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

Evacuation in Complex Structures: An Original Cellular Automaton Model with Quasi-potential Field

Emergency evacuation in public places is a real-life issue with multi complexities. The Louvre, as one of the most popular destinations in France, is deadly needing optimized evacuation model under the increasing threat. Without a suitable plan, the chaotic crowd in Louvre would bring a disaster of public safety and the artworks. In order to better develop evacuation plans, we propose a novel emergency evacuation model based on cellar automaton and the quasi-potential field.

Benefit from its ability of characterizing individual behavior, Cellular automaton has been an invaluable tool for establishing the evacuation model. Inspired by the plant roots, we propose a novel quasi-potential field to provide guidance for decision-making process of cells. After the computer simulation, we design an evacuation strategy based on the data we obtained. The crowd, under the guidance, gathered to the middle of the aisle and proceeded to the nearest exit. The opening of emergency exits, based on the quasi-potential field, would improve the efficiency of evacuation. This strategy is not optimal, but it allows the quick entry of emergency employers and prevent crowds from getting confused. It also protects precious artworks from the crowd.

Our suggested solution, including plans of evacuation and emergency exits, has high adaptability so it could be easily deployed to different complex large buildings. Our model can also handle it easily when there is any threat that altering or removing segments of possible routes to safety.

Contents

1 Introduction **1**
1.1 Problem Background . . . 1
1.2 Literature Review . . . 1
1.3 Our work . . . 2

2 Preparation of the Models **2**
2.1 Assumptions . . . 2
2.2 Notations . . . 2

3 Modelling **3**
3.1 Cellular Automaton Model of Evacuation of a Single Room . . . 3
3.1.1 Introduction of CA . . . 3
3.1.2 Simplified Model of a Room . . . 3
3.2 Quasi-potential Field of Building based on Root System Model . . . 4
3.2.1 Generation of the Root System Model within One Floor . . . 4
3.2.2 Root Growth Model of Potential of Pixels on Skeleton . . . 4
3.2.3 Root Water Uptake Model of Potential of Pixels off Skeleton . . . 5
3.2.4 Floor Interaction . . . 6
3.3 Combined Model with CA and Quasi-Potential Field . . . 8

4 Results **9**
4.1 Quasi-potential Field . . . 9
4.2 Where the Bottle Neck of Evacuation in Louvre Museum Is . . . 10
4.3 Where the New Emergency Exit Should Be . . . 11
4.4 Simulation of the Destructive Disaster . . . 11
4.5 Simulation of the Evacuation within Any Area . . . 12

5 Discussion **13**

1 Introduction

1.1 Problem Background

The Louvre Museum in Paris was attacked by terrorists on 3 February, 2017, raising public awareness of emergency evacuation. Louvre, with 3 wings, 4 entrances and 5 floors(of which 2 are underground), is seeking a feasible evacuation plan. The evacuation should be fast and safe, taking individual characteristics of tourists into consideration. Apart from the normal 4 entrances: the Pyramid main entrance, the Passage Richelieu entrance, the Carrousel du Louvre entrance, and the Portes Des Lions entrance, additional exits may be utilized at certain time according to our model. Technology methods including the application "Affluences" can be used. Moreover, the emergency plan should be adaptable to various emergent situations and building layouts.

This paper is expected to give discussions of the following issues:

- Establish models to describe the evacuation dynamics in Louvre Museum and locate potential bottlenecks.
- Characterize the prediction capability and reliability of the model.
- Develop a reliable evacuation strategy based on the model.
- Test the adaptability of the models based on other large buildings or variable threats.

1.2 Literature Review

Various research methods have been applied to describe the evacuation model, e.g. agent-based model[3], artificial potential field model[7], cellular automaton model[4], social force model[6], etc. A variety of emergency situations have been discussed, e.g. fire[10], earthquake[9], terrorist attacks[5], etc.

However, in all the papers we researched, the map used to design and examine the models are plain, spacious room with several exits. The obstacles in real life like concave-polygon-shape corners, pillars and thin-wall folding screens are not considered.

Our models are established on the real floor map of Louvre Museum. We carefully choose the most representative region with narrow corridors and complex structures to train our models. Our models are aimed at solving the low adaptability problem of previous models and improving simulation accuracy.

1.3 Our work

1. We describe the behaviour of evacuees in a single room using a improved Cellular Automata model. Then the algorithm is used on binary maps of 4 ïňĆoors of Louvre respectively. We developed a highly creative Root System Model to judge the most accessible exit in a complex, multi-exit structure. After that, distinct ïňĆoors are connected by marking stairwells and escalators as transport nodes.

2. We demonstrate our modelâĂŹs stability and reliability based on part of the Louvre to characterize the quasi-potential field and its combination with cellar automaton model.

3. We demonstrate the adaptability of our model by imitating various threats, altering or removing segments of possible routes to safety.

4. We propose our evacuation strategy based on the model, including the entry of rescuers and the opening of emergency exits.

2 Preparation of the Models

2.1 Assumptions

1. We ignore most features of pedestrians, e.g. height, figure, sex, etc. An occupant is represented by a pixel, while the size of pixel maps adapts to it. The parameters we use to describe the *cells* are: size, stepping distance, so that we can describe team-up and mobility-impaired evacuees.

2. We assume that all accessible stairwells are for downstairs. The passer-bys will be transported to the lower floor as soon as he steps on the stair region. The passing time of stairwells is discussing in a isolated Stair Model, dependent on people flow and velocity.

3. Based on on-line comments of Louvre visitors, we conclude that all four entrances, including the Pyramid main entrance, leads to the two-story underground lobby beneath the pyramid. Therefore, we assume that if a evacuee reaches the three central stair region on first floor underground.

4. We assume that new patches can be released for *Affluence* to achieve addition functions, e.g. gleaning location information from users, pointing out real-time direction paired with mobile phone built-in compass.

2.2 Notations

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

Table 1: Notations

Symbol	Definition
A	the first one
b	the second one
α	the last one

3 Modelling

3.1 Cellular Automaton Model of Evacuation of a Single Room

3.1.1 Introduction of CA

Each evacuee is described with a pixel, namely a *cell*. Each cell has two possible states, black(representing 0) and white(representing 1). The neighbourhood of a cell is the nearby cells. The two most common types of neighbourhoods are the von Neumann neighbourhood and the Moore neighbourhood, here we adopted the former one.

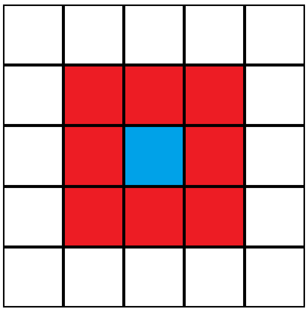
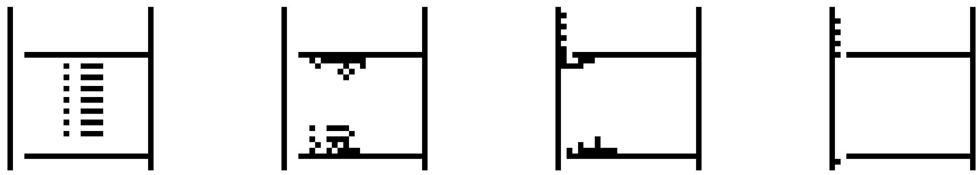


Figure 1: Moore Neighbourhood of the blue cell

3.1.2 Simplified Model of a Room

We build a demo map with the essential factors of a complete binary map: surrounding walls, perpendicular corners, several exits, evenly dropped evacuees. Two destinations were set at G positions.

For each *Moore neighbourhood*, we calculate its *Manhattan distance* from two G positions, and have sum, named as *obstacle amount*. The cell will move to the neighbourhood with the least obstacle amount.



Initial State. Step 6. Srep 20. Step 37.

Figure 2: The demo map of a single room

3.2 Quasi-potential Field of Building based on Root System Model

3.2.1 Generation of the Root System Model within One Floor

We first attain the floor plan of Louvre from its website using screen capture software and remove the inaccessible area.

Because the three main stairwells to the second floor underground were labelled as terminal nodes of evacuation, the map of the underground two was not processed. The maps of the second floor, the first floor, the ground floor and the underground one are attained likewise. The location of stairs is emphasised with red(R=237, G=28, B=36).

We use the skeleton algorithm [2] to stimulate the path of crowd centre. The skeleton algorithm is a iterative thinning algorithm that can extract the one-pixel-width skeleton of shape binary images. Using this algorithm, a new model (Figure 3) can be obtained. It's named as *Root System Model* because the pattern of skeleton lines converging looks like the roots of plants in arid areas.

Figure 3: From the RGB image to its root map: Take the ground floor as an example.

3.2.2 Root Growth Model of Potential of Pixels on Skeleton

The grey pixels in Figure 4 represents the skeleton of accessible region.The red pixels are the intersections of skeleton and red stairwell regions, defined as destinations. According to the principles of Morphological skeleton, each point on the skeleton leads to at least one destinations.

We assign potential value 1 to the skeletal pixels adjacent to the destination pixels. Then the value of its von Neumann neighbourhoods(Figure 5), if on the skeleton, will be higher by 1. The assignment process from each destination will move step by step at the same pace. After a designed number of rounds, every pixel on skeleton will be assigned a potential value.

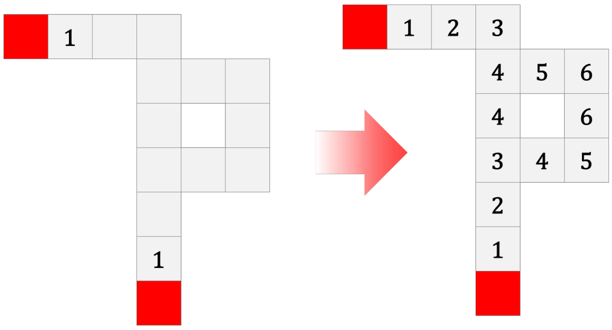


Figure 4: The incremental algorithm of root growth

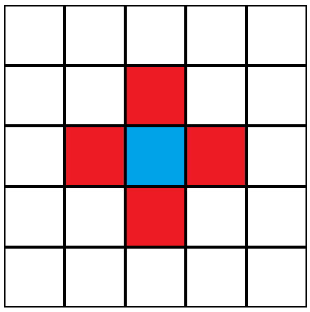


Figure 5: von Neumann Neighourhood of the blue cell

3.2.3 Root Water Uptake Model of Potential of Pixels off Skeleton

On the basis of potential values of pixels on skeleton, the method of calculation potential values of pixels outside skeleton is shown in Figure 6.

Our goal is to calculate the potential value of the blue pixel. In the first iteration, we generate a Neumann-shape search frame *N1* of four pixels. Each pixel in the search frame is one-pixel-Manhattan-distance from the blue pixel. If *N1* does not cover a skeleton pixel, in the second iteration we generate N2 of 8 pixels, in which each pixel is 2-pixel-Manhattan-distance from the blue pixel, and so on. In Figure 6, the search frame retrieve a skeleton pixel in the third iteration. The value of the blue pixel is defined as

$$\phi\left(x_{goal}, y_{goal}\right) = \phi\left(x_{skeleton}, y_{skeleton}\right) + d_M\left(\left(x_{goal}, y_{goal}\right), \left(x_{skeleton}, y_{skeleton}\right)\right), \tag{1}$$

where

- $\phi\left(x_{skeleton}, y_{skeleton}\right)$ is the potential value of the retrieved skeleton pixel, which is defined as

$$\left(x_{skeleton}, y_{skeleton}\right) = \operatorname*{argmin}_{x,y} d_M\left(\left(x_{skeleton}, y_{skeleton}\right), (x, y)\right) \tag{2}$$

- $\phi\left(x_{goal}, y_{goal}\right)$ is the potential value of the goal pixel;

- d_M is the Manhattan distance from the goal pixel to the retrived skeleton pixel. It is worked out following

$$d_M\left(\left(x_{goal}, y_{goal}\right), \left(x_{skeleton}, y_{skeleton}\right)\right) = |x_{goal} - x_{skeleton}| + |y_{goal} - y_{skeleton}| \quad (3)$$

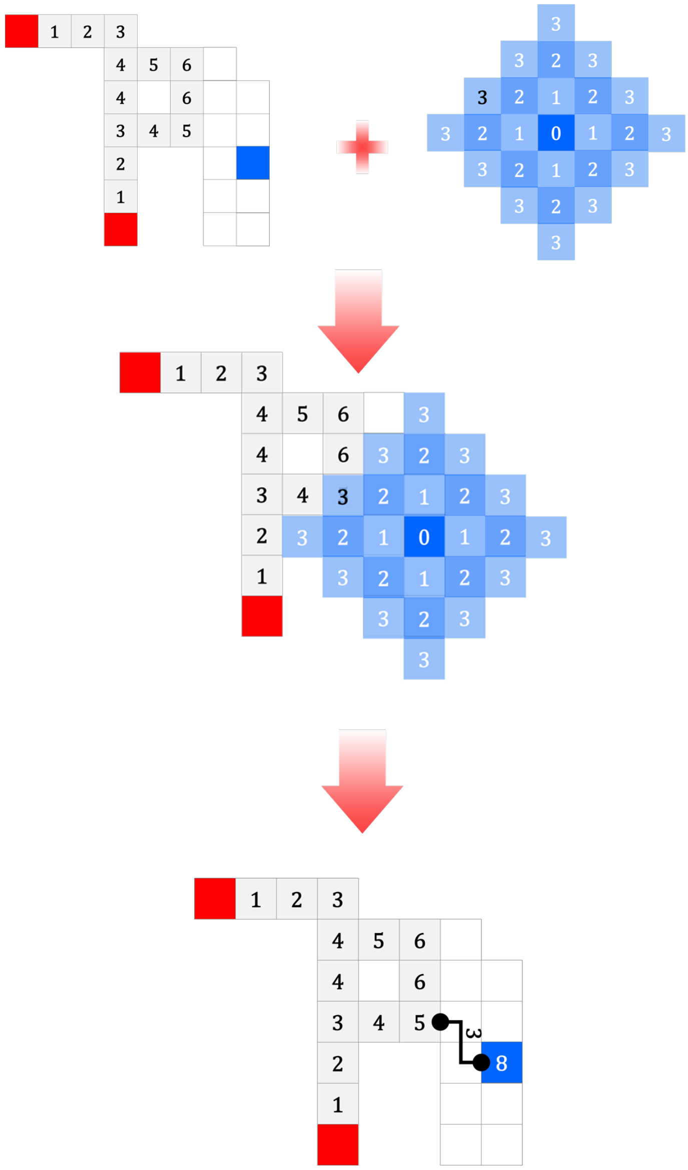


Figure 6: The potential value of pixels outside skeleton

3.2.4 Floor Interaction

Considering the facts:

1. The floor plan on Louvre website [1] only labels the main entrance of Pyramid.
2. Tourists' comments and photos imply that the Passage Richelieu entrance, located in a subway station, leads to the underground lobby on the second floor underground.
3. Tourists' comments and photos imply that the Carrousel du Louvre entrance as well as the Portes Des Lions entrance are closed almost all the time and are distant from the three wings.

We assume the second floor underground is safe region and the three stairwell regions on the first floor underground is the final terminal node. Therefore, we define the first floor underground as the Main Floor and assign 0 to the three terminal nodes. Based on that, the potential fields of other floors can be calculated through following procedures (Figure 7):

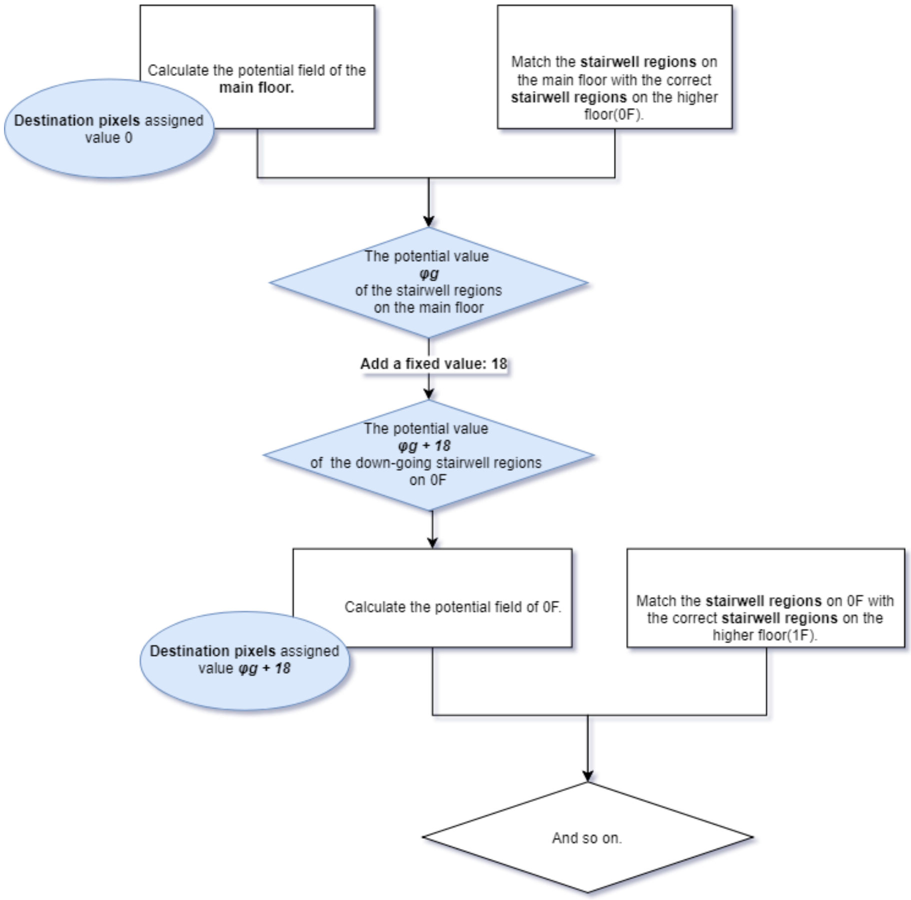


Figure 7: The flowchart of calculating potential field of four floors

During this process, we should take the interaction between different floors into consideration. We estimate the equivalent length of stairwells from photographs on the Internet and take average. The average increment of passing a stairwell region is 18(Figure 8).

The potential of stairwell regions ϕ_g on the main floor(-2F) underground is calculated independent of other floors. The stairwell regions on -1F that matches the stairwell region on the main floor is assigned a potential of $\phi_g + 18$. The potential value of other pixels on -1F is calculated according to the Root Growth Model. When the potential of up-going stairwell regions is determined, the value is transferred to the upper floor with a increment of 18. The transfer chain ends when all pixels of 2F is covered.

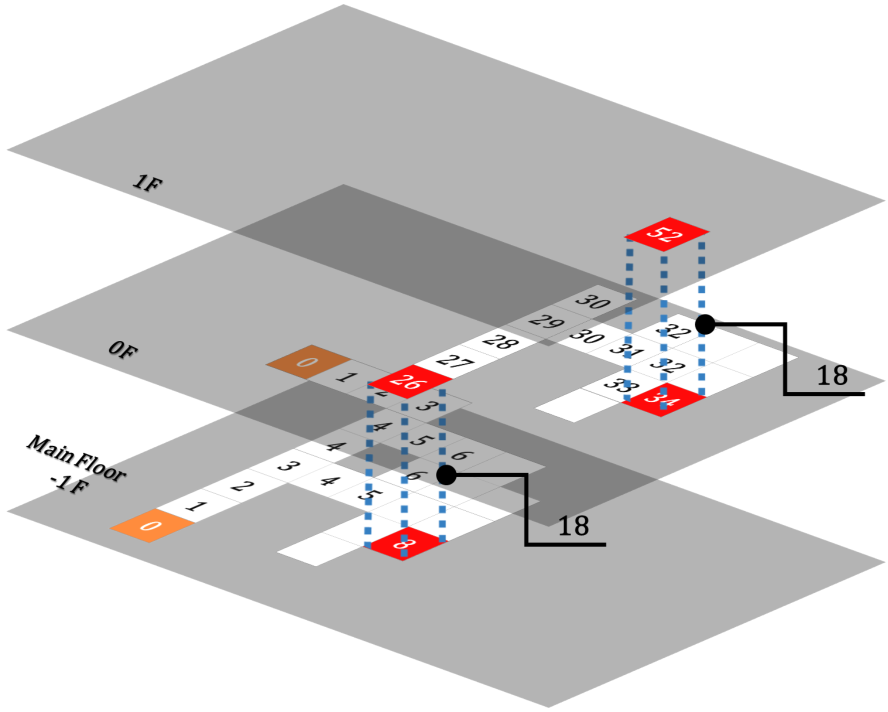


Figure 8: The transfer of potential between floors

3.3 Combined Model with CA and Quasi-potential Field

Let the quasi-potential field be $\Phi = (\phi_{ij})_{m\times n}$, define an initial matrix $H = (h_{ij})_{m\times n}$, in which

$$h_{ij} = \begin{cases} 1, & \text{if there is a human} \\ 0, & \text{OTW} \end{cases} \tag{4}$$

and let the gate matrix $G = (g_{ij})_{m\times n}$, where

$$g_{ij} = \begin{cases} 1, & \text{if there is a gate} \\ 0, & \text{OTW} \end{cases} \tag{5}$$

then we can combine the cellular automaton with the quasi-potential field following the Algorithm 1.

Because there is a gradient along the root and the gate is minimal value, the algorithm will let the human go to the nearest root at first, then, the human will go to a specific gate following the root. So we know

- if the gradient of Φ disappears, the human will be trapped;
- if the root lets the human go to a saddle point, the human will be trapped.

Algorithm 1 QPFCA(Φ, H, G)

$\lambda = \sum_{i,j} H(i,j)$
while $\lambda > 0$ **do**
> **for** $i = 1$ to m **do**
> > **for** $j = 1$ to n **do**
> > > **if** $H(i,j) = 1$ **then**
> > > > $\Phi(i,j) \leftarrow \max\limits_{a,b} \Phi(a,b)$
> > > > **for** $x = -1$ to 1 **do**
> > > > > **for** $y = -1$ to 1 **do**
> > > > > > **if** $\Phi(i,j) > \Phi(i+x, j+y)$ **then**
> > > > > > > $\tau \leftarrow \tau + 1$
> > > > > > > $(\hat{x}, \hat{y}) \leftarrow \operatorname*{argmin}\limits_{x,y} \Phi(i+x, j+y)$
> > > > > > > $H(i,j) \leftarrow 0$
> > > > > > > $H(i+\hat{x}, j+\hat{y}) \leftarrow 1$
> > > > > > > $H(i,j) \leftarrow 0$
> > > > > > > $H(i+x, j+y) \leftarrow 1$
> > > > > > > **if** $G(i+x, j+y) = 1$ **then**
> > > > > > > > $\lambda \leftarrow \lambda - 1$
> > > > > > > **end if**
> > > > > > **end if**
> > > > > **end for**
> > > > **end for**
> > > **end if**
> > **end for**
> **end for**
end while

4 Results

4.1 Quasi-potential Field

With those methods mentioned above, we can assign a potential value to every pixel in the space.

The gradient maps of two real parts within one floor of Louvre are shown in Figure 9.

In these gradient maps, blue region indicates the low potential value while the red one indicates the high value. For people in Louvre, high low potential means evacuees in these regions are farther from known exits, which adds to their difficulty of escaping.

After that, we also generate the corresponding quasi-potential fields of four floors, which are showed below:

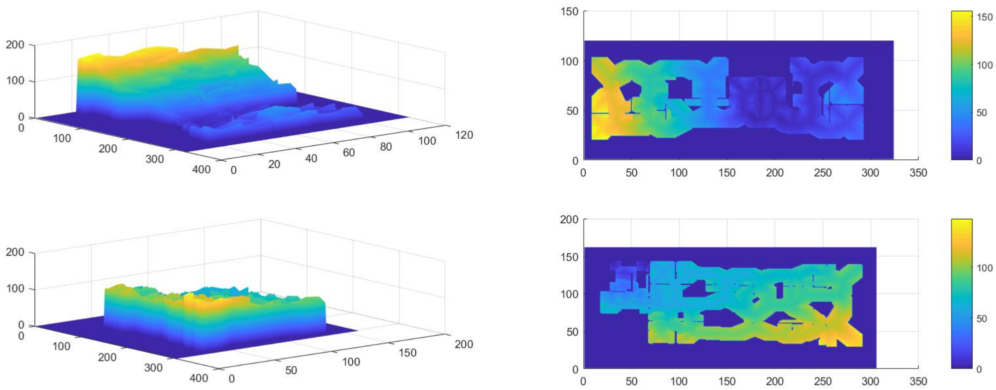


Figure 9: The gradient map of two real parts within the same floor of Louvre.

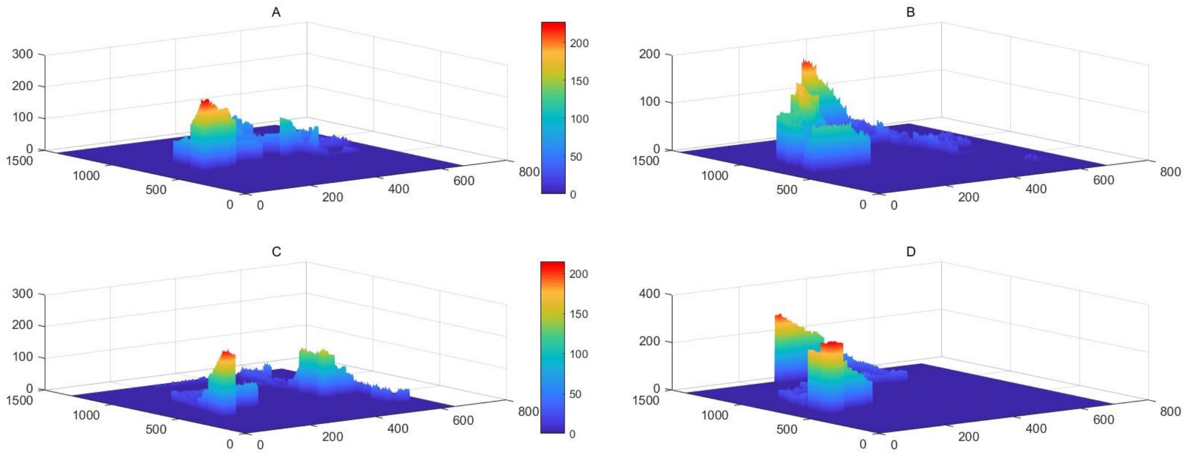


Figure 10: The quasi-potential fields of four floors. A is the first underground floor, B is the ground floor, C is the first floor and D is the second floor.

4.2 Where the Bottle Neck of Evacuation in Louvre Museum Is

Just like what we have discussed before, the quasi-potential field will let the human be trapped if

- the gradient of Φ along the root disappears

$$\nabla\phi\left(x_{root}, y_{root}\right) \rightarrow 0 \tag{6}$$

where (x_{root}, y_{root}) is the direction vector of the root $\hat{R}$, which satisfies

$$\forall r \in \hat{R},\ \varepsilon > 0, \phi\left(x_r, y_r\right) > \phi\left(x_r + \varepsilon x_{root}, y_r + \varepsilon y_{root}\right). \tag{7}$$

- the human is guided to a saddle point, where

$$\forall\left(\delta_1, \delta_2\right) \in \mathbb{R}^2, \nabla\phi\left(x_{human} + \delta_1, y_{human} + \delta_2\right) > 0, \tag{8}$$

and

$$\phi\left(x_{human}, y_{human}\right) > 0. \tag{9}$$

On the other hand, this means the human runs slowly or even stops. Usually, it's highly possible for people to do so when they are located at a dead end or forced to follow the opposite direction from the gate. If the distance between the human and the gate is large at the same time, the situation will become worse. By analysing the gradient of Φ, we can find those bottle necks, which will be showed in the next subsection.

4.3 Where the New Emergency Exit Should Be

We can define a function $\beta : \mathbb{R}^2 \to [0, +\infty)$ to find the bottle neck. After that, there should be a new emergency exit at there if possible.

In detail, the function is defined as

$$\beta(x, y) = \frac{\phi(x, y)}{|\nabla\phi(x, y)|}, \tag{10}$$

based on this function, we can take both the gradient and the distance between the human and the gate into consideration. If $\beta(x, y) \to +\infty$, then it might be necessary to build a new emergency exit at (x, y).

By calculating, we can generate the following distributions of four different floors:

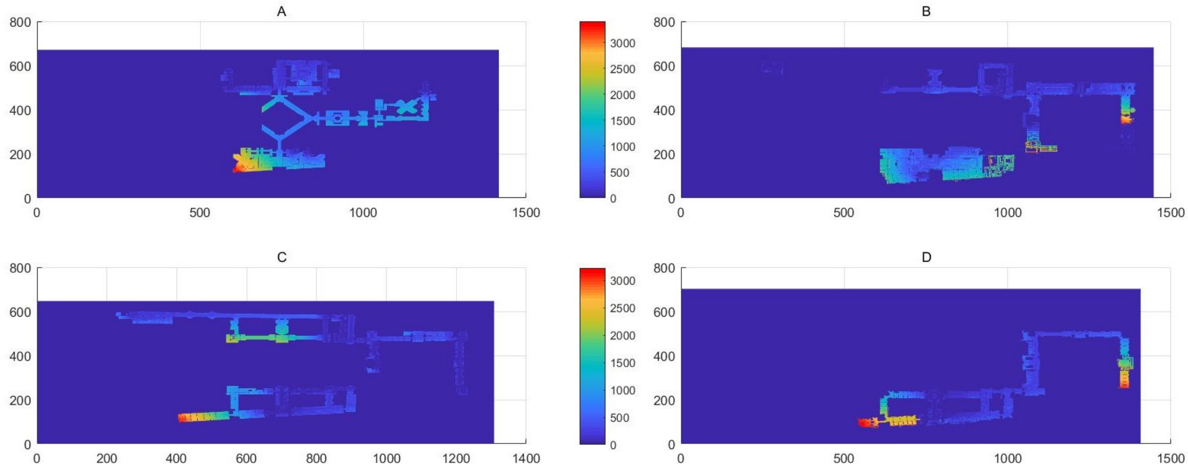


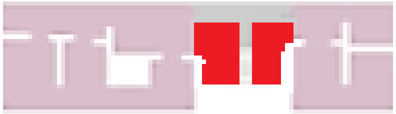
Figure 11: The quasi-potential fields of four floors. A is the first underground floor, B is the ground floor, C is the first floor and D is the second floor.

In those graphs, the points marked as red or orange are the ideal places to open new emergency exits.

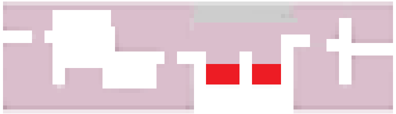
4.4 Simulation of the Destructive Disaster

Here we want to prove the responsiveness for destructive disasters of our model. The disasters can be terrorist attacks, earthquakes and so on. Let's assume there is a terrible disaster and it damages the Louvre Museum badly.

For a specific area, the disaster destroys and blocks the corridor in it, thus the whole terrain has been changed significantly.



Before the disaster.



After the disaster.

Feeding this area twice (before and after the disaster), we can prove that our new model has high responsiveness for the impact of destructive disasters.

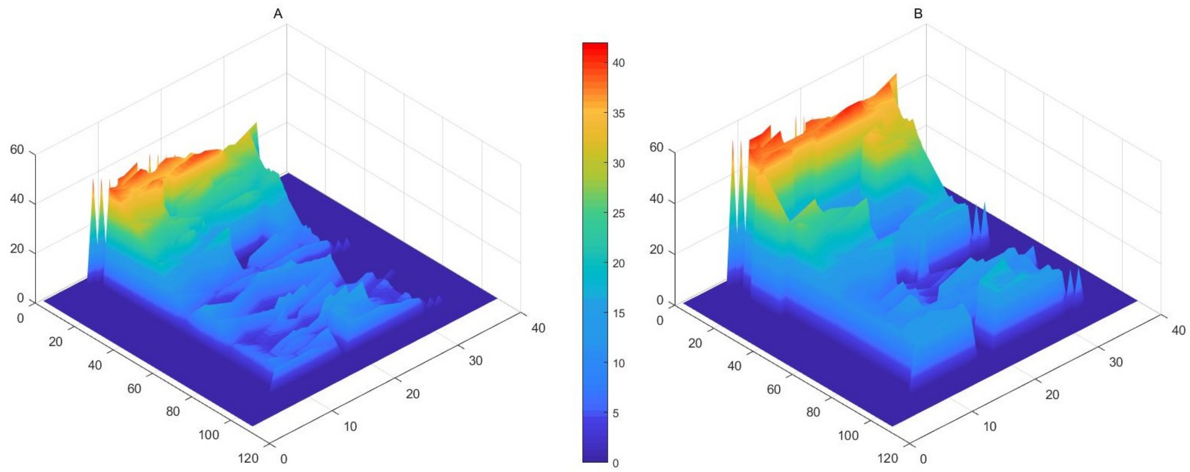


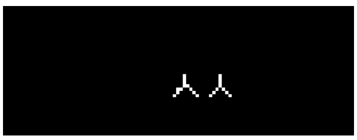
Figure 13: The quasi-potential fields before and after a destructive disaster.

It's clear that the quasi-potential field rises after the disaster, especially in the region destroyed by the disaster.

4.5 Simulation of the Evacuation within Any Area

Now we also prove the robustness of our model by doing experiments. The two real parts within the same floor will be used for simulation. Their quasi-potential fields have been showed in the Figure 10.

Take one of them as example, the corresponding root system model is generated

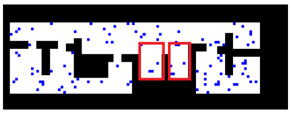


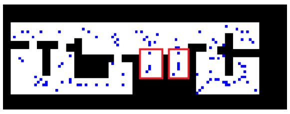
Step 1.

Step 4.

Srep 8.

There are 100 people in our experiments, they need to do evacuation in this area. The following graphs indicate their situation sequence:


Initial State.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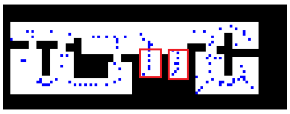
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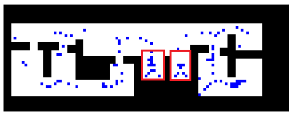
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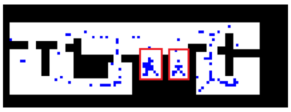
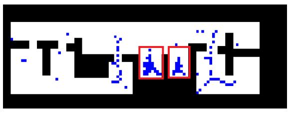

Step 46.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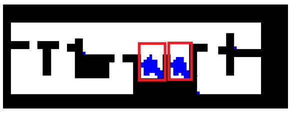
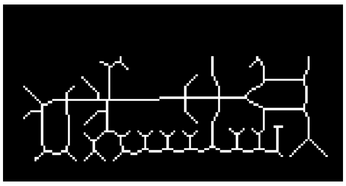
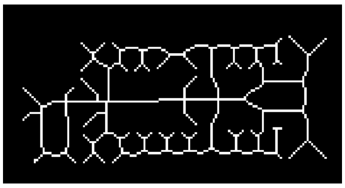

Step 107.

Note that people are marked as blue, walls are marked as black while the gate is marked as red.

As for another area, the structure of it is much more complex.


Step 1.


Step 7.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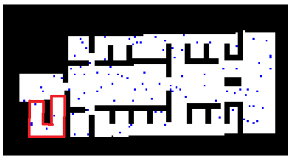
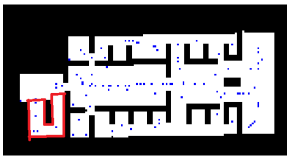
However, our model can still finish the evacuation task quickly in the experiment, which proves the robustness and generalization ability of our model.


Initial State.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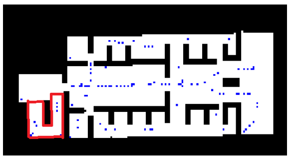
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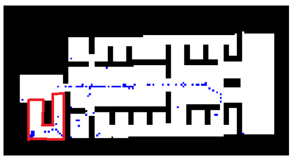
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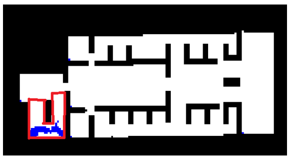
Step 46.

5 Discussion

Cellular automaton has been an invaluable tool for simulation of emergency evacuation due to its meticulous characterization of individual behavior, while the quasi-potential field play a pivotal role in the decision-making process of the cell. Common fields are difficult to use when building cellular automaton in complex buildings, which may lead to painful conditions of cell trapping.

Inspired by the water absorption of plant roots in nature, we proposed a novel quasi-potential field. Combined with the cellular automaton, our model is able to guide cells to find their shortest way to the exits and won't be bothered by complicated structures. Moreover, both sides of the channel will be inclined to be reserved, thus allowing emergency personnel to enter the building as quickly as possible. It could also save those precious artworks from the flustered crowd. Evacuation strategies based on our model can effectively maintain the order of the crowd, thus avoiding the disaster caused by chaos. The most important thing is the strong adaptability of our model. Once the original routes are altered or removed due to an emergency, our model could easily generate a new quasi-potential field to guide evacuation.

However, our model has limitations on the simulation of herd mentality. Integrating the ant colony algorithm in the cellular automaton model may be helpful to get close to the better evacuation strategy. Hoping that this model can provide ideas for the evacuation model based on cellular automata in complex buildings, we will continue our working to improve it in future research.

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