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Cellular automaton simulation of building interior evacuation considering the crossable obstruction

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ABSTRACT

Building interior evacuation in the emergency scenario is becoming more and more common. However, there are lots of obstructions in the building, and most majority works are focus on how to go around those obstructions. In fact, pedestrian can cross some obstructions to reduce the evacuation time. This paper addresses this issue by presenting two concepts: cross influence zone and crossable zone, which indicate how the pedestrian cross the obstruction. The validation of the concepts was conducted with two experiments. We use the random cross probability to simulate the uncertainty of evacuation process for different gender, and the experiment results show that the evacuation time of crossable obstruction case is less than the regular obstruction case and when the random cross probability increase, the evacuation time become less.

KEYWORDS

Crossable obstruction; Distance map; Building interior evacuation; Multiple obstruction space; CA.

INTRODUCTION

With the deepening of city-oriented development, large scale, high standard, and modern high-rise buildings have been built in many large and medium-sized cities. Most of these buildings are crowded, complex internal structured and with other characteristics, once an emergency happens like a fire, often causes heavy casualties and property losses. How to evacuate the room quickly, effectively and safely has become an important issue recently[1,2]. Due to a large number of tables, chairs counters and other obstructions inside the building, research on obstructions inside the building has influence on personnel emergency evacuation which plays an important role in indoor emergency evacuation[3,4,5].

Currently, researches on variety of obstruction indoor evacuation mainly centralize on teaching buildings, theaters, and conference halls with multiple rows of seats. And also, some researchers extend these algorithms to planes, trains and other large transport tools. For example, Weckman H. etc[6] did pre-notice fire evocation exercise in Performance Hall which can hold 600 audience, and comprised the results with three different evacuation modes. Guo.etc[7] and Li Jian[8] studied on emergency evacuation in classroom, they adopt opaque patch to simulate evacuation process of limited view, and made comparison with normal evacuation. Qiong, T., & Yihang, X[9] and Zhu Kongjin[10] researched on differences of evacuation effect with different layout of tables, chairs and passageway separately, and they pointed out evacuation is more efficient if the layout has corridor close to exit. J.A. Capote.etc[11,12] analyzed two fire scenarios of the train by exit model, and studied on several common pre-evacuation behaviors at the beginning of the fire. Galea.etc[13] researched on evacuation process of large passenger aircraft， and pointed out in large uneven place, using evocation exit of the plane to distract people can improve efficiency of evacuation.

From above analysis, we found that the evacuation environment of most evacuation exercise or evacuation modes is indoor or inside of large vehicle with many obstructions. They didn’t consider that in some special environment, the evacuees may stride over or climb some short obstructions to arrive exit more rapidly in the process of evacuation. Therefore, this paper proposes considering distance map for crossable obstruction and studies on evacuation process of multiple obstructions based on cellular automaton model. It analyzes shape of crossable obstruction has effect on evacuation rate in detail and evacuation process for people of different gender.

The structure of the paper is as follows: section 1 introduces meaning of the research and current state of multiple obstruction space emergency evacuation. Section 2 builds cellular automaton model for crossable obstruction and also gives assumed conditions. Section 3 puts forward two concepts， one is cross influence zone, the other is crossable zone, and gives how to build distance map for crossable obstruction. Section 4 provides simulation and analysis results. The conclusion and future work are discussed in section 5.

BUILDING CELLULAR AUTOMATON MODEL

Model description

In our model, the evacuation space is divided into W×H same size rectangle grid, each grid indicates a cellular, in which W, H separately stands for size of x-axis and y-axis of evacuation space. In the same time step, each cellular has two states: empty or occupied by pedestrian, and the grid size is $0.4\times0.4m^2$[14]. Location of pedestrian can synchronize to update, the new state of cellular is decided together by current state of the neighbors. Neighbors are defined as all cellular distant from the current cellular within three steps. In each time step， people can move one cell or stay still. Size of time step is depended on the velocity of the pedestrian.

According to our experience, the average speed of pedestrian is about 1.3*m/s* in normal condition; however, it can reach 1.8*m/s* in nervous condition. In evacuation process, the moving principles of pedestrian are as following:

Firstly, moving towards the exit as possible

Secondly, moving towards personnel low density place

Thirdly, avoiding un-crossable obstruction in evacuation process.

Fourth, avoiding crossable obstruction selectively, the selective standard is described in section 2.4.

Cellular attraction

The next state of time step for each cellular depends on current state of itself and all neighbor cellular. Von Neumann neighbor and Moore neighbor are commonly applied in CA simulation. In each time step, pedestrian can move one cell at most, when the velocity is constant, the moving distance will be constant. In Moore neighbor, the distance towards up, down, left and right is not equal to the inclined direction. But in von Neumann neighbor, the moving distance is equal regardless of moving in any direction. Therefore, we adopt von Neumann neighbor in the proposed model, which the neighbor of any cellular is defined as the cellular within three steps of all cellular.

In von Neumann neighbor, there are five moving directions including up, down, left, right and stay still in each time step. In our work, we introduce concept of cellular attraction, which means we can choose target cellular by computing attraction in the same shortest distance which is distinct from evacuation model[15] based on probability. Pedestrian always move to the cellular which is attractive to oneself. In the same time step, the cellular of five moving directions has different attraction.

$Grid_{cur}$ stands for current cellular, and $Grid_{adj}$ stands for all neighbor cellular around the $Grid_{cur}$. The attraction between $Grid_{cur}$ and $Grid_{adj}$ can be represented by F_{adj}, initial value is 0. The distance between $Grid_{cur}$ and $Grid_{adj}$ can represented by D_{adj}, and the minimize distance can be D_{minadj}. Check the $Grid_{adj}$ in turn and follow the description below:

If $Grid_{adj}$ is empty and the $D_{adj} < D_{minadj}$, then $F_{adj} = F_{adj} +5$, which can ensure the pedestrian choose the nearest celluar;

If $Grid_{adj}$ is empty and the $D_{adj} = D_{minadj}$, then $F_{adj} = F_{adj} +1$, which pedestrian choose the lower density cellular under the same shortest distance condition;

If $Grid_{adj}$ is empty and $D_{adj} > D_{minadj}$, then $F_{adj} = F_{adj}$;

If $Grid_{adj}$ is not empty, then $F_{adj} = F_{adj}$.

Cellular state updating rules

We use $minDistance_{adj}$ to represent the distance between $Grid_{adj}$ and the exit, and use $minDistance_{cur}$ $minDistance_{cur}$ to represent the distance between $Grid_{cur}$ and the exit. There are four rules in cellular state updating.

(1) If there is only one $Grid_{adj}$ with empty state, and its $minDistance_{adj} < minDistance_{cur}$, then pedestrian will choose the $Grid_{adj}$ as target; If there are multiple $Grid_{adj}$ satisfied those conditions, then pedestrian will choose the $Grid_{adj}$ with maximize F_{adj}; If there are multiple $Grid_{adj}$ satisfied those conditions and they have the same F_{adj}, then pedestrian will choose the $Grid_{adj}$ randomly.

(2) If there is no $Grid_{adj}$ satisfied the requirements in (1) but there are $Grid_{adj}$ with empty state, and its $minDistance_{adj} = minDistance_{cur}$, then pedestrian choose the cellular with maximize F_{adj} as target. If the F_{adj} of those $Grid_{adj}$ is the same, then choose $Grid_{cur}$ as target.

(3) If there is no $Grid_{adj}$ satisfied the requirements in (1) and (2), and there is no $Grid_{adj}$ with empty state, and its $minDistance_{adj} < minDistance_{cur}$ -1. But there are $Grid_{adj}$ with empty state within two steps, and its $minDistance_{adj} > minDistance_{cur}$, then pedestrian will choose the $Grid_{adj}$ randomly. This rule indicates that pedestrian will move backward to avoid the jam of crowd.

(4) There will be a conflict when pedestrians choose the same target. We choose one pedestrian to move by equal probability, and the others stay still.

Moving rules in multiple obstruction space

The pedestrian are easy obstructed when they move in multiple obstruction space. If the obstruction is wall or un-crossable high board, the pedestrian should go round. As is shown in Figure 1, if we adopt common cellular grid, the pedestrian will move to the exit until they meet un-crossable obstruction. Then, they will select path1 or path2 to go around the obstruction to the exit according the cellular state of neighbor. Obviously, it is not confident with usual practice of the pedestrian. Therefore, we introduce obstruction repulsion to solve the problem. The radius of repulsion is r, if the initial position is within repulsion of un-crossable obstruction， the repulsion can be ignored, and we compute moving path of the evacuees according to normal cellar grid.

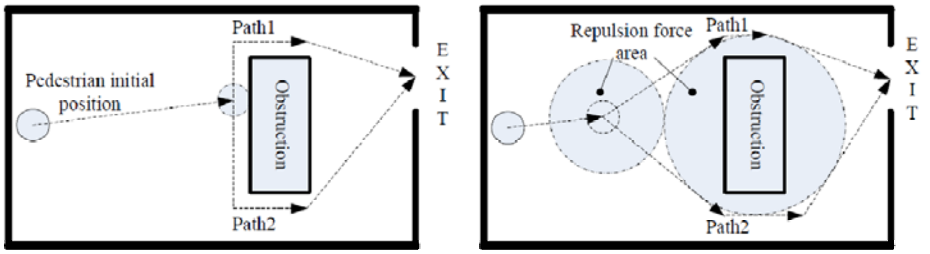

Figure 1: Regular CA and repulsive CA passing around the obstruction

If the obstruction are table or chair (height of crossable obstruction is not exceed two-thirds of pedestrian's height), the pedestrian can go round or cross the obstruction. It should be noted that, whatever structure or location of table and chair in classroom or conference room, it is not suit for across under the obstruction; therefore, we don't consider this situation.

In evacuation process, we need considering multiple factors to confirm whether to cross the obstruction when the pedestrian meet the crossable obstruction. We assume the width of obstruction is L_w, the length of obstruction is L_l, the distance of pedestrian pass around the obstruction is D_a, the distance of pedestrian cross the obstruction is D_l. the details factors that influence the moving path are described as following:

1) Shape and height of the obstruction: we assume the initial position of the pedestrian is fixed. The D_a will increase when L_w increases, and the time of the pedestrian goes around the obstruction will increase. The D_l will increase when L_l increases, and the time of pedestrian crosses the obstruction will increase.

2) Gender, height and body strength of the pedestrian: different individual has different response, generally speaking, male beat female in height and strength, so, the male is more likely to cross the obstruction. Based on experience, the cross probability of male is set to 0.7-0.8 and the cross probability of female is set to 0.5-0.6.

3) Initial position of the pedestrian: the further the initial position is away from the obstruction, the more time we can plan alternate routes in advance, and vice versa; as is shown in Figure 2, when the pedestrian is near to the crossable obstruction, the further far away from P_a, the greater the D_a will be, and vice versa;

4) Neighbor cellular state: when the pedestrian meet crossable obstruction, if the neighbor cellular state is occupied, pedestrian need to moving backward and go around the obstruction, the D_a will increase. In this case, we should compare the D_a and D_l to decide whether cross the obstruction.

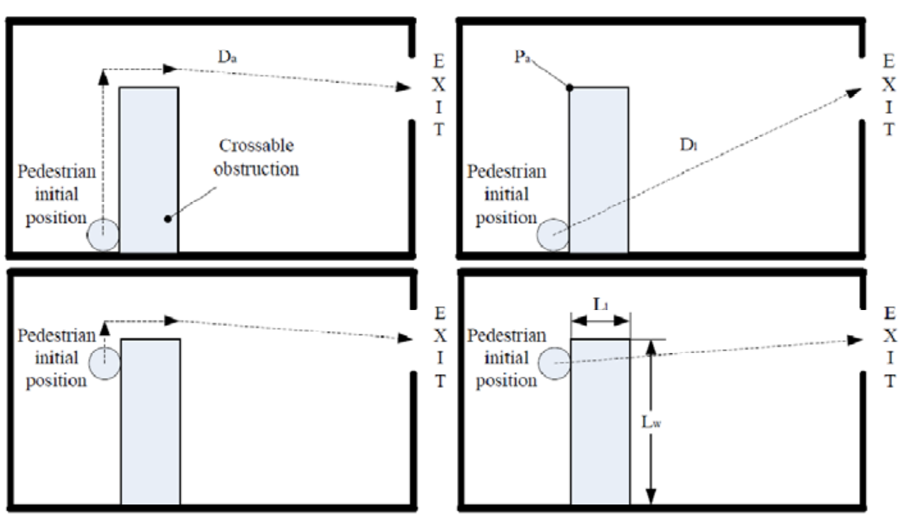

Figure 2: Four scenarios of pedestrian passing around or cross the obstruction

DISTANCE MAP OF CROSSABLE OBSTRUCTION

Definition of distance map

Distance map is a grid map covering current architectural floor, we just discuss rectangular floor in this paper. In the distance map, each grid stores a value, which record the shortest distance between the grid and the exit of current space. In the present model, the unit of the distance is time step. There can be one or more exit for each distance map.

The value stored in each grid is not just crow flight distance between the current grid and the exit. It also indicates that the un-crossable obstruction such as: the wall, etc have impact on the shortest distance in evacuation.

One target of creating distance map is to assure the pedestrian prefer to move to the grid that near to current exit, and reach target exit finally. The other target is that the pedestrian can avoid the un-crossable obstruction automatically according to the distance map, which avoid extra obstruction detection and improve efficiency of the model.

Distance map of the fixed obstruction

There are four steps to generate the distance map:

(1) We set two variables for every grid in distance map, one is *minDistance* which indicates the minimize distance between current grid and the nearest exit, the other is $Grid_{state}$ which stores the state of the grid, 1 means empty and 0 means occupied. The two variables of all the grids in distance map have initial value. The *minDistance* of exit is 0, and the others is 99999. The $Grid_{state}$ of un-crossable obstruction is 0, and the others are set to 1.

(2) Create a grid queue as *Queue<Grid>*, and push all the grid of the exit into the queue.

(3) Pop out the first grid at head of queue, and name it $Grid_{cur}$. Check all the neighbor cellular, and name them $Grid_{adj}$. If the $Grid_{state}$ of $Grid_{adj}$ =1 and $minDistance_{adj} > minDistance_{cur} + 1$, then set $minDistance_{adj} = minDistance_{adj} + 1$, and push the $Grid_{adj}$ into tail of the queue.

(4) Repeat step (3) until the Queue<Grid> is null.

From above analysis, the generation steps of distance map are similar to get the shortest distance from Dijkstra. We regard the grid not occupied by obstruction as nodes. Each node is connected to neighbor nodes by each side, and the weight of the side is 1. The distance map is generated as Figure 3, and the distance map with obstruction which is marked in grey is shown on the right.

19	18	17	16	15	15	16	17	18	19
18	17	16	15	14	14	15	16	17	18
17	16	15	14	13	13	14	15	16	17
16	15	14	13	12	12	13	14	15	16
15	14	13	12	11	11	12	13	14	15
14	13	12	11	10	10	11	12	13	14
13	12	11	10	9	9	10	11	12	13
12	11	10	9	8	8	9	10	11	12
11	10	9	8	7	7	8	9	10	11
10	9	8	7	6	6	7	8	9	10
9	8	7	6	5	5	6	7	8	9
8	7	6	5	4	4	5	6	7	8
7	6	5	4	3	3	4	5	6	7
6	5	4	3	2	2	3	4	5	6
5	4	3	2	1	1	2	3	4	5
				0	0				

24	23	22	21	20	19	18	17	18	19
23	22	21	20	19	18	17	16	17	18
22	21	20	19	18	17	16	15	16	17
21	20	19	18	17	16	15	14	15	16
20	19	18	17	16	15	14	13	14	15
19	18	17	16	15	14	13	12	13	14
							11	12	13
							10	11	12
11	10	9	8	7	7	8	9	10	11
10	9	8	7	6	6	7	8	9	10
9	8	7	6	5	5	6	7	8	9
8	7	6	5	4	4	5	6	7	8
7	6	5	4	3	3	4	5	6	7
6	5	4	3	2	2	3	4	5	6
5	4	3	2	1	1	2	3	4	5
				0	0				

Figure 3: Example of distance map

From Figure 3 we can see that the grids on the up side of obstruction are further from the exit, and it takes a very long time for pedestrian to reach the exit, which well simulated the fact that pedestrian need to bypass the obstruction to get to the exit.

Crossable zone and cross influence zone

Crossable zone is generated based on distance map with obstruction, and it is used to represent the possible zone that the pedestrian cross the obstruction. The other concept is crossing influence zone, which has triangle shape generated according to crossable zone. When the initial position of pedestrian is in the cross influence zone or the pedestrian move into the cross influence zone during the evacuation process, then the moving pedestrian can move to the obstruction and cross it by following the cost of cross distance. The cost of cross distance and the cost in distance map are stored and calculated separately. Once the pedestrian is out of crossable zone and cross influence zone, then the moving of pedestrian will be calculated by distance map.

We assume the obstruction is crossable in Figure 3, the cross zone and the cross influence zone are generated as following steps:

(1) Generate the grid for the crossable obstruction. The size of grid is the same with the CA model we used.

(2) Calculate the crossable zone of obstruction. The crossable zone is specified by the shape and position of obstruction. We assume the size of obstruction is $L_w \times L_l$. Then there are two rules for generation of crossable zone.

Rule 1: L_w should be greater than three grids ($3 \times 0.4m$) and L_l should be less than L_w, or pedestrian will go around the obstruction. As we can see in Figure 4, the pedestrian will cross the first obstruction and go around the other two.

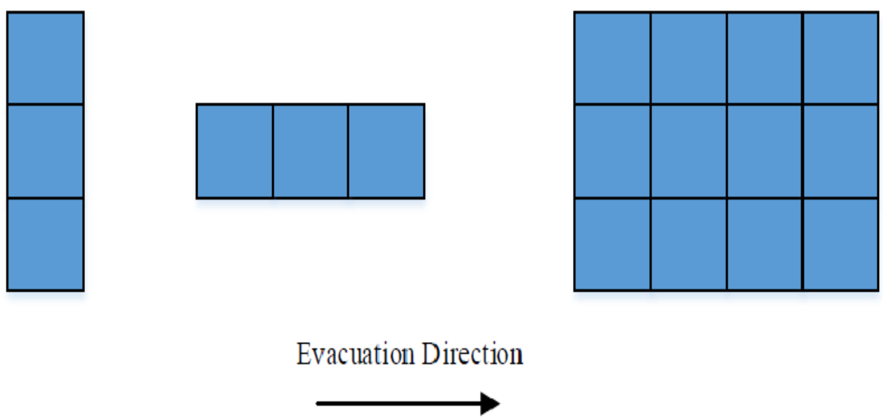

Figure 4: Shape of obstruction

Rule 2: the length of crossable zone is equal to the L_l, and the width of crossable zone falls into two categories (shown in Figure 5), the first are the both sides of obstruction are passable and the width of crossable zone is equal to L_w /3, the second are the only one side of obstruction are passable and the width of crossable zone is equal to L_w /2.

(3) Calculate the cross influence zone by crossable zone. First, traverse all the neighbor cellular of crossable zone, and find out the grid which has shortest distance to the exit and name it $Grid_{mark}$. Second, push the $Grid_{mark}$ into *queue<Grid>*, and calculate the (*minDistance*, $Grid_{state}$) of all the grids in crossable zone by the method in section 3.3. At last, calculate the (*minDistance*, $Grid_{state}$) of all the grids in cross influence zone base on the crossable zone. The example of distance map with the crossable obstruction is shown in Figure 6.

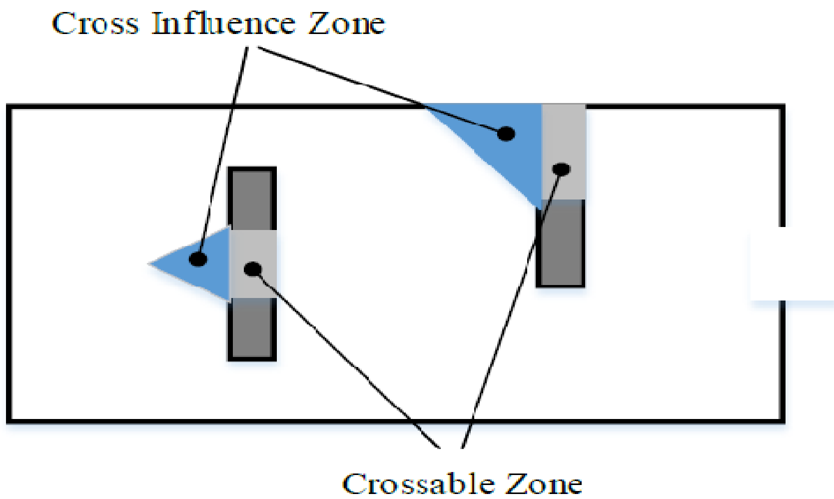

Figure 5: Example of crossable zone and cross influence zone

19	18	17	16	15	14	13	12	11	10	9	8	7	6	5		
18	17	16	15	14	13	12	11	10	9	8	7	6	5	4		
17	16	15	14	13	12	11	10	9	8	7	6	5	4	3		
18	17	16	15	14	13			8	7	6	5	4	3	2		E
19	18	17	16	15	14			7	6	5	4	3	2	1	0	X
20	19	18	17	16	15			7	6	5	4	3	2	1	0	I
21	20	19	18	17	13			8	7	6	5	4	3	2		T
22	21	20	19	13	12	11	10	9	8	7	6	5	4	3		
23	22	21	15	14	13	12	11	10	9	8	7	6	5	4		
24	23	17	16	15	14	13	12	11	10	9	8	7	6	5		

Figure 6: Distance map with the crossable obstruction

EXPERIMENT AND ANALYSIS

Experiment initial parameters description

We set up a room with its size 24×16*m*, and the width of the exit is 1m. The average speed of pedestrian is 1.0*m/s*. In our model, the size of cellular is 0.4×0.4*m*, and the time step is 0.4*s*. The room is covered by 60×40 grids, and the exit is covered by 2 grids (we only consider the effective width). We assume the maximum flow of pedestrians is 2 people per second. There is a crossable obstruction with its size 8×1*m*, and its position is shown in Figure 7. We generate the initial position of pedestrians uniformly and randomly. In order to simulate the uncertainty of evacuation process, we present two coefficients. One is random stay probability: P_{stay}=0.05, the other is random cross probability: P_{cross} (Male for 0.8 and female for 0.7). P_{stay} indicates the probability of pedestrian stay where they are when random event happened. P_{cross} indicates the probability of pedestrian moving towards obstruction when they in cross influence zone.

When pedestrian is out of cross influence zone, the final probability P_{ij} that they choose to move to the grid $Grid_{ij}$ is:

$$P_{ij}=A \cdot P_{ca} \cdot (1-P_{stay}) \quad \textbf{(1)}$$

When pedestrian is in cross influence zone, the final probability P'_{ij} that they choose to move to the grid $Grid_{ij}$ is:

$$P'_{ij} = A \cdot P_{ca} \cdot (1 - P_{stay}) \cdot Pcross \quad \textbf{(2)}$$

In (1) and (2), i and j indicate the position of grid, A is the adjustment parameter, and P_{ca} is conversion probability of cellular.

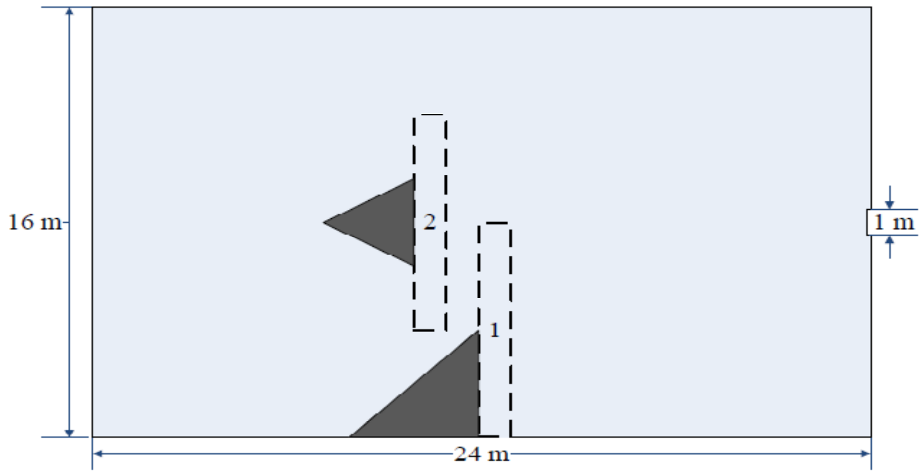

Figure 7: Experimental environment

The relationship between crossable obstruction and evacuation efficiency

In this experiment, we use our experiment initial parameters to test evacuation efficiency of two different crossable obstructions. Those two obstructions have different initial position. As shown in Figure 10, obstruction 1 is against the wall, and obstruction 2 is on the middle of room. The two gray triangles are the cross influence zone of obstructions. From section 3.3, we can calculate the cross influence zone of obstruction 1 is a right triangle with its base and height both are 4*m*, obstruction 2 is equilateral triangle with its edge is 2.7*m*. We use 0.4×0.4*m* grid to cover those two cross influence zones. For ease of calculation, we cover the cross influence zone of obstruction 1 with 10×10 grids, and cover the cross influence zone of obstruction 2 with 8×8 grids. We put the evacuation time result into two matrixes *M1* and *M2*. For each obstruction, we calculate the time that pedestrian passing around and cross the obstruction respectively. The results are shown in Figure 8 and 9.

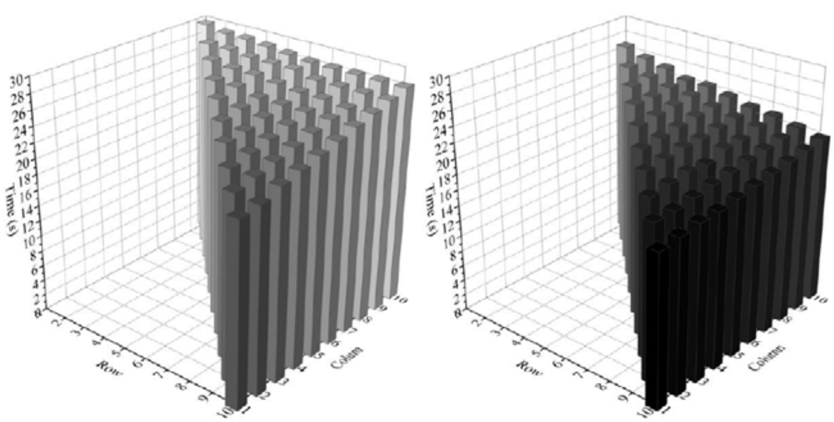

Figure 8: Average time of passing around or cross obstruction 1

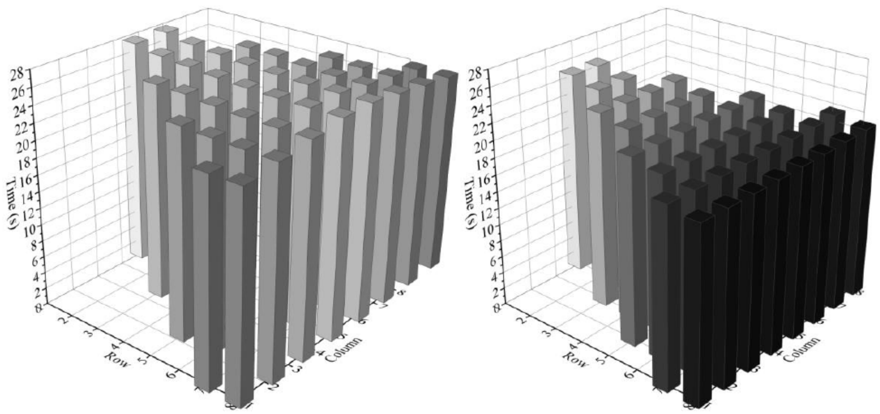

Figure 9: Average time of passing around or cross obstruction 2

Figure 8 and 9 show that the evacuation time will increase when the distance between current grid and exit increase, but they are not linear with each other. Either obstruction 1 or obstruction 2, the crossing time is shorter than the passing around.

Evacuation simulation of gender difference

We consider the evacuation simulation of gender difference on two situations. One is pedestrians with different gender try to move to the same grid in the same time step, and the other one is pedestrians with different gender has different probability to choose whether cross the obstruction. In first situation, we use the pair-wise competition method which is described in[1] to determine the winner. In this work, we set the probability of pair-wise competition is equal for male and female. In second situation, we use different random cross probability: P_{cross} to simulate the evacuation of different gender. We take obstruction 2 to process the simulation, and set the population of evacuation from 40 to 150 which divided into 12 groups. Each group has female-to-male ratio of 1:1, and we will run each group 10 times and take the mean to eradicate the discrepancies.

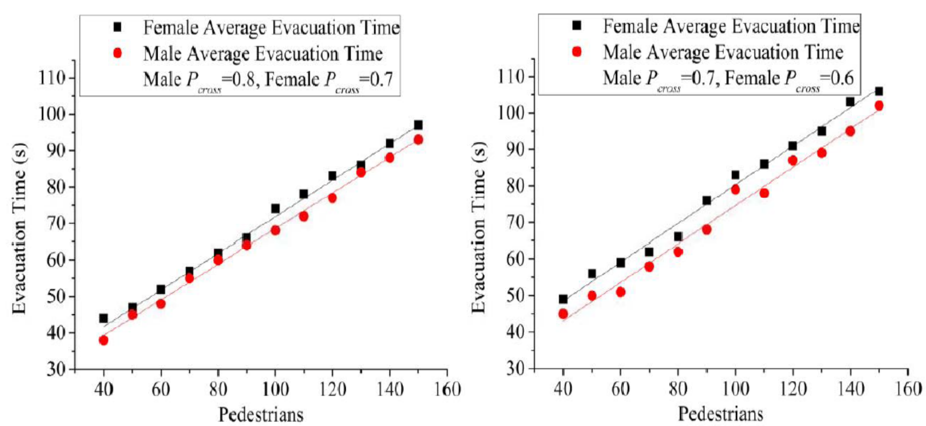

Figure 10: Average evacuation time

As shown in Figure 10, average evacuation time increases when number of pedestrian increases. Reference[1] indicated that when population density reaches the critical value, then the evacuation time will be very long because of the crowd. We don't consider that extreme case in our experiment. If we use t_{male} and t_{female} to represent the average evacuation time of male and female, then basically t_{male} are less than t_{female} cause male's P_{cross} is greater than female's. Contrast two graph in Figure 10, the t_{male} and t_{female} are increasing in varying degrees when the P_{cross} decreases from 0.8 and 0.7 to 0.7 and 0.6.

CONCLUSION AND FUTURE WORK

In this paper, we simulate the indoor evacuation process by using CA model and computer technology, especially the scenario with multiple obstructions. To represent the pedestrian crossing the obstruction, we propose two concepts: cross influence zone and crossable zone, and we provide the generation method of two concepts for different obstructions. We also introduce the random cross probability to simulate the uncertainty of evacuation process for different gender. From the experiment in section 4, we can come to the conclusion that summarized in two propositions. First, it will cost less evacuation time when pedestrian cross the obstruction. Second, evacuation efficiency is impacted by random cross probability, when random cross probability increases, the evacuation time becomes less.

However, the evacuation process in reality is very complex, it is affected by many factors, such as: environment of building interior, psychological bearing ability and physical ability of pedestrian, evacuation as group. In our work, we haven't discussed the subjective factor of pedestrian, but it can be achieved by the multi-agent model in the future. In multi-agent model, every pedestrian can have individual property like height and age which can make the simulation closer to real world.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this article.

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