Crowd Evacuation Dynamics under Shooting Attacks in Multi-story Buildings

Peng Lu[1,3], Dianhan Chen[1,3], and Pengfei Lv[2,3,]

[1] Central South University, Changsha 410083, China
[2] University in Wuhan, Wuhan 430072, China
[3] PKU-WUHAN Institute for Artificial Intelligence, Wuhan 430070, China
lvpengccps@vip.qq.com
chen.dh@csu.edu.cn
lvpengfei@whu.edu.cn

Abstract. The mass shooting has caused large casualties. Due to building complexity, it is more challenging to capture the crowd dynamics under mass shooting incidents. The Bataclan Shooting (13 November, 2015) is taken as our target case. We use multi-agent system to model both the killing force (shooting) and counter force (the anti-terrorism mechanism). According to real situation, the dynamic behavior of three types of agents (civilians, police, and shooters) during the shooting accident is modeled to explore the key mechanism of individual behavior. Taking civilian casualties, police deaths, and shooter deaths as the real target values, two combinations of optimal solutions fitting the target values are obtained. Under the optimal solutions, we verify the effectiveness and robustness of the model and infer the dynamic shooting process reversely. In addition, we infer the counterfactual situation to explore the impact of police anti-terrorism strategies and building exits on public safety evacuation. The results show that for real cases, the optimal anti-terrorism size of the police is four people, and the optimal response time is 40 ticks. For double-layer buildings, it is necessary to set exits on each floor, and the uniform distribution of exits will be conducive to evacuation under emergencies. And neural networks are used to estimate the influence of related factors. These findings can improve the rationality of police patrol routes and the location of police stations. Also, they promote the ability to create public safety structures to encourage the urban emergency response capacity and the level of public safety governance.

Keywords: Public safety · Crowd evacuation dynamics · Agent-based Modeling · Multi-story buildings · Counter terrorism forces.

1 Introduction

Terrorism shooting cases threaten human lives and cause social losses [26]. Most shootings occur in buildings, and it is necessary to study the crowd dynamics in shootings in multi-story buildings. According to FBI reports, there are 277 shooting cases in the USA (2010-2018), which have killed 2,430 people [5]. Only 37 of them happened in open space (13%), and the rest (87%) took places in buildings [19]. The trend of mass shootings still grow [39]. Mass shootings [12] often occur in public places, such as schools [28], churches [31], and government branches [9]. Shooters or terrorists efficiently target these places because of their high population density. For multi-story buildings, crowd dynamics in shooting case are more difficult to capture due to environment complexity. Crowd behavior and buildings' structural characteristics [35] affect evacuation results [24]. The irrationality and organization of collective panic [34] increased the casualties. Environmental settings also hinder crowd evacuation, such as too few exits [10], walls [41], stairs [25,27], etc. Thus, we focus on crowd evacuation dynamics under shooting attacks in multi-story buildings.

The frequently happened mass shooting incidents and their serious harm have attracted increasing research attention on crowd disasters. However, crowd dynamics are complex resulting from the constant interactions between individuals. Especially when panic involved [16], individuals tend to show non-adaptive crowd behaviors [33] and selfish competitions [20], such as trampling [37], knocking and pushing [17]. Researches on this kind of human collective actions are limited in traditional way while modeling technologies work better since they can recur the catastrophe in simulation without harming any subject. They simulate pedestrian flow to capture the characteristics of complex pedestrians behaviors. Helbing & Molnar (1995) treated pedestrians as particles in the physical world, and applied social force model to describe their movement trajectories [18]. Later, Helbing (2000) further applied it based on self-driven many particle systems to the fire scenario involving panic escape [16]. Bain & Bartolo (2019) modeled crowd motion as fluid flow and applied it to the management of crowd in high density, such as marathon events [4]. Toyama et al. (2006) presented an agent-based simulation of pedestrian dynamics to show how different pedestrian characteristics result in various macroscopic behaviors [40]. Besides, the computational modeling and simulation was applied in the study of shootings [6]. Hayes and Hayes (2014) created an agent-based simulation to examine key parameters in mass shootings and to examine the potential effectiveness of Senator 's assault weapons and high-capacity magazines bill [14]. Lee et al. (2018) used AnyLogic software to model the active shooter incidents at a general densely populated area and discussed effect of parameters (civilian evacuation time, the response of police, firearm discharge by the shooter and police) on casualty rates [22]. Abreu et al. (2019) developed an Object-oriented model with Microsoft Visual C# 2017 to explore the potential effect of people characteristics and response in mass shooting [1]. Arteaga and Park (2020) used agent-based modeling to explore the impact of three important building design parameters (exit width, door width and hall width) on the reduction of casualties and efficiency of evacuation in the shooting accident [3]. The applications of these simulation approaches help preventing or controlling the occurrence of accidents in public gathering places, which is of great significance to safety governance.

In the indoor shooting incident, the shooter's attack strategy and scale, the civilians' behavior, and the internal structure of the building jointly affect the result of the incident. For example, the individual's access to the shooter's location information can improve the survival rate [30]. The shooter's attack strategy and scale will reduce civilians' survival rate [29]. And the difference between shooting scene [2] and building design [3] will also lead to the difference in the result. Although the shooting process seems irrational, it is more reasonable to consider the motivation of shooting behavior in the scope of rational choice. According to the theory of rational choice [21], the shooter measures the benefits and costs of the action before attacking [13]. The shooter chooses to strike when the benefits outweigh the costs [29]. Moreover, the crowd heterogeneity and environment complexity need to be fully considered. Individual heterogeneity is a crucial factor in individual behavior decision-making. Densely populated commercial buildings have become an essential target for terrorists [38]. Therefore, the swarm behaviors in commercial buildings under the shooting cases should be modeled to match the reality.

We use agent-based modeling (ABM) to explore the mechanism of human behavior in shooting cases with complex indoor buildings. By defining the behavior rules of micro agents, agent-based modeling achieves the emergence of macro phenomena [36]. It is the most appropriate tool for studying complex systems [15]. NetLogo can explore the impact of micro agent behavior on macro events and reveal system-level phenomena based on individual behavior. In case of emergency, human beings in multi-story buildings are more vulnerable [23]. Hence, we use NetLogo to build our agent-based model and explore the impact of human behavior and environment design on casualties. Artificial neural networks (ANN) were initially used to simulate the performance of the biological nervous system [11]. A typical ANN construct consists of three types of neuron layers—input, hidden, and output layers. In general, an ANN model contains at least one hidden layer. The input layer receives the input vector X and distributes the information to the neurons in the hidden layer. The hidden layers distribute the processed data to the result layer, and the result of the given input is obtained by the output layer. We also use ANN to detect the predictive stability of the input parameters of the ABM model on the output results.

2 Materials and Methods

2.1 The real target case

We take the Bataclan attacks case (13 November, 2015) as target case (More detailed information about this shooting incident can be found at [42, 43]). At the time of the crime, a concert was being held in Bataclan theater, with about 1500 audience. At about 21:50, three shooters killed three people outside the theater, then rushed into the theater with an explosive vest and opened fire on the crowd inside the theater, causing panic among the civilians. A few minutes later, the hall fell into darkness with only the flash of the shooter's gun, creating difficulties for civilians who tried to flee. Two shooters went to the stairs to shoot, and the other shooter went to the emergency exit near the stage. At 22:15, two policemen entered the theatre with pistols and shot and killed the shooter standing on the stage. Subsequently, two other shooters took about 20 hostages for negotiations. Finally, one shooter detonated his explosive vest, and the other tried to do the same but got shot. During the final stage, no hostages were injured or killed. Since the negotiation took a long time, in which no civilians and police were injured or killed, our simulation process is from the shooters rushing into the theater to the police killing a shooter. In this process, a total of about 1500 audiences were present. Three shooters and two policemen responded later. Finally, 87 civilians, 1 shooter, and no police officer were killed. Also, more than 200 civilians were injured. These result data are used as simulation targets.

2.2 Environment setting

We use NetLogo software (6.0.4) to simulate the real target case. Figures 1A and 1B show that the target case scene is a two-story building, including the hall on the first floor and balcony on the second floor. The first floor comprises a gray stage at the bottom, a standing area in the middle, and seat areas on both sides. The building has three exits: the main exit facing the street and two on the side. In the model, they are represented by white patches. The shooter entered through the door facing the street. In Figure 1C, we set the model's environment regarding subfigure D. Balcony is the light orange part surrounding the middle area. And the blue floor is the first-floor area. The dark blue part is the seating area, while the light blue part is the standing area. Access (stairs) on the first and second floors are simplified as yellow patches. We set up four stairs in similar locations according to the real environment. Black patches are walls or railings that agents cannot pass through. Different shapes and colors represent different types of agents. For civilians, dark green circles denote civilians in the initial state. We also consider that people run and fall in a dark environment with panic, so the pink circles represent civilians who fall. And the red "x" indicates the dead civilians. Besides, orange triangles are the shooters, with an exclamation point representing dangerous elements. A gray arrow denotes the shooter's bullet trajectory. Blue uniforms indicate the police, whose bullet tracks are represented by red arrows from the executor of the shooting to the target.

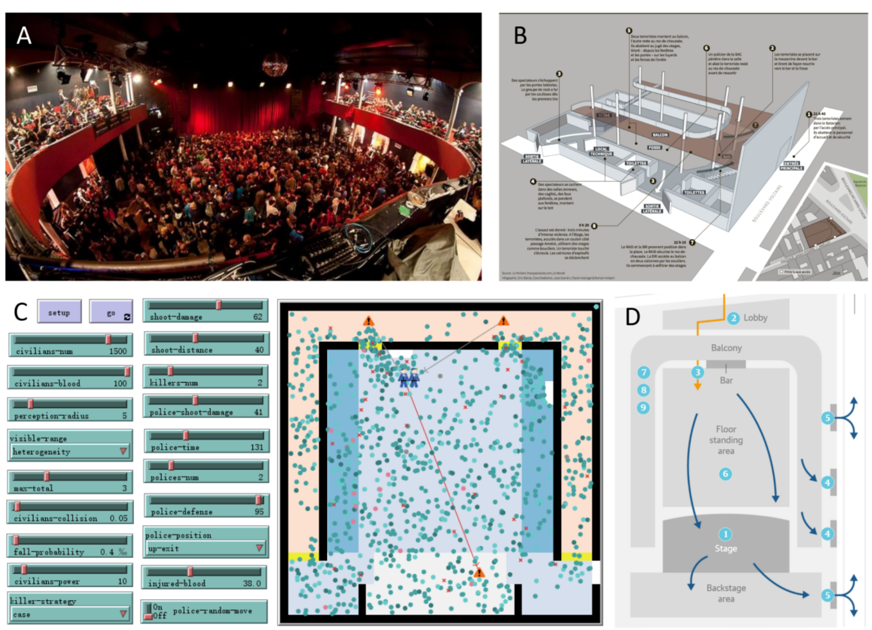

Fig. 1. The real scene of the case and NetLogo Modeling Interface. The picture on the left above shows the scene of the concert. The picture on the right above shows the 3D structure of the Bataclan theater. Subgraph C is the simulation interface in NetLogo software. Subfigure D is a schematic plan of the Bataclan theater.

2.3 The mechanism of pedestrian dynamics

In the real target case, people had a series of panic behaviors after being shot. They began to run around looking for an exit or fall to the ground. For the modeling of pedestrian dynamics in a panic state, we refer to the work [16] of Herbing (2000) and make the following settings: **(a) Movements.** We set civilians to move at different speeds in different areas. Considering that in the real environment, chairs will hinder the movement of civilians, civilians are slower in the area with chairs than in the standing area. In addition, as shown in Figure 2, civilians follow the basic principle of social force [18] in the process of moving. **(b) Escape.** As shown in Figure 2 (b), the escape guidance of agents mainly comes from the attraction of environmental facilities to them. When civilians perceive these facilities, civilians on the second floor will rush to the stairs, while civilians on the first floor will run to the exit. **(c) Fall.** Panic makes people run aimlessly, which increases the risk of falling. Therefore, we use the falling probability to set a certain proportion of people to fall randomly. The falling agent loses the ability to move and needs ten ticks to get up and continue to move. **(d) Collision and trampling.** When two mobile agents collide on the same patch, they will hurt each other. And when a mobile agent passes a fallen agent, the fallen agent is trampled. **(e) Avoidance.** When the number of people on the current patch exceeds the maximum population, the agent will go to the patch with the least number of people within the 1.2 patches and 270 ° ahead. **(f) Death.** When the life level of the agent is 0, the agent dies. Dead agents cannot move and attack.

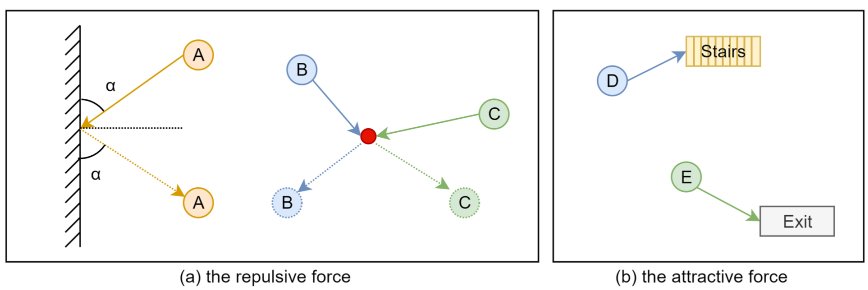

Fig. 2. Application of social force in pedestrian dynamics. Subfigure (a) shows the application of repulsive force in pedestrian dynamics. The action trajectory of pedestrian A reflects the repulsion of the environment (wall) to pedestrians, while the motion trajectories of pedestrians B and C reflect the repulsive force between agents. Subfigure (b) describes the application of attractive force in pedestrian dynamics. The motion trajectories of pedestrians D and E respectively reflect the attraction of stairs and exits to moving pedestrians.

2.4 Civilian settings

In our agent-based modeling, we have three classes of agents, including civilians, police officers, and killers (shooters). In real cases, the audience, performers, and staff are civilians since they are unarmed. The relevant settings for civilians are as follows: **(a) Perception radius R.** Perception range refers to the ability of pedestrians to perceive the external environment and other agents [8]. In the case of perceived radius heterogeneity, some information is private, not shared [32]. The larger the perception radius, the more likely the agent can perceive the environment and other agents. Therefore, we set the heterogeneity of perception radius to obey Poisson distribution. The overall perception range R of civilians will increase over time. The mean R of perception radius homogeneity and heterogeneity is the same. **(b) "Life level" blood.** "Life level" refers to the health level of agents, which is measured by the parameter blood. Due to the population difference, agents' life levels and blood are also heterogeneous. Generally speaking, there are three types of people: strong, normal, and weak. The weaker people belong to vulnerable groups such as children and the elderly [7]. Equation (1) shows the relationship between blood and the agent's life level.

$$Blood_{it}^{Agent} = \begin{cases} Healthy & if Blood_{it}^{Agent} = Blood_{i0}^{Agent} \\ Injury & if Blood_{it}^{Agent} < Blood_{i0}^{Agent} \\ Death & if Blood_{it}^{Agent} \leq 0 \end{cases} \tag{1}$$

2.5 Shooter and counter terrorism force setting

Although the shooting was antisocial and irrational, the shooter's attack strategy and scheme resulted from rational selection [13,21]. We set the Shooter and counter terrorism force mechanism as follows: **(a) Hitting range.** The hitting range refers to the range where the shooters or police can hit the target and cause damage to the target. After the shooting starts, all the lights in the field are extinguished, which leads to a dark environment reducing the shooters' vision. We set the slider shoot distance as the shooters' hitting range. The shooters' hits on the police will be reduced. We set the shooting range of shooters against the police to be half that of civilians. **(b) Shooting damage.** The shooter will cause damage to the target when the shooter's target is within the hit range. **(c) Shooting target selection.** For shooters, armed police pose a more significant threat than unarmed civilians, so they will choose to attack the police first. For the police, they only attack the shooters. **(d) Live level Blood setting.** When suffering from shooting, police and shooters they have better equipment and body to reduce their probability of death and injury. **(e) Equipment defense.** The police entering the scene wore complete protection devices, including bulletproof vests and shields. We set a slider police defense to find this damage defense ratio.

3 Optimal Solution Outcomes

3.1 Solving optimal solutions

Our target values of Y variables are 87 civilian deaths (Y1), 205 civilian injuries (Y2), 1 shooter death (Y3), and 0 police death (Y4). We assume the civilian injuries (Y2) is 205 as it shows more than 200 civilian injuries but no specific figures in all public data in this case. is used as a real objective function that has four values. In the model simulation, should be matched well. If the simulation is effective, we can get at least one combination of optimal parameters close to the real situation. We build the model and traversal parameters. We have obtained many simulation results, and each result has an error with the real values. Mean Square Error (MSE) can indicate the degree of difference between the simulation value and real target value in equation (5). Each combination of parameters is simulated 100 times in the experiment, and the average value of 100 simulation results is calculated. Finally, we find two combinations of optimal solutions $parameter(*)$: **(a) Parameter 1**: The optimal solution parameter 1 is as follows: the perception radius is 5, the shooting damage of shooters is 62; the probability of tumble is 0.4%; the perception range pattern of civilians is homogeneity; the shooting distance is 40 patches; the shooting damage of police is 41; each trampling reduces 10 Blood; civilians are deemed as injured when the blood volume was lower than 39.6% of the total blood volume; the collision damage of the civilians is 0.03; the time of police arrival is 170 ticks; the police equipment can reduce the damage from shooters by 95%. **(b) Parameter 2**: The other optimal solution parameter 2 is as follows: the perception radius is 5, the shooting damage of shooters is 56.8; the probability of tumble is 0.4%; the perception range pattern of civilians is heterogeneity; the shooting distance is 40 patches; the shooting damage of police is 41; each trampling reduces 10 Blood; civilians are regarded as injured when the blood was lower than 40% of the total blood; the collision damage of the civilians is 0.05; the time of police arrival is 180 ticks; the police equipment can reduce damage from shooters by 95%.

$$MSE = E(f_{sim}^{*}() - f_{real}^{*}())^2 \tag{2}$$

$$Parameters(*) = Argmin(\triangle) = Argmin(MSE) \tag{3}$$

3.2 Validity of the Optimal Solution

The optimal solution matching the final result of the real target case should be back-calculated for the entire shooting process. In Figure 3, We present the results of the 1000 simulations based on optimal solutions (parameter 1, parameter 2), which fit well with our real target case.

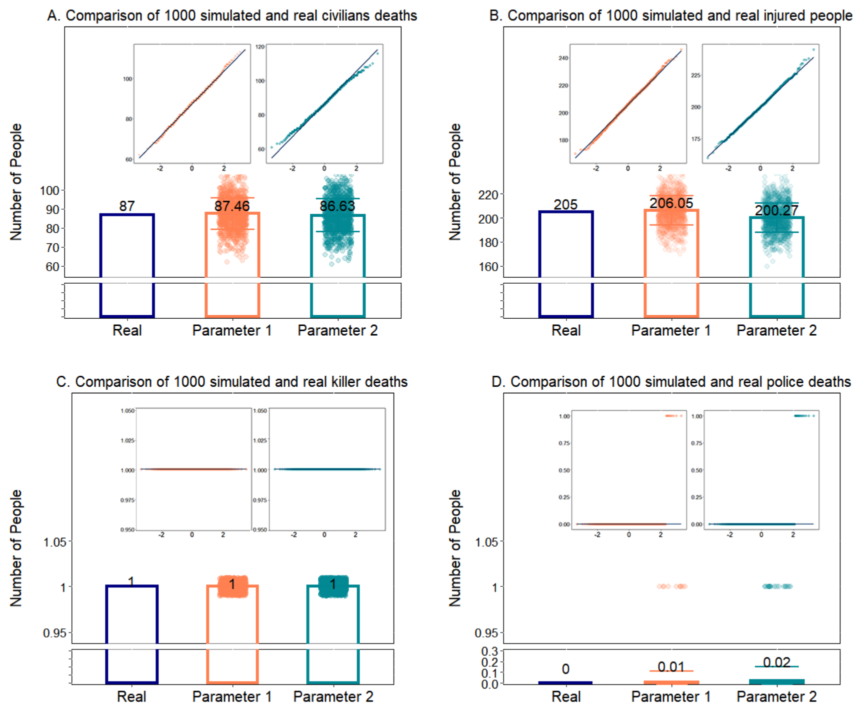

Fig. 3. Number of people in 1000 simulation results under the optimal solution parameters. Panel A compares the numbers of civilian deaths between the real case and the simulation. And Panel B compares the numbers of civilian injuries. Then, Panel C and D compare the numbers of shooter and police deaths. The mean, distribution, and error bars of the real (real) and simulation results (parameter 1 and parameter 2) are shown separately in each panel. At the same time, we also used Q-Q plots to test the distribution law of 1000 simulations to check whether they obey the normal distribution. The blue bar represents the real case, the orange bar represents parameter 1, and the green bar represents parameter 2.

4 Counterfactual inference.

Counterfactual inference can be used to infer situations that are still possible that did not occur in the real world. Using the parallel simulation method, we can infer the counterfactual results that are meaningful to the real world. Based on the optimal parameter combination, the counterfactual inference is used to explore the impact of anti-terrorism forces (police officers) and escape exits on the shooting incident.

A. Number of police. We consider the impact of varying police sizes on the shooting outcome based on the two combinations of optimal solutions parameters. Figures 4A and 4B show the changes in civilian deaths and injuries as the number of police increases, respectively. From the general trend, the number of civilian deaths and injuries decreased with the increase in police. The key point is 4 police. When the police number was increased from 1 to 4, civilian fatalities and injuries decreased significantly. Besides, when the number of police is greater than 4, the number of civilian deaths and injuries has not decreased significantly. Hence, for police savings and reducing civilian casualties, the best police size is 4 when there are three shooters.

Figures 4C&D show that two police officers can kill a shooter, but the officer will be killed if only one is there, which is dangerous for the police officers, even with 95% defense. Thus, the police must fight against terrorism jointly. Overall, the best size of police intervention is 4 police officers, effectively reducing civilian deaths and injuries and preventing the police from being in extreme danger. At the same time, it can obtain high social security returns with relatively few social resources.

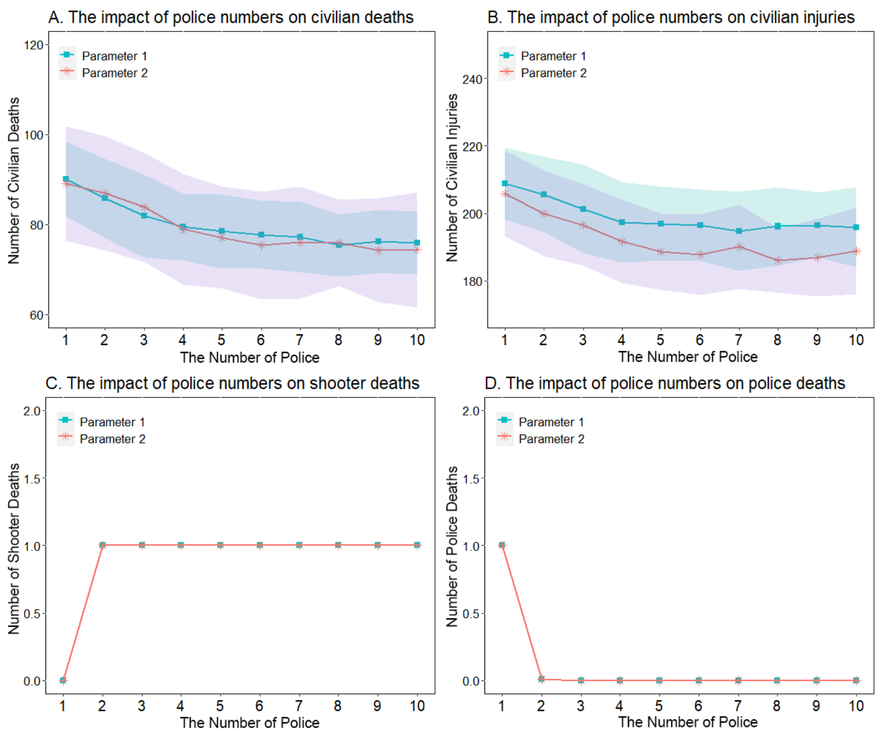

Fig. 4. the number of death or injury with the growth of police. Subfigures A and B show the civilian casualties with the police size from 1 to 10 under parameter 1 and parameter 2. And subfigures C and D describe the change in shooter and police deaths with the police size from 1 to 10 under parameter 1 and parameter 2. Shadow represents the range of standard deviation of 100 simulation results.

B. Police response time. After discussing the impact of police numbers on terrorist attacks, we try to find the effect of police response time on the entire incident. We set the police response time from 10 to 250 with a step size of 10. In the case, it took 25 minutes from the start of the shooting until the police arrived at the scene. In parameters 1 and 2, the police arrived in 170 ticks and 180 ticks, respectively. Therefore, 1 tick represents $0.15 \approx \frac{25}{170}$ minutes (in parameters 1) and $0.14 \approx \frac{25}{180}$ minutes (in parameters 2), respectively. The simulation results are shown in Figure 5. Undoubtedly, the earlier the police arrive, the safer the civilians, and the fewer injuries and deaths. It was almost impossible for police to reach the scene at the beginning of the shooting incident because of the reaction time needed. In light of the casualties of civilians, shooters, and police, the best time for the police to intervene is 30 ticks. At this time, the death toll of the shooters exceeded 2, the police death was close to 0, and civilian casualties were less.

C. Building exit. We added three exits at different locations based on the real case. Figure 6 compares the outcome under a real case and other possible exits. We compare the outcome under two optimal solutions of parameter 1 (homogeneity) and parameter 2 (heterogeneity). From Figure 6 A2 to H2 and Figure 6 A3 to H3, the deaths of shooters and police are similar in each scenario, which are 1 shooter death and 0 police death. And the number of civilian deaths and injuries has a relatively significant difference. New exits slightly ease the congestion of people but make civilians with the same perception radius still suffer severe congestion and stampede. With heterogeneous perception ranges, the more exits, the safer civilians are, proving the importance of orderly evacuation. In conclusion, increasing exits on the second floor is necessary, significantly reducing civilian deaths. In addition, the uniform distribution of exits is conducive to improving the evacuation efficiency of civilians and decreasing collisions and stampedes.

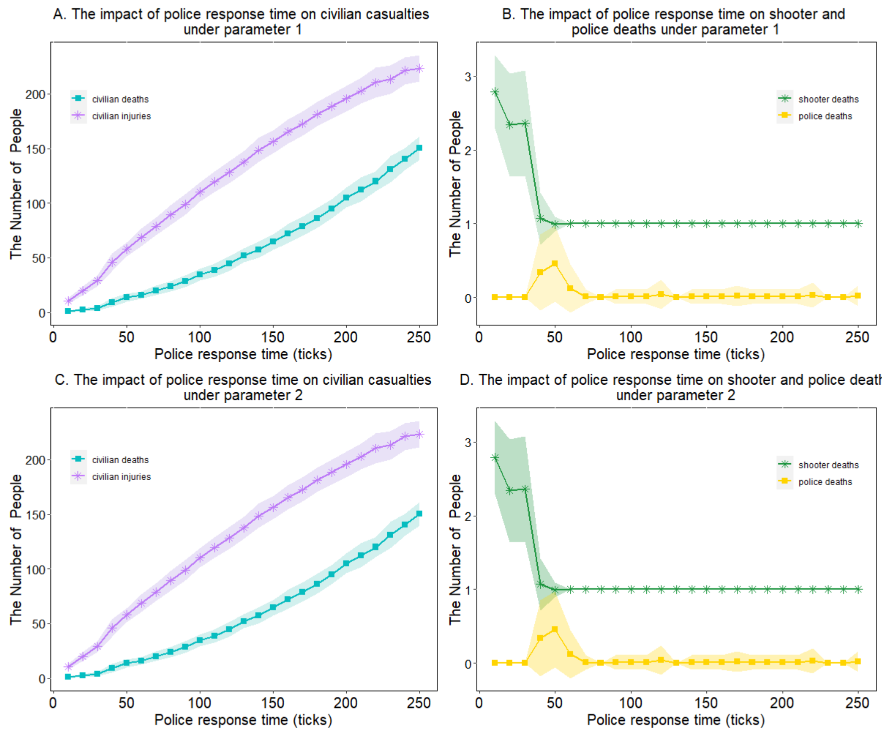

Fig. 5. Impact of police response time on results. Subfigures A and C show the impact of police response time on civilian casualties under two combinations of the optimal solution. The blue line is the number of civilian deaths, and the purple line represents the number of civilian injuries. Subfigures B and D depict the impact of police response time on shooter and police deaths under two combinations of the optimal solution. The green line is the number of shooter deaths, while the yellow line indicates the number of police deaths. Each data is the mean of 100 independent simulations. The upper and lower bounds of shadow are the standard deviation of 100 simulation results.

D. Artificial Neural Network. Figure 7 shows our ANN model's architecture and the loss curve of training and testing. The best optimization method, activation function, and network architecture were determined by trial and error. The optimization method is Adam (Adaptive Moment Estimation), and the activation function is the Relu. Our ANN model has an input layer, two hidden layers, and an output layer. The input layer contains five neurons, into which we input five parameters, including shooter damage, perception radius, injured blood, civilian collision, and police response time. After debugging, the first hidden layer has 20 neurons and the second hidden layer has 5 neurons. The output layer outputs two variables: civilian deaths and civilian injuries. The training set and verification set data account for 80% and 20% of the data set, respectively. And the number of training iterations of the model is 500. In Figure 7B, the blue line is the loss curve of the training, from 0.363 to 0.009, while the orange line is the loss curve of the verification, from 0.376 to 0.008. Finally, the loss values are less than 0.01 and tend to be stable, which shows that the model has good convergence and prediction performance.

5 Conclusions and Discussions

An agent-based model of three classes of agents (civilians, shooters, and police) has been used to model the crowd dynamics of civilians in the shooting incident. In particular, we also consider the impact of indoor

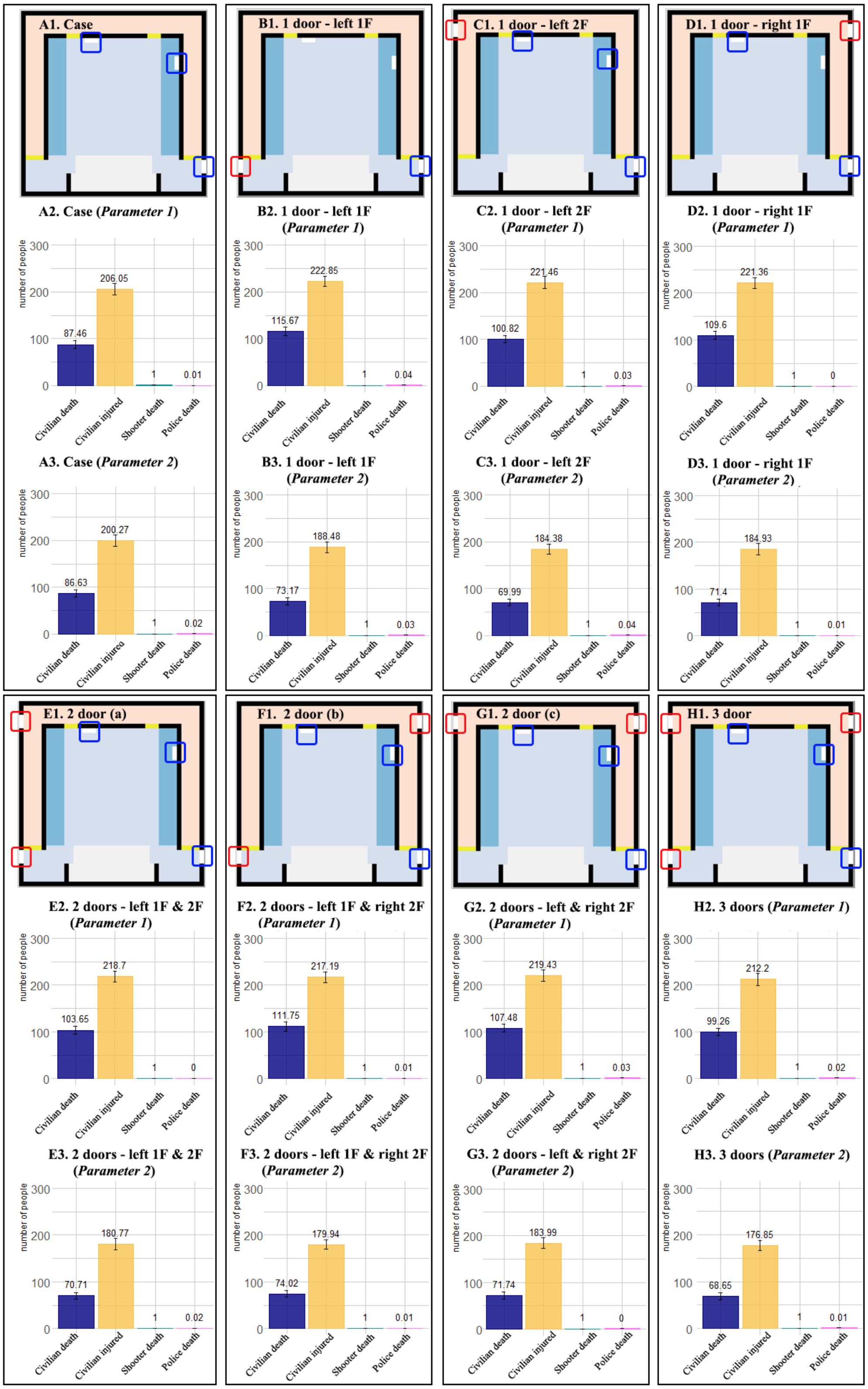

Fig. 6. Sizes and locations of possible exits. A1 refers to the real case whose outcome is under the sketch map. Subfigures B1 to H1 explore the counterfact and outcomes under them. The blue box marks the existing exits in the real case, and the red box marks the new exits in the counter-fact. Subfigures A2-H2 and A3-H3 represent the number of casualties under parameter 1 and parameter 3, respectively, corresponding to the exit situation. The dark blue bar represents the number of civilian deaths, the yellow bar represents the number of civilian injuries, the light blue bar represents the number of shooter deaths, and the pink bar represents the number of police deaths. Each result is the mean of 100 parallel simulations.

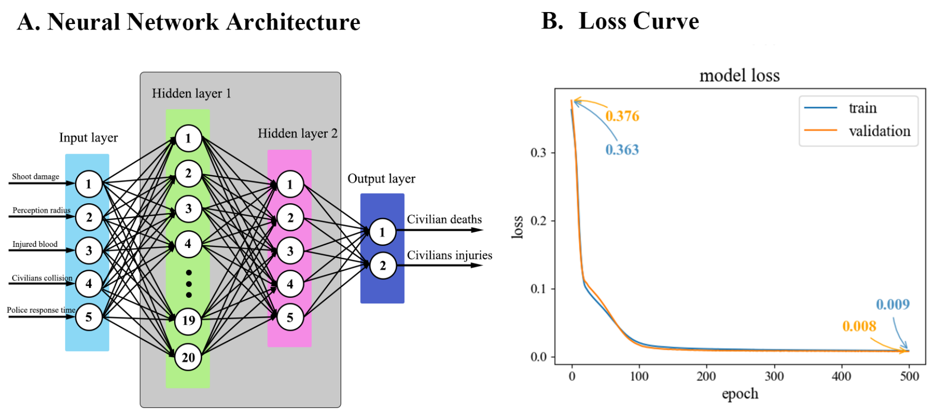

Fig. 7. Artificial Neural Network (ANN) construct and Loss Curve. Subfigure A is the ANN architecture used in this study, and subfigure B is the loss curve of the training and validation results of the ANN model with 500 iterations.

double-layer buildings. The internal three-dimensional structure of the building affects the crowd dynamics and the interaction between police and shooters in the shooting incident. For example, the stairs increase the probability of trampling and collision, and the railings on the second floor hinder the police from fighting terrorism. We simulated the dynamic process of real shooting cases and matched the real results. On this basis, two combinations of optimal solutions are obtained. Based on the simulation results of real cases, we also need to simulate other counterfactual situations, such as the number of police, police response time, and the location and number of buildings, which are beneficial for social governance and public security management.

(a) Existence of optimal solution. The existence of the optimal solution can verify the ability of the model to match the real case. In this paper,6 we obtain two combinations of optimal solutions. The numbers of civilian deaths and injuries, police deaths, and the shooters' deaths are well matched with the real case. We have carried out 1000 independent simulations and normal distribution verification based on the optimal solution to ensure its effectiveness and robustness. Through the optimal solution, we can find key factors to understand the behavior rules and crowd dynamics of various agents in the shooting incident. Therefore, our model can calculate the critical behavior mechanisms of individuals.

(b) The best anti-terrorist scale. Mass shooting often causes vast casualties, so the anti-terrorism force of the police is particularly critical to diminishing deaths. From the shooting incident result, the more police, the greater the shooters' death rate and the greater the possibility of the police defeating the shooter. Due to the limited human resources of the police, the optimal anti-terrorism scale of the police should be calculated. The best anti-terrorism scale is 4 police officers under the two optimal solutions.

(c) The optimal response time. Response time refers to the period from the start of the shooting incident to the police intervention at the scene, reflecting the response speed of the police. From the simulation results, the faster the response time of the police, the better the results of the shooting incident, which means the death and injury rate of civilians are lower, and shooters get shot to death in a shorter time. Nevertheless, the police cannot arrive at the scene immediately at the beginning of the shooting accident in the real world. So, the optimal response time for the police is 30 ticks to arrive at the scene according to the simulated results of the death and injury rates of civilians, police, and shooter. This part of the conclusion has referential significance to establishing urban police patrol and police post locations.

(d) Outlet location distribution. The exit is the life passage for civilians to escape the scene. In buildings with complex internal structures, the location and number of exits will also affect the results of the shooting incident. We have added $1 \sim 3$ exits based on real cases. From the results, with civilians' heterogeneous perception range, the more exits, the better the result of the shooting incident. If the civilians' perception range is homogeneous, the opposite is true. Distributing the exits evenly on the first and second floors is most conducive to better results if the number of exits is limited. This part of the conclusion could guide the internal structure setting of buildings in improving public safety.

It should be noted that our discussion and research on terrorist attack patterns and police response strategies are aimed at better assisting in the formulation of policies to resist terrorist attacks, preventing terrorist attacks and reducing harm to maintain urban public safety. For possible ethical issues, we believe that we need to see the duality of things. Just as studying models for the spread of infectious diseases can also make it easier for criminals to spread the disease, studying this process is still necessary because it can also prevent or slow down the spread of infectious diseases. In fact, we can also see many other studies on terrorist attacks, and many of these studies and exchanges have helped promote the formulation of policies to resist terrorist attacks. Science and technology themselves are neutral, and it depends on how we use them. **More importantly, the conclusions of this study can clearly inform terrorists that regardless of the strategy, the police have the optimal strategy to resist terrorist attacks, thereby reducing the confidence and likelihood of shooter attacks.** This study also has certain limitations, for example, we did not examine the psychological state and communication of agents in more detail. These issues will be further addressed in future work.

References

1. Abreu, O., Cuesta, A., Balboa, A., Alvear, D.: On the use of stochastic simulations to explore the impact of human parameters on mass public shooting attacks. Safety Science **120**, 941–949 (2019)
2. Anklam, C., Kirby, A., Sharevski, F., Dietz, J.E.: Mitigating active shooter impact; analysis for policy options based on agent/computer based modeling (2014)
3. Arteaga, C., Park, J.: Building design and its effect on evacuation efficiency and casualty levels during an indoor active shooter incident. Safety science **127**, 104692 (2020)
4. Bain, N., Bartolo, D.: Dynamic response and hydrodynamics of polarized crowds. Science **363**(6422), 46–49 (2019)
5. Boyd, P., Molyneux, J.: Assessing the contagiousness of mass shootings with nonparametric hawkes processes. PLoS one **16**(3), e0248437 (2021)
6. Briggs, T.W., Pollard, J.W.: Beyond first-person shooter video games: Using computational modeling and simulation of mass violence for threat assessment and management. Journal of Threat Assessment and Management **6**(3-4), 182 (2019)
7. Cacciattolo, M.: Ethical considerations in research. In: The Praxis of English Language Teaching and Learning (PELT), pp. 55–73. Brill (2015)
8. Cao, S., Song, W., Lv, W., Fang, Z.: A multi-grid model for pedestrian evacuation in a room without visibility. Physica A: Statistical Mechanics and its Applications **436**, 45–61 (2015)
9. Capellan, J.A., Silva, J.R.: An investigation of mass public shooting attacks against government targets in the united states. Studies in Conflict & Terrorism **44**(5), 387–409 (2021)
10. Chen, C., Tong, Y., Shi, C., Qin, W.: An extended model for describing pedestrian evacuation under the threat of artificial attack. Physics Letters A **382**(35), 2445–2454 (2018)
11. Dasgupta, D.: Artificial neural networks and artificial immune systems: similarities and differences. In: 1997 IEEE International Conference on Systems, Man, and Cybernetics. Computational Cybernetics and Simulation. vol. 1, pp. 873–878. IEEE (1997)
12. DiMaggio, C., Avraham, J., Berry, C., Bukur, M., Feldman, J., Klein, M., Shah, N., Tandon, M., Frangos, S.: Changes in us mass shooting deaths associated with the 1994–2004 federal assault weapons ban: Analysis of open-source data. Journal of trauma and acute care surgery **86**(1), 11–19 (2019)
13. Dugan, L., LaFree, G., Piquero, A.R.: Testing a rational choice model of airline hijackings. Criminology **43**(4), 1031–1065 (2005)
14. Hayes, R., Hayes, R.: Agent-based simulation of mass shootings: Determining how to limit the scale of a tragedy. Jasss-the Journal of Artificial Societies and Social Simulation **17**(2) (2014)
15. Heath, B., Hill, R., Ciarallo, F.: A survey of agent-based modeling practices (january 1998 to july 2008). Journal of Artificial Societies and Social Simulation **12**(4), 9 (2009)
16. Helbing, D., Farkas, I., Vicsek, T.: Simulating dynamical features of escape panic. Nature **407**(6803), 487–490 (2000)
17. Helbing, D., Farkas, I.J., Molnar, P., Vicsek, T.: Simulation of pedestrian crowds in normal and evacuation situations. Pedestrian and evacuation dynamics **21**(2), 21–58 (2002)
18. Helbing, D., Molnar, P.: Social force model for pedestrian dynamics. Physical review E **51**(5), 4282 (1995)
19. of Investigation, F.B.: 2000 to 2018 active shooter incidents. https://www.fbi.gov/file-repository/active-shooter-incidents-2000-2018.pdf/view (2019)
20. Johnson, N.R.: Panic at the who concert stampede: an empirical assessment. Social Problems **34**(4), 362–373 (1987)

21. LaFree, G., Dugan, L., Xie, M., Singh, P.: Spatial and temporal patterns of terrorist attacks by eta 1970 to 2007. Journal of Quantitative Criminology **28**, 7–29 (2012)
22. Lee, J.Y., Dietz, J.E., Ostrowski, K.: Agent-based modeling for casualty rate assessment of large event active shooter incidents. In: 2018 Winter Simulation Conference (WSC). pp. 2737–2746. IEEE (2018)
23. Lestari, D., Sabri, A., Handhika, T., Sari, I., Fahrurozi, A., et al.: The simulation of evacuation from multistorey building using netlogo. In: IOP Conference Series: Materials Science and Engineering. vol. 854, p. 012060. IOP Publishing (2020)
24. Li, S., Zhuang, J., Shen, S.: A three-stage evacuation decision-making and behavior model for the onset of an attack. Transportation Research Part C: Emerging Technologies **79**, 119–135 (2017)
25. Li, W., Gong, J., Yu, P., Shen, S., Li, R., Duan, Q.: Simulation and analysis of congestion risk during escalator transfers using a modified social force model. Physica A: Statistical Mechanics and its Applications **420**, 28–40 (2015)
26. Littleton, H., Kumpula, M., Orcutt, H.: Posttraumatic symptoms following a campus shooting: The role of psychosocial resource loss. Violence and Victims **26**(4), 461–476 (2011)
27. Liu, R., Fu, Z., Schadschneider, A., Wen, Q., Chen, J., Liu, S.: Modeling the effect of visibility on upstairs crowd evacuation by a stochastic ffca model with finer discretization. Physica A: Statistical Mechanics and its Applications **531**, 121723 (2019)
28. Lu, P., Chen, D., Li, Y., Wang, X., Yu, S.: Agent-based model of mass campus shooting: Comparing hiding and moving of civilians. IEEE Transactions on Computational Social Systems (2022)
29. Lu, P., Wen, F., Li, Y., Chen, D.: Multi-agent modeling of crowd dynamics under mass shooting cases. Chaos, Solitons & Fractals **153**, 111513 (2021)
30. Lu, X., Astur, R., Gifford, T.: Effects of gunfire location information and guidance on improving survival in virtual mass shooting events. International Journal of Disaster Risk Reduction **64**, 102505 (2021)
31. McIlroy-Young, R., Anderson, A.: From welcome new gabbers to the pittsburgh synagogue shooting: The evolution of gab. In: Proceedings of the international aaai conference on web and social media. vol. 13, pp. 651–654 (2019)
32. Moussaïd, M., Perozo, N., Garnier, S., Helbing, D., Theraulaz, G.: The walking behaviour of pedestrian social groups and its impact on crowd dynamics. PloS one **5**(4), e10047 (2010)
33. Pan, X., Han, C.S., Dauber, K., Law, K.H.: A multi-agent based framework for the simulation of human and social behaviors during emergency evacuations. Ai & Society **22**, 113–132 (2007)
34. Quarantelli, E.L.: Panic behavior: some empirical observations (1975)
35. Ran, H., Sun, L., Gao, X.: Influences of intelligent evacuation guidance system on crowd evacuation in building fire. Automation in Construction **41**, 78–82 (2014)
36. Rand, W., Rust, R.T.: Agent-based modeling in marketing: Guidelines for rigor. International Journal of research in Marketing **28**(3), 181–193 (2011)
37. Saloma, C., Perez, G.J., Tapang, G., Lim, M., Palmes-Saloma, C.: Self-organized queuing and scale-free behavior in real escape panic. Proceedings of the National Academy of Sciences **100**(21), 11947–11952 (2003)
38. Stewart, M.G.: Cost effectiveness of risk mitigation strategies for protection of buildings against terrorist attack. Journal of performance of constructed facilities **22**(2), 115–120 (2008)
39. Sutherland, M., McKenney, M., Elkbuli, A.: Gun violence during covid-19 pandemic: paradoxical trends in new york city, chicago, los angeles and baltimore. The American journal of emergency medicine **39**, 225 (2021)
40. Toyama, M.C., Bazzan, A.L., da Silva, R.: An agent-based simulation of pedestrian dynamics: from lane formation to auditorium evacuation. In: Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems. pp. 108–110 (2006)
41. Wang, J., Ni, S., Shen, S., Li, S.: Empirical study of crowd dynamic in public gathering places during a terrorist attack event. Physica A: Statistical Mechanics and its Applications **523**, 1–9 (2019)
42. Wikipedia: Bataclan (theatre). https://en.wikipedia.org/wiki/Bataclan$_(theatre$)(2023)
43. Wikipedia: November 2015 paris attacks. https://en.wikipedia.org/wiki/November$_2$015$_Paris_attacks$(2023)