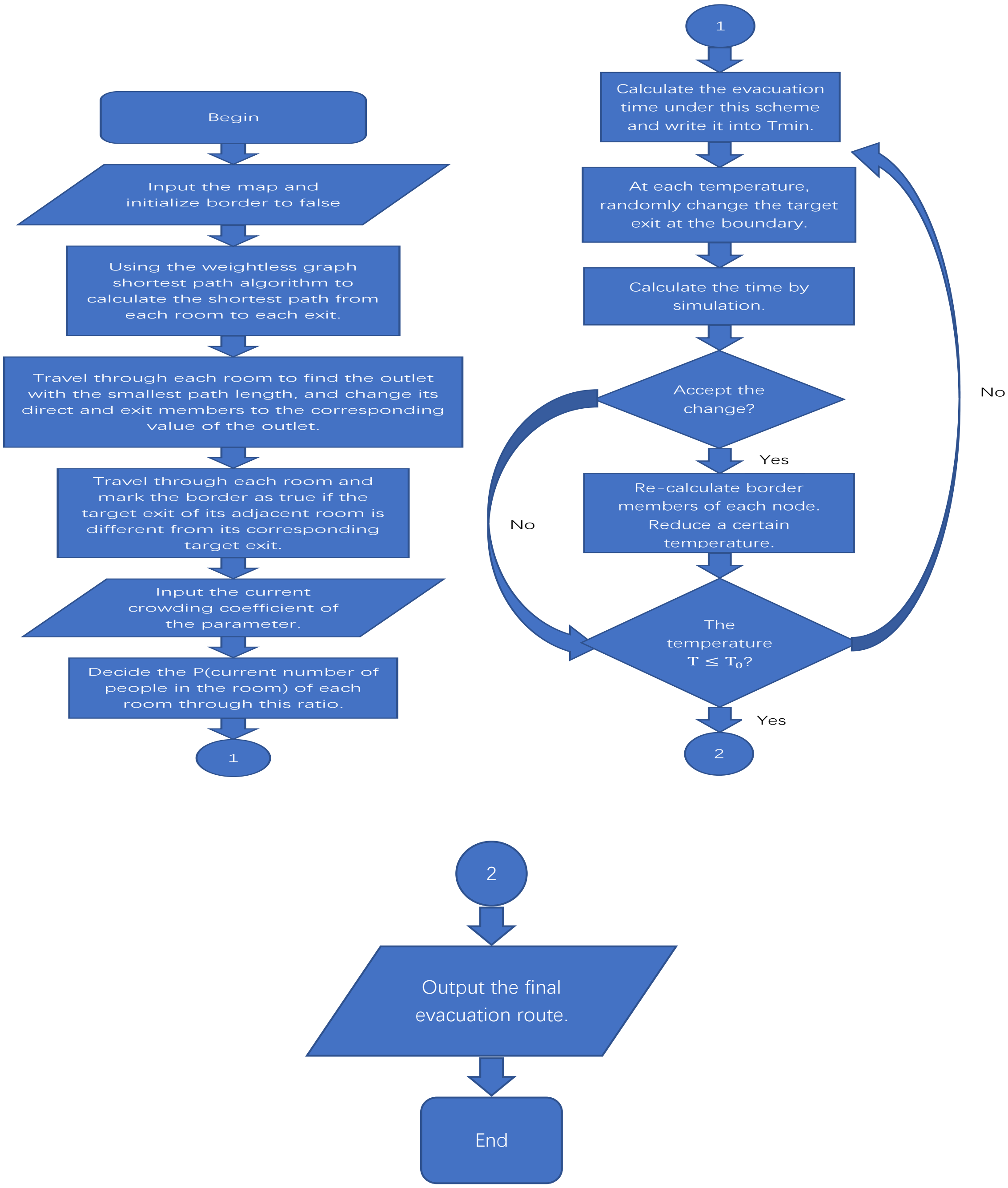


Figure 4: flowchart

7 The Model Results

7.1 The Evacuation Route

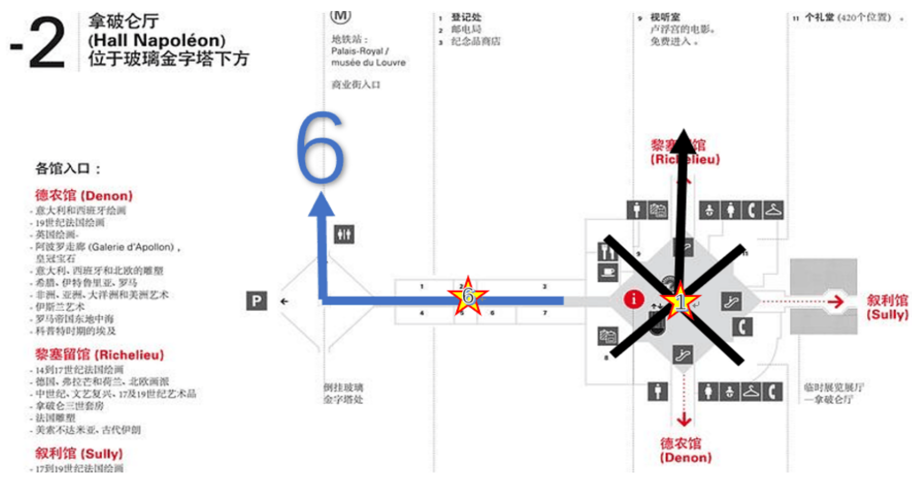
According to the survey, the daily flow of the Louvre is about 15,000.Input congestion factor rate 0.46. the number of people in the Louvre is 15,222,which match the reality.Under this condition, Through the calculation of the algorithm, we obtained a specific evacuation route, which is shown in the following pictures. Among them, arrows of different colors indicate different exits. Then we use eye-catching logos and reasonable manual guidance so that visitors can follow the route and leave the building in an orderly manner.

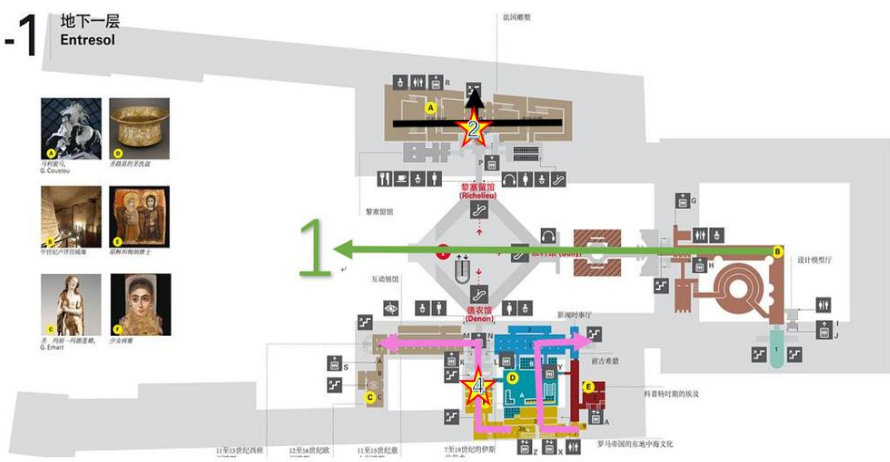
Table 1: Exit

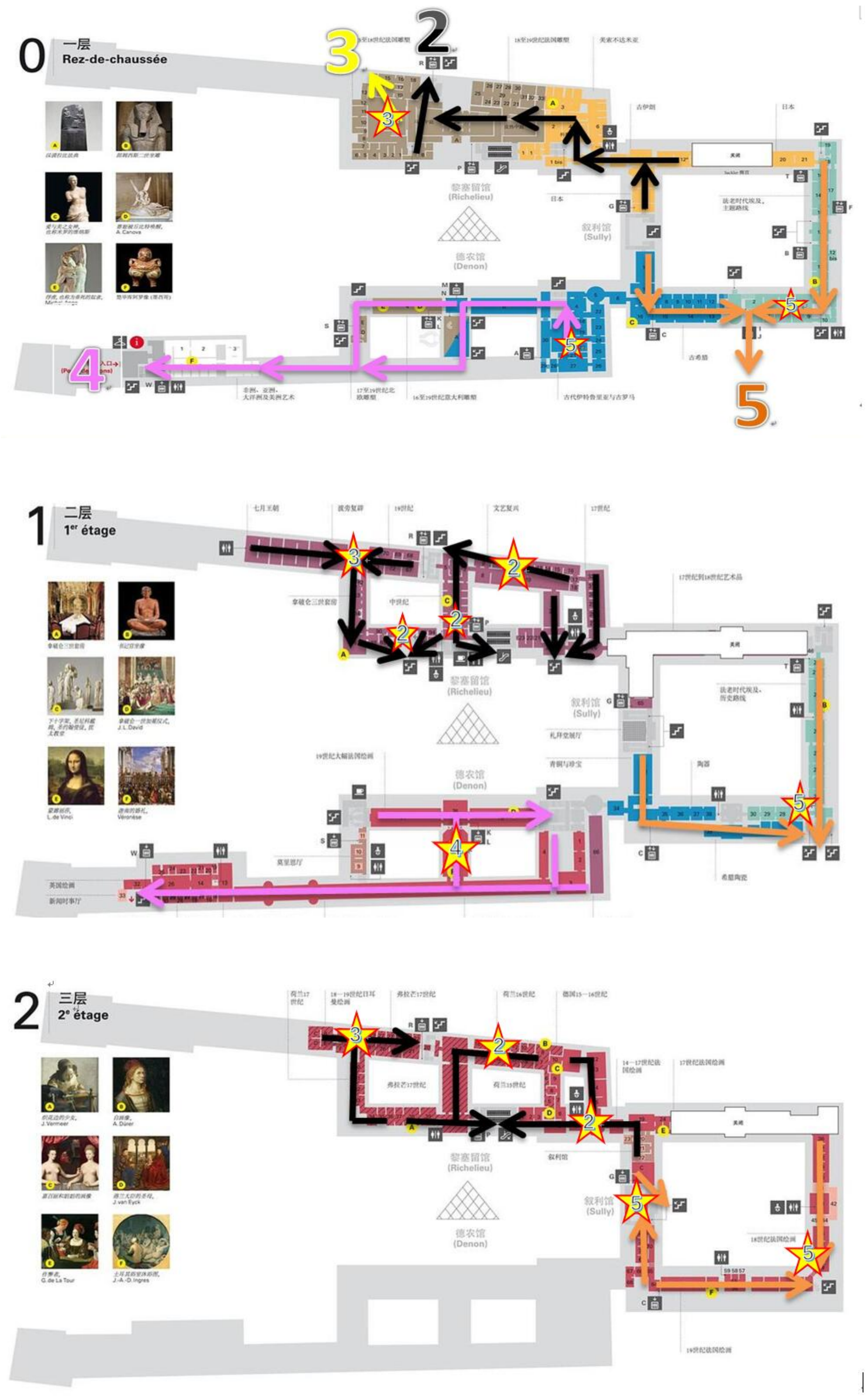
Exit	Number	Color
Pyramid	1	Green
Richelieu Channel	2	Black
Caluses	3	Yellow
Lion Gate	4	Pink
Art Gate	5	Orange
Metro	6	Blue

We found some bottlenecks after running the program. We used the star to mark these bottlenecks on the map. The entrance for the guard is pointed by the number at the center of the star. Since there are already arrows on the map, in order to prevent the pictures from getting messy, the guard's moving route is not marked on the map.

The evacuation routes we obtained by running the program are showed as followed:



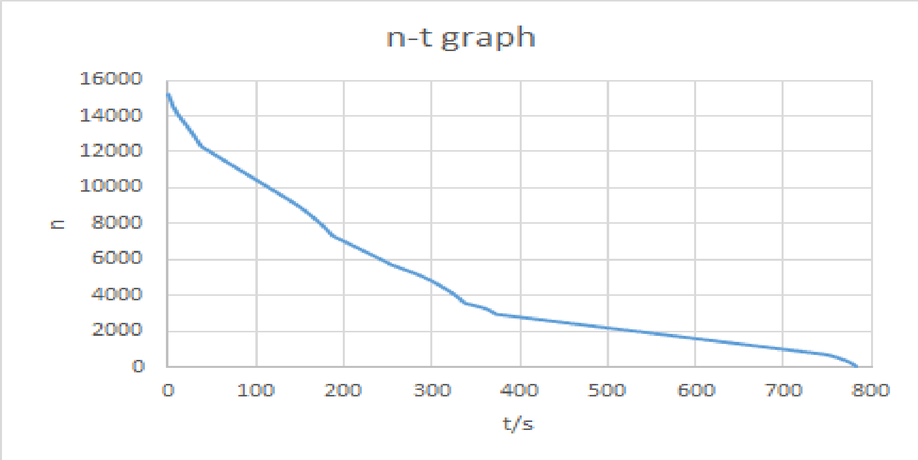




7.2 The Crowd Evacuation Process

Under the above conditions, the evacuation process of the visitors is simulated, and an image of the number of people who have not been evacuated (n) versus time t (unit: second) is obtained.

The evacuation time was 792 seconds (13 minites).



7.3 The Guard

7.3.1 Guard position

We input a coefficient by the simulation of the final evacuation plan. When the simulation found that the number of people in a room exceeded the maximum occupancy of the room,we call this room a bottleneck.In the bottleneck, we need guards to guide and increase the speed of personnel passing through the room.

7.3.2 The optimal path for the guard to arrive at the right location

Under our assumption, the evacuation of personnel and the movement of guards do not interfere with each other.The shortest path and path length from each equipped point to 6 exits can be directly calculated by using the breadth-first traversal (BFS).According to the length of each path, we can know where the police get into the building and the route they move in the building.

8 Further Discussion

8.1 Take other small exits into consideration

Since considering the changes in other exports, there is no substantial change to our model, only the increase in the number of exports, we can directly add these exports to the map, and recalculate to get the optimal evacuation plan.Of course,the evacuation conditions of these exports are not as good as other major exports, so the safety performance, efficiency performance of other small exits can be assessed by the staff.The staff decide a flow that can be tolerated during evacuation, change the parameters of these exits in the map, and recalculate it. In this way, we can make the algorithm more widely used.

8.2 Response to other accidents

Considering that the consequences of terrorist attacks are not limited to accidents such as fires, and there are often incidents in which the attacker has a knife and wounded. In this case, evacuation should be considered to avoid terrorists. Owing to this,time becomes a secondary factor. The problem to be solved is to evacuate the personnel to the exits of the suspects and minimize the casualties.The problem we have to solve is to let the tourists leave the terrorists as soon as possible and get to the safe place as soon as possible.So as to ensure the personal safety of the personnel.

We can get the evacuation route through the following process:

1. Enter the position of the suspect into the program, calculate the position of the guard to the suspect, the optimal entrance and the corresponding route, and time of getting to that position is t_{min}.
2. Get an initial optimal solution
3. The simulation annealing algorithm is also used to continuously improve the scheme, and the energy corresponding function is changed from the evacuation time to the derivative of reciprocal distance from the suspect after the t_{min}, the nearest visitor to the suspect.

8.3 Apply this algorithm to other large buildings

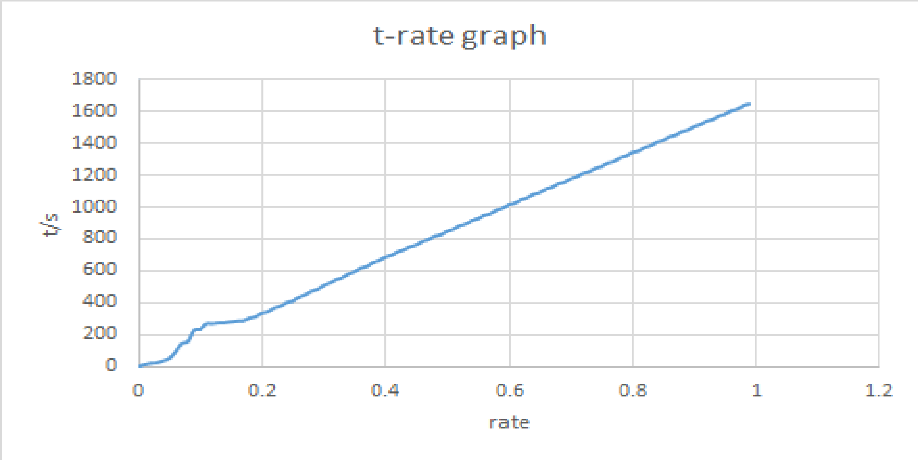
For other large buildings, just enter the map into the program, then:

1. Recalculate the speed of personnel flow between two rooms according to the type of passage in the building .
2. Re-establishing the criteria for determining the bottleneck.
3. Re-determine the maximum number of people in each room.

Then use the same process to calculate an optimal solution.

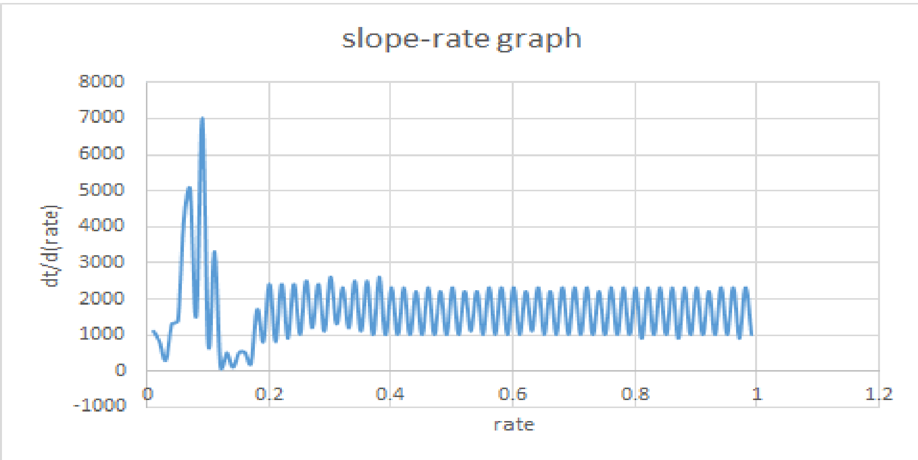
9 Validating the Model

Under the optimal evacuation scheme calculated by $rate = 0.46$, if the actual number of people corresponding to the rate parameter is not 0.46, the simulated evacuation time varies with the rate.



This simulation is made under the assumption of $r = 0.46$, but the actual r is not necessarily equal to 0.46, so sensitivity analysis is needed to make the model more realistic.

We derive this function and the slope of the original function fluctuates around a fixed value. The closer to 0.46, the smaller the amplitude, so we can see that our model has a certain realistic value.

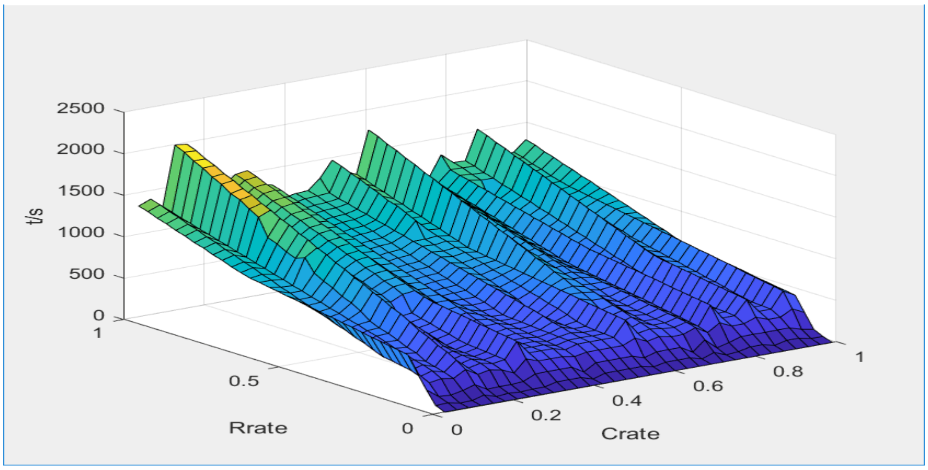


Further, for inputting different rate parameters, the optimal solution in the corresponding case is obtained. Under these schemes, different actual rates correspond to the simulated evacuation time,and make the following chart.

Crate: The rate parameter entered when calculating the optimal evacuation plan.

Rrate: The actual number of visitors corresponds to the rate.

t: Evacuation time.



10 Conclusions

1. The Louvre staff should set up evacuation signage at appropriate places in the museum to connect the controls to the program.

2. In the event of a terrorist attack,staff should firstly determine the type of attack and input it to the program. For the incident in which the terrorists attack people by a knife,the staff should enter the location information of the suspect.

3. Based on this information, the program calculates the optimal evacuation plan and controls the display of the signage.According to the plan,the staff control the display of the signage to help people get out of the dangerous place. At the same time, the program calculates the location of the bottleneck, and the best route to these locations.The guards, "emergency personnel"will get to these locations according to the instructions to guide visitors to evacuate.

11 Strengths and weaknesses

11.1 Weakness

1. The solution of the model takes some time (about ten seconds), which may have some negative effects on evacuation activities.

2. The model believes that people are completely following the instructions, which is not completely consistent with the actual situation, some irrational actions of people may increase the actual evacuation time.

11.2 Strength

1. The evacuated route calculated by the model allows visitors to leave the Louvre safely in the shortest possible time.

2. The scope of adaptation is large and can be targeted at different types of events. And the location of the attacker and the congestion of the venue can also be used as a parameter to input model, so the application of the model is flexible. In addition, this model is applicable to the evacuation of tourists in other large buildings.

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Appendices

Appendix A First appendix (C++ File)

We simulate this problem with C++.

A.1 museum.h

Modeling the Louvre, expressed by program:

```
#ifndef MUSEUM_H_INCLUDED
#define MUSEUM_H_INCLUDED

#include "typedef.h"
#include <iostream>
#include <queue>
#include <fstream>
#include <assert.h>
using namespace std;

class museum
{
private:
    room roomList[700];
    void Insert(int x, int y, char type);
    int flow(int start, int End)const;
    double rate;
```

```
public:
    int totalP;         //headcount
    museum(double rate);
    void dataInput();
    void unweightedShortDistance(int route[6][700], int cost[6][700])const;
    void judgeDirection(int route[7][700], int cost[7][700]);
    //Assign values to direct and border
    void judgeP(double rate);   //The P member is determined by the rate
    void judgeBorder(vector<int> &border);
    int calculateTime();        //Calculate the evacuation time under the current plan in secor
    bool exist(int r1, int r2)const; //judge if there's a channel between r1 and r2
    void change(int n); //Change the target exit of room n
    int exit(int r)const{return roomList[r].exit;}
    int dire(int r)const{return roomList[r].direct;}
    void change(int n, int exit, int dire){roomList[n].exit = exit; roomList[n].direct = dire;}
};

#endif // MUSEUM_H_INCLUDED
```

A.2 simulator.cpp

The evacuation process of tourists is simulated and the evacuation time is calculated.

```
#include "museum.h"
#include <cmath>

int museum::calculateTime()
{
    const int Inf = 2147483647;
    int t=0, flowP, errorC=0;
    int exitP = 0;  //Already alienated
    int texitP = 0; //Number of people evacuated at the last moment
    while(exitP<totalP)
    {
        for(int i=100; i<700; ++i)
        {
            if(roomList[i].property == room::V) continue;
            flowP = flow(i, roomList[i].direct);
            roomList[i].P -= flowP;
            roomList[roomList[i].direct].P += flowP;
        }
        texitP = exitP;
        exitP=0;
        for(int i=1; i<=6; ++i)
            exitP+=roomList[i].P;

        if(texitP==exitP) ++errorC;
        if(errorC >= 1000)  //The scheme is stuck in an endless loop
        {
            t = Inf;
            break;
        }
        ++t;
    }
    judgeP(rate);
    return t;
}
```

A.3 main.cpp

Optimize the evacuation plan, and keep approaching the optimal solution.

```
#include <iostream>
#include "museum.h"
#include <vector>
#include <cstdlib>
#include <time.h>
#include <cmath>
using namespace std;

int main()
{
    double rate;
    cout<<"Please enter congestion level(rate)(0-1)"<<endl;
    cin>>rate;
    museum louvre(rate);
    louvre.dataInput();
    //bfs
    vector<int> border;            //Store boundary node number
    int route[7][700];
    //route[i][j] represents the next node under the shortest path from node j to exit i
    int cost[7][700];
    //cost[i][j] Represents the number of rooms traversed by the shortest path from room j to e
    for(int i=0; i<7; ++i)  //initializing
        for(int j=0; j<700; ++j)
        {
            route[i][j]=0; cost[i][j]=0;
        }
    louvre.unweightedShortDistance(route, cost);    //bfs
    //Build the initial evacuation plan
    louvre.judgeDirection(route, cost);
    louvre.judgeBorder(border);
    louvre.judgeP(rate);
    int tp = louvre.calculateTime(), t;
    const double rt = 0.99, Te = 5;
    double T = 500;
    //Simulated Annealing
    cout<<"In the calculation process, the time required for the evacuation of the intermediate
    int e1, e2, d1, d2, r1, r2;
    srand(time(NULL));
    double possi;   //probability
    const int Inf=2147483647;
    while(T>Te)
    {
        //Calculate the new evacuation plan
        do
        {
            r1 = rand()%border.size();
            r2 = rand()%border.size();
        }while(r1==r2 || louvre.exist(border[r1], border[r2]));
        e1 = louvre.exit(border[r1]);
        e2 = louvre.exit(border[r2]);
        d1 = louvre.dire(border[r1]);
        d2 = louvre.dire(border[r2]);
        louvre.change(border[r1]);
        louvre.change(border[r2]);
        t = louvre.calculateTime();
        if(t<tp)                                    //accept
        {
```

```
            louvre.judgeBorder(border);
            tp = t;
        }
        else
        {
            possi = exp((tp-t)/double(T));
            if(t==Inf || rand()/double(RAND_MAX)>possi) //reject
            {
                louvre.change(border[r1], e1, d1);
                louvre.change(border[r2], e2, d2);
            }
            else                                        //accept
            {
                louvre.judgeBorder(border);
                tp = t;
            }
        }
        T = T*rt;
        cout<<tp<<endl;
    }
    return 0;
}
```

Appendix B Second appendix (Matlab File)

We use Matlab to validate our model and find the relation among the evacuation route, evacuation time and the density of evacuated population. In addition, we also evaluated the stability of evacuation schemes using Matlab.

In the sensitivity test, the calculated time data are used to make a three-dimensional diagram through this program.

Input matlab source:

```
ratex = 0.03:0.03:1; %The rate when calculating
ratey = 0:0.03:1;    %The rate when simulating
[rateX, rateY] = meshgrid(ratex, ratey);
time = importdata("check.txt");
%"Check.txt" the evacuation time calculated
%by c++ program corresponding to different
%ratex and ratey
time = time';
surf(rateX,rateY,time);
```