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2019
MCM/ICM
Summary Sheet

Summary

As the world's largest art museum and a landmark of Paris, *Musée du Louvre* attracts more than 10 millions people a year, which makes it necessary to construct efficient evacuation plans for different emergent circumstances. In this paper, two models are set up in order to simulate the evacuation situation from several connected rooms and calculate the time needed.

In the first model, rooms are simplified as small wall elements and exit elements. All the people inside the room are represented by agents. For each specific individual, he or she experiences both repulsive forces from the walls and other agents and attractive forces from the exits. All those forces together will change the agent's state of motion at any time. Meanwhile, the positions of agents also change ceaselessly, resulting in simultaneous change of forces. Such kind of dynamic system will eventually force all the people escape from the room. The model is implemented with MATLAB & Simulink. Some representative rooms of the museum are chosen as the test region and 500 people are placed inside the rooms with random initial positions. It takes 81 seconds for all people to evacuate from the test region, which coincides with the result of a former experiment conducted by Smith (1995).

After the construction of the first model, AnyLogic is used to simulate the evacuation situation for G floor of the museum. Referring to the guidance map given in the museum's official website, the floor plan was drawn. The tourists were represented with agents (circles) as before, while the diameters of the circles were calculated referring to proportional scale. The movement speed of agents was calculated with the same method. Each room could generate some visitors, and the generation rate is the same as that of the first model. After the agents get to their destination (stairs or exits in our case), they will simply disappear in the program.

Finally, we made some analysis on these two models, where one is microscopic while the other one is macroscopic. Robustness and rationality are enhanced after our modification for the first model. However, there still exist some remaining weakness in our model. In the end, we made some suggestions to the museum's personnel based on the simulation conduced by these two models.

Evacuation Model for *Musée du Louvre*

January 29, 2019

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Keywords: Agent-based simulation; MATLAB & Simulink; AnyLogic; Potential Field

Contents

1 Introduction

1.1 Background

Musée du Louvre is known as one of the world most famous museums. Possessing plenty of historical collections, the museum attracts more than 10 million per year, including various groups from researchers to students. As a former palace, Musée du Louvre occupies large volume and has complicated structure. Ruling out the secret entrances and the emergency exits, there are still four official exits for daily usage. Thus, even though there are some signs inside the museum, it is hard for visitors to find a way out of the museum under emergent circumstances.

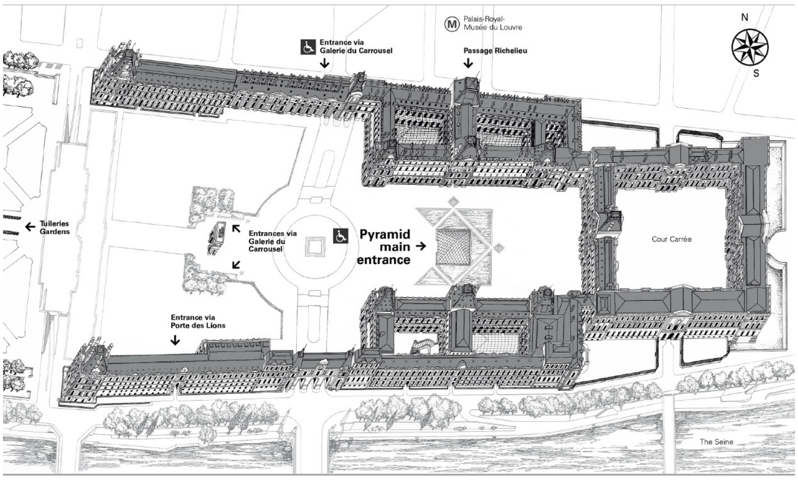

Figure 1: *Musée du Louvre*

In 2018, a number of terrorist attacks took place in France, where *Musée du Louvre* locates in. On 23rd March, a series of gun shooting accidents took place in southern France, causing around four death and fifteen injury. On 12nd May, a knife attack happened in Paris. One citizen was killed and at least four pedestrians were injured in this incident. Another terrorist attack occurred on 11st December in Strasbourg. The criminal, armed with a revolver and a knife, killed five and wounded at least eleven innocent people. From incidents listed above, it seems that there is a high possibility that terrorists attacks happen in France recently.

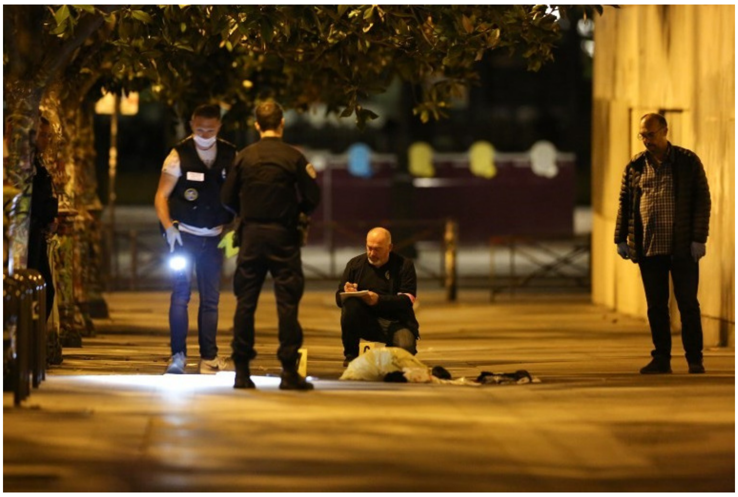

Figure 2: Terrorist attack

With so many visitors every day, Musée du Louvre and its nearby area might be chosen as the location of terrorist attacks. There is no deny that the security inspection of Musée du Louvre is of strictness, which implies that gun shooting or knife attack is not likely to happen inside the museum. However, when an accident happened somewhere near the museum, the visitors are still likely to be panic after noticing the abnormal situation. At this moment, it is necessary to organize an evacuation, enabling tourists to move to a safe area out of the museum. Except for evacuation drills, using simulation to estimate the evacuation time on computer may also contribute a lot for further study and the design of evacuation route.

1.2 Our main Work

Instead of analysing the whole floor, we firstly analysed a typical room in the museum. The simulation of evacuation in some small rooms was conducted with a MATLAB program modified from the code written by Daniel Zund and Simon Schmid. Outside walls were built up according to the map and some blocks were set up to simulate the inside structures of the room. Then people were filled in for the simulation of the evacuation process.

After figuring out the situation of those separate rooms, we simulated the evacuation of a whole floor (G floor) with AnyLogic. Some of the parameters were decided by the analysis mentioned above. We made an animation to simulate the situation when an accident happened and also calculated the time needed for evacuation.

2 Problem Restatement

In this paper, we attempted to solve the following questions:

- Construct a model for the evacuation of *Musée du Louvre* which enables all the visitors to reach the exits when different kind of terrorist attack take place. The model should be able to apply to different circumstances, that is, when different kinds of terrorist attacks happen.
- As an ancient palace, *Musée du Louvre* has a complex structure inside, leading to some potential bottlenecks which could limit speed of movement towards the exits. The model should consider the different scenarios in different doors.
- Since there are some secret exits which are only known by museum officials, the model should be flexible so that emergency personnel could be possible to enter the museum quickly.

3 General Assumptions

- Assume that there are 10 million visits in *Musée du Louvre* for per year. On average, each person will spend four hours in the museum. It could be calculated that each floor will be visited by 2400 people per hour. Separate them uniformly, a single room will be visited by around 150 visitors every hour.
- Considering different figures of different tourists, we investigated the proportion of visitors in *Musée du Louvre*, distinguished by their nationality. BMI (Body Mass Index) for citizens from different countries was used to estimate their height-weight ratios. In our model, the people elements were treated as small circles, so different radius of each circle reflected different height-weight ratios for each visitors. In a real evacuation, the time for a visitor to pass through a door is usually positively proportioned with his or her BMI, thus the radius of those circles mentioned above affected the running time of our model.

4 Model of a Typical Room in Louvre

4.1 Description

Normally, most of the people try to leave the room as soon as possible at the moment that terrorist attack happens. However, the limited capacity of the exits only allow several people to pass through at the same time. As a result, most people will slow down as they get closer to the exit.

Newton's First law indicates that in an inertial frame of reference, an object either remains at rest or continues to move at a constant velocity, unless acted upon by a force. In our model, the velocity of an particular individual in the room is changed in each iteration. Both of the velocity's modulus and direction will change as time passes by. Hence, this kind of change should be the result of some forces acted on the agent. These forces produced by the muscles around the body actually follow the decisions made by human mind. Several factors will contribute to decisions, such as the positions of the exits, walls, obstacles and other people. Since these factors can be easily detected in our model, the forces inside human body are simplified as several specific forces caused by the outside world.

The room can be dissembled as four parts: walls, obstacles, doors and people. Doors represent exits, and they must be embedded in the walls. Obstacles are internal piles blocking the movement of visitors. Three rules are imposed in the model. Firstly, people cannot pass through the walls and piles. Hence, when they make movement, they tend to get away from obstructions. Secondly, they are attracted by the doors, resulting in the movement heading for exits. Thirdly, people can interact with each other. For example, as more and more people are blocked near the exits, those people who come later will gradually slow down. The influences of these three parts towards a specific individual i are abstracted as forces in the model.

4.1.1 Definition of three forces

- Forces from walls and obstacles

  Since the walls and obstacles are static during the whole procedure of the evacuation, we can discrete them as congruent square elements. Each element j will act a force on the person i, which can be denoted as $F_{w,i,j,t}$. Since the people always choose to get away from the walls or obstacles, we can assume that the modulus of $F_{w,i,j,t}$ is inversely proportional to the distance $r_{i,j,t}$ between the element j and person i. The formula can be written as:

$$|\vec{F}_{w,i,j,t}| = k_w \cdot \frac{1}{r_{i,j,t}}$$

  Where k_w is called the *coefficient of the wall.* All small forces are treated as vectors and all of them are added up according to the vector addition. All forces acted by the walls and obstacles on an individual i can be calculated as:

$$\vec{F}_{w,i,t} = \sum_{m=1}^{j} \vec{F}_{w,i,j,t}$$

- Forces from the doors

  The influences from exits are quite similar to walls and obstacles mentioned above. All of the them can be divided into small elements as well. But the formula of the forces is a little different. The forces acted by the element k are proportional to the square of the distance $r_{i,k,t}$ from person i. The formula can be written as:

$$|\vec{F}_{e,i,k,t}| = k_e \cdot (r_{i,k,t} + s)^2$$

  Where k_e is called the *coefficient of the exit.* We adapt a parameter s to avoid the situation that when a person is quite close to the exits, the force from the exits approaches to zero, which is not proper when considering the reality. In a real scheme, people feel at ease when getting closer to the exits, while they are still attracted by the exits. Here the total force acted by the exits on an individual i can be calculated as:

$$\vec{F}_{e,\,i,\,t} = \sum_{m=1}^{k} \vec{F}_{e,\,i,\,k,\,t}$$

- Forces from other agents

  From the eyes of a specific individual i, other agents are nothing but obstacles, which will provide repulsive forces. However, the biggest difference between them is that people can move to another place when time changes. Hence, it is more difficult to calculate the distance between two individuals. What's more, we assume that other people will not act forces on the selected individual i until i is located inside some regions around them. We denote this kind of regions as *interacting region*, which can be viewed as a circle with radius R_n. When individual i is inside an interacting region, she will be influenced by a force which is inversely proportional to the distance $r_{i,\,n,\,t}$ between the agent n and person i. The formula can be written as:

$$|\vec{F}_{a,i,n,t}| = k_a \cdot k_d \cdot \frac{1}{r_{i,\,n,\,t}}$$

  Where k_a is called the *coefficient of the agents* and k_d is called the *coefficient of determination*. k_d can be used to determine whether the individual i is inside the interaction region of the agent n. If $r_{i,\,n,\,t}$ is larger than R_n, we choose k_d to be 0. On the other hand, if $r_{i,\,n,\,t}$ is less than or equal to R_n, we will choose k_d as 1. Hence, the total force acted by other agents on an individual i can be represented as:

$$\vec{F}_{a,\,i,\,t} = \sum_{m=1}^{n} \vec{F}_{a,\,i,\,n,\,t}$$

4.1.2 Total Forces Act On the individual i at time t

For each individual i at time t, the total force act on her can be viewed as the simple vector addition of three kinds of forces mentioned above. The formula can be written as:

$$\vec{F}_{i,\,t} = \vec{F}_{a,\,i,\,t} + \vec{F}_{e,\,i,\,t} + \vec{F}_{w,\,i,\,t}$$

In order to visualize our concept of forces acting on people, a simple model of evacuation was draw. In the image 'Force', the small circles represented for people and black boundaries represented for the walls. An exit was set in the left side of the boundary. All of the people move ahead for the door when emergence happens. We simply chose an individual and draw the visualization of the forces acted on her at the given time. Hence, the speed of the individual i will change according to the total force $\vec{F}_{i,\,t}$.

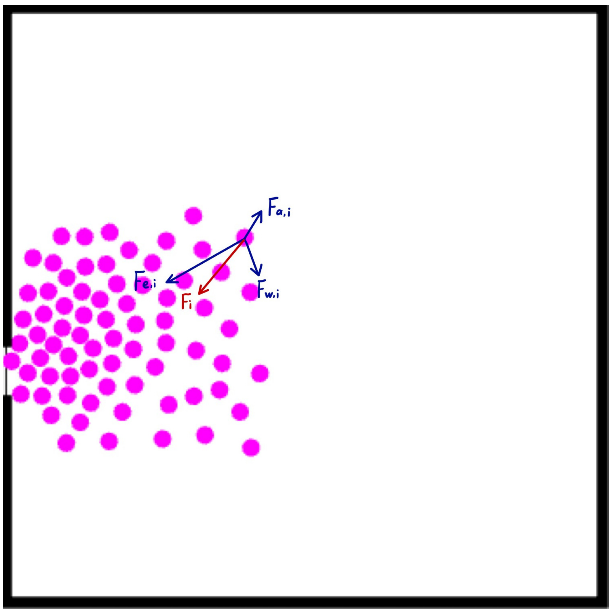

Figure 3: Forces in 4.1.2

4.1.3 Velocity and Position of individual i at time 0

In the model, time 0 is assumed to be the exact moment before the emergency happens. Under such kind of assumption, all of the people at time 0 have random positions and initial velocities. We firstly simplified our model by assuming that everyone has the same initial velocity v_0. However, in reality, there are some disabled people who cannot move as fast as others. Hence, in our further experiment, the initial velocity will be adjusted according to different kinds of people.

4.1.4 Solve Velocity and Position of individual i at time t

According to the Newton's Second law, in an inertial frame of reference, the vector sum of forces $\vec{F}$ imposed on an object is equal to the mass m of that object multiplied by the acceleration $\vec{a}$. Hence, after figuring out the initial position and velocity of an individual i and the total force act on i at time t, we can calculate the velocity and position of i at any time t by the following formula:

$$\vec{F}_{i,t} = m \cdot \frac{d^2\vec{x}}{dt^2} = m \cdot \frac{d\vec{v}}{dt}$$

In theory, the equation is solvable since all the conditions that is required are known. However, it is a little complex to solve it directly. Hence, a numerical method was introduced for solving this kind of equation.

4.1.5 Numerical Method to Solve Velocity and Position of individual i at time t

We can discrete the time into small intervals to simplify the calculation. When $\triangle t \to 0$, the total force acted on a specific individual remains unchanged. Meanwhile, the velocity changes at the beginning of every time segment and remains unchanged (both modulus and direction) during the time segment $\triangle t$. Hence, during $\triangle t$, we can treat the movement of the individual as uniform linear motion. Knowing the velocity of an individual at time t, we can calculate the velocity at time $t + \triangle t$ by the formula:

$$\vec{v}_i(t + \triangle t) = \vec{v}_i(t) + \vec{a} \cdot \triangle t = \vec{v}_i(t) + \triangle t \cdot \frac{\vec{F}_{i,t}}{m}$$

Meanwhile, knowing the position of an individual at time t, we can also calculate the position at time $t + \triangle t$ by the formula:

$$\vec{v}_i(t + \triangle t) = \vec{x}_i(t) + \vec{v}_i(t + \triangle t) \cdot \triangle t$$

Notice that all the positions, velocities and forces in the formulas above are vectors and should be calculated according the rules of vectors.

4.2 Simulation

In this session, several connected rooms in the museum with typical shapes were chosen for simulation. The rooms were simplified and converted into the walls and exits models for further analysis. The empty rooms are shown in the image below:

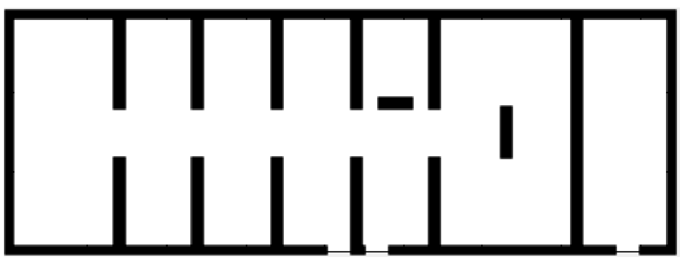

Figure 4: An Empty Room

The black lines are walls and obstacles. Each room has one or more doors that connect it to the nearby rooms. There are three exits from which people can finally escape the room. These doors are all on the lower boundary. Furthermore, people need to be filled into our model. Since the body sizes are different among people around the world, every individual has her own interacting region with different radius. In order to simplify our model, the radius of interacting region was assumed to be proportional to the shoulder width, and the shoulder width is proportional to the height. According to Louvre Press Release (2018), in 2017, the visitors of Louvre mainly came from France (30%), the United States (13%), China (8%), Brazil (3.5%), the United Kingdom (3.4%), Germany (3.1%), and Spain (2.7%). Hence, we mainly considered the average radius of interacting region of the people in these countries. People from other countries will be considered to have the same radius of interacting region as the world average one, which is defined in our model as 1.5 meters for male and 1.38 meters for female. Besides, we retrieved the average height of male and female in different countries from the website WorldData. Data of the countries that mentioned above are chosen and calculated to obtain the average radius of interacting region of the male and female. The results are listed in the table below:

		WORLD AVERAGE	FRANCE	U.S.	CHINA	BRAZIL	U.K.	GREMAN	SPAIN
M	Height(m)	1.75	1.79	1.77	1.71	1.73	1.78	1.80	1.76
	Radius(m)	1.50	1.53	1.52	1.46	1.48	1.53	1.54	1.51
F	Height(m)	1.61	1.65	1.64	1.59	1.60	1.64	1.66	1.63
	Radius(m)	1.38	1.41	1.40	1.36	1.37	1.41	1.42	1.40

Figure 5: The Table of Dimensions of People in Different Countries

In the simulation, we randomly generate 500 people in one room at the beginning (t=0). We assume that the proportions of tourists' nationalities in a single room are the same as those in the whole museum. Hence, there are 150 tourists from France, 65 from the US, 40 from China, 18 from Brazil, 17 from the UK, 16 from Germany, 13 from Spain and 181 from other countries. Meanwhile, we assume that the ratio of male and female are 1 to 1.With the assumptions stated above, we abstracted each individual to be a circle with its own radius of interacting region and add them into the rooms. The result is showed as following:

Figure 6: A Typical Room with Tourists

The simulation was implemented with MATLAB and Simulink based on code provided by Daniel Zund & Simon Schmid (2010), which are open-source codes published on GitHub. We defined the positions of each wall elements and exits elements in several csv files. Meanwhile, we recorded the radius of interacting region of each individual in another csv file named as rad.csv. In our model, we innovatively define an evacuation plan. As Daniel Zund & Simon Schmid (2010) mentioned in their model, all of the tourists in a given room are only attracted by the final exits (the exits on the lower boundary in our example). However, it is not the case in many circumstances. For example, people in the leftmost room can only see the door which connects the adjacent room. Hence, they can hardly be attracted by the final exits since they may even do not know the locations of final exits. It is much more reasonable to assume that people in every small room can only be attracted by the doors of the certain room.

We choose $k_w = 5$, $k_e = 60$, and $k_a = 15.85$ in our model and use the MATLAB to do the simulation. The result is presented below:

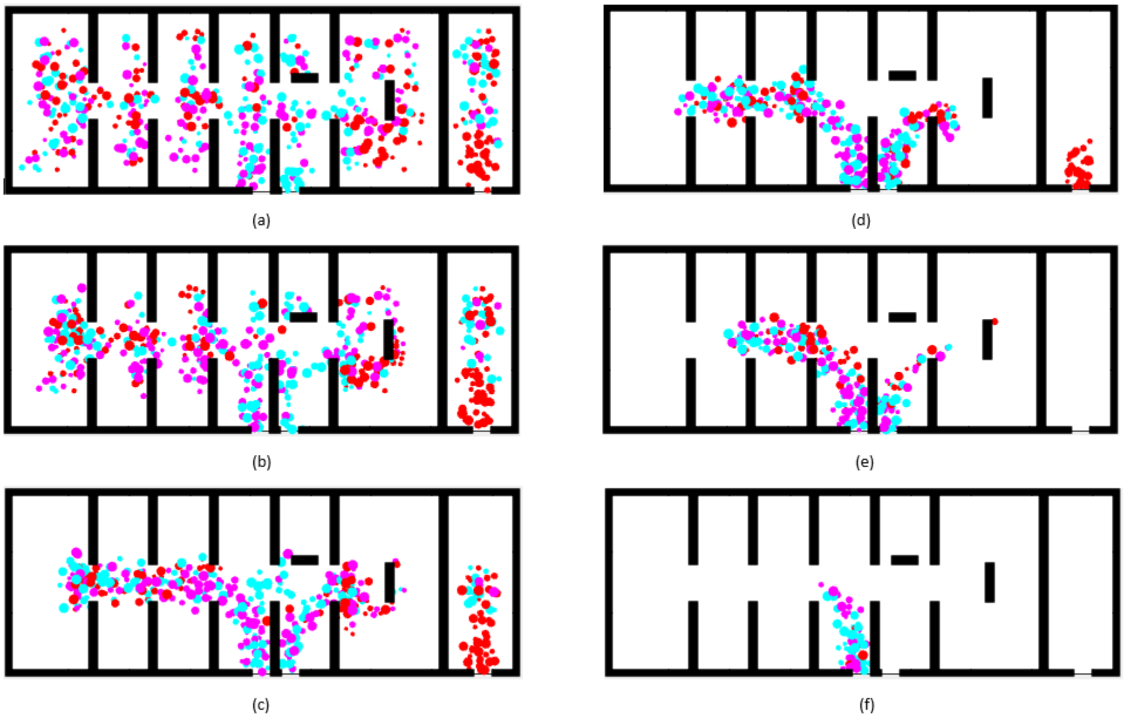

Figure 7: The Simulation Process of Model 1

5 Model of A Whole Floor

Apart from constructing the evacuation model for a single room in the museum, we also construct a model for a whole floor with AnyLogic. We firstly draw the blueprint according to the guidance map provided by the museum's website.

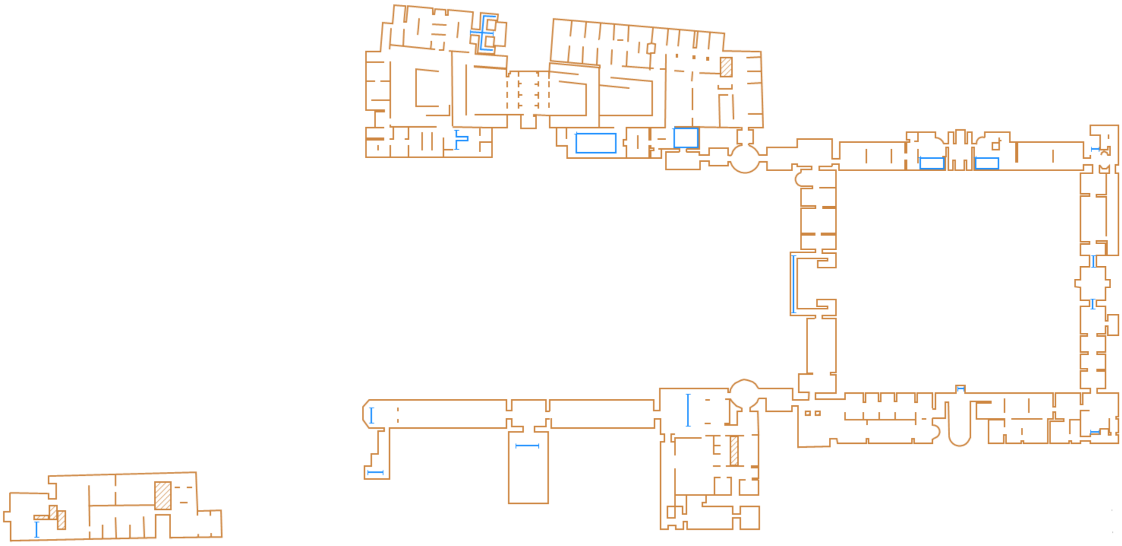

Figure 8: The Floor Plan of *Musée du Louvre* G Floor

In the model, the brown lines represent the walls or obstacles which would block tourists' way, the blue lines/rectangles represent the stairs or exits where tourists can exit the museum or going downstairs and the green polygons represent the regions where tourists could be when the terrorist attacks happen. Instead of letting tourists appear at the very beginning, we created some sources which could generate agents continuously. The whole floor is separated into several parts and agents in each part are assigned to specific stairs (usually the nearest one). When an terrorist attack take places, agents in each region will go to exits as assigned.

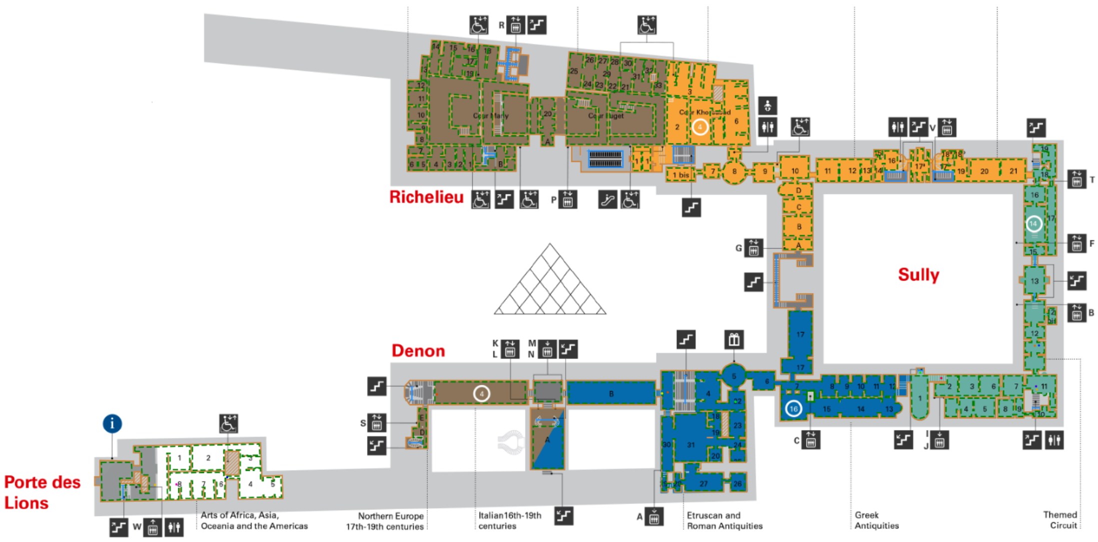

Figure 9: The Tourist Map of *Musée du Louvre* G Floor

In the model, tourists appear as circles with certain diameters on the map. Considering the different dimensions of people from different countries as well as larger volume people occupy when escaping, we set the range of the diameters to be 0.8 meter to 0.9 meter with uniform distribution. The initial velocity of each agent is set to be from 0.3 to 0.7 meter per second, uniformly distributed, considering different states of agents (some may be sitting on the bench while others are walking). The comfortable speed is set to be from 0.5 to 1 meter per second, uniformly distributed, since it is nearly impossible for people to move fast when it is crowded.

The figures below shows the process of simulation. The colourful circles insides simulate tourists.

Figure 10: Simulation Process of Model 2 for Upper Half of *Musée du Louvre* G Floor

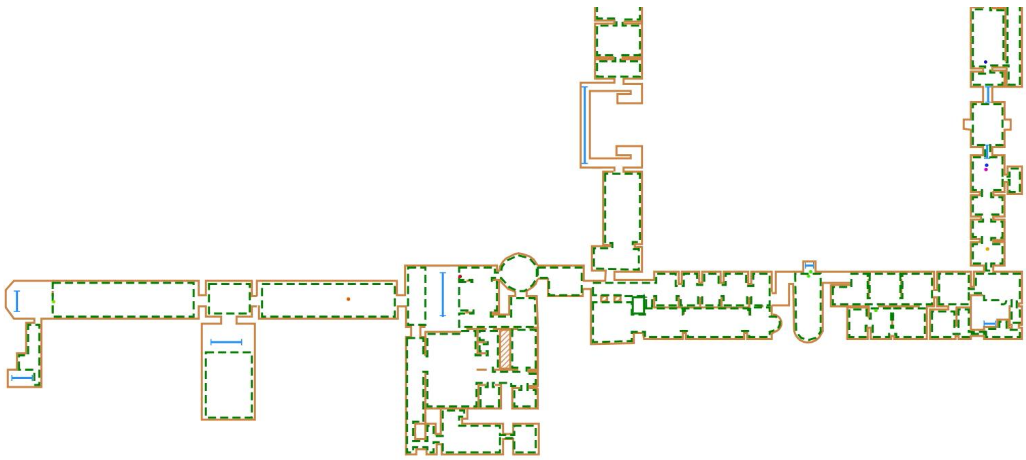

Figure 11: Simulation Process of Model 2 for Lower Half of *Musée du Louvre* G Floor

6 Validation of the Model for a Typical Room

According to Smith (1995), when emergency happens in a room, the evacuation rate is around 60 persons/(m · min), which means 60 people can escape from the room every minute through a door with width of one meter. In our model, the width of each exit is 2m. Under the assumptions of Smith (1995), the evacuation time in our model is around 83.3 seconds, which is quite close to the result of simulation. Hence, our model is valid and can be applied to other kinds of rooms.

7 Strength and Weakness

7.1 Strength

1. In our first model, after considering the proportion of visitors and the average height-weight ratios for different countries, the circles have different radius, which made the simulation more realistic.

2. In our first model, which the door is to be chosen as the final exit is not randomly decided in our model. The block inside the room affected the decisions made by agents. Then the situation that some people can never reach the exit they choose because of the block limitation will not happen.

3. Since our second model was conducted using a software, it is very flexible. With some modifications of parameters or addition of flowcharts, the model can be applied to other buildings for evacuation simulation.

7.2 Weakness

1. Our first model only studied a typical kind of room in Louvre. However, in the real situation, each room has its own structure, which may lead to different evacuation time.

2. In our second model, only one floor was considered while in the whole Louvre, each floor has some differences and may require different evacuation plan.

3. All the official exits are located at the -2 floor, indicating that all the visitors need sometime going downstairs. However, our model did not simulate the situation of going downstairs while this process happened in a confined space which should be further analysed.

8 Suggestions

Our model simulated the situation that all the visitors try to run out of the museum when a terrorist attack happens. However, leaving the museum may not be an optimal choice. As we mentioned in the introduction part, the security of Louvre is very strict, so the chance that a terrorist attack happens inside Louvre is relatively low. Sometimes staying in the museum is a better choice than leaving.

Thus, different evacuation plans should be applied for different kinds of terrorist attacks. If there is a knife attack or gun shoot outside, it could be much safer for tourists to stay in a basement which is impossible for terrorists to break in. It is also hard for tourists to find the exits considering the complicated structure of the museum. Even though there are explicit signs to the exits, it might be time consuming for tourists to go out of the museum, which makes staying inside a better choice. But if there were a conflagration, there is no doubt that visitors should leave as soon as possible.

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