Classroom Evacuation Behavior Simulation At a Beijing High School and Optimized Design

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Abstract
Schools play a crucial role in not only academic advancement, but also in building a safe environment for student and local community growth at large. One of the most important pillars of constructing a secure environment is a well-designed campus evacuation plan, which would enable orderly evacuation and minimize chaos and financial lost. This paper presents a pedestrian behavior modeling in which a classroom student flow was analyzed. Different classroom layouts and evacuation schemes are presented, and their impact on classroom evacuation efficiency is simulated using Anylogic accordingly. The results show that the overall evacuation time can be effectively reduced by organizing the students flow and setting reasonable classroom layouts. This result can provide useful insights for school policy makers in designing campus evacuation plan.

1.Introduction

Education has always been the important part of societies' growth and progress, and schools serve as the primary place for acquisition and dissemination of knowledge within modern societies. Over the past 10 years, the number of kindergartens in China increased by 76.8%, and the population with higher education has reached 240 million (Embassy of The People's Republic of China, 2022). As educational institutions proliferate and students populations expand, campus safety has become a major concern for both schools and local governments. In recent years, numerous incidents have underscored the critical need for enhancing campus safety preparedness. For instance, on October 24, 2021, 11 people got injured and 2 people died in a fire in a university laboratory in Jiangsu, China. On January 19, 2024, 13 people died in a fire at a boarding high school in Henan, China (Wang, 2024) .These events highlight the imperative for schools to prioritize campus safety and develop comprehensive evacuation strategies to mitigate risks and protect their communities.

The evacuation of schools during emergencies presents unique challenges due to the high population density and the developmental immaturity of the student population. As Fruin (1993) observed, "the behavior of crowds in emergency situations is often characterized by panic and herd mentality, leading to potentially dangerous bottlenecks and trampling" (p. 45). This dynamic is particularly salient in school settings, as students are well-acquainted with their surroundings and will instinctively gravitate towards familiar routes in an attempt to reach safety as quickly as possible (Proulx, 2001), for which will easily cause severe stampede accidents.

This paper utilizes mathematical modeling and computer simulation to investigate evacuation scenarios within the high school classroom setting. Classrooms are the fundamental units of the campus, and they serve as the critical starting point for effective evacuation planning. However, many of the present mathematical models were used in analyzing the pedestrian behavior and improving the layouts for large environments, such as subway stations, airports, and hospitals (Xu et al., 2020; Zhong et al., 2018; Abir et al., 2022), and the evacuating behavior and layouts within the classroom context has not been the subject of extensive research. Additionally, existing researches are mostly focusing on enhancing school preparedness under emergencies by the improving the design of the width of the exit, the number of exit, and the width of passage, etc. These are reasonable changes, however, they are hard to realize since the teaching building have already been build. On the other hand, this study, by simulating the pedestrian behavior based on the social force model and visualized through Anylogic, examines the impact of pushing chairs during evacuation and the impact of leaving the seats from different sides. The findings of this study offer insights in guiding student evacuation behaviors, focusing on procedural rather than infrastructural modifications. These strategies are not only effective but also readily implementable, allowing educational institutions to immediately benefit from the enhanced evacuation protocols.

2.Literature review

2.1.Pedestrian Behavior Simulation Model

Existing computational models for simulating pedestrian dynamics can be categorize into two types, which are the macroscopic model and microscopic model. The macroscopic model was first proposed by Henderson(1974), in which he used the Boltzmann equation to simulate the flow of the crowd as the movement of fluid. This type of model only pay attention to flow density and speed, which neglects the interactions between individuals and take people as identical agents, simulating the dynamic process using rules form physics. As they can not describe the complex behavior and the non-linearity of pedestrian dynamics, they are mostly applied in organized environment with simple structure such as stadiums(Zhang et al., 2007) and transport hub(Chen et al., 2020). The microscopic model treats pedestrians as rational individuals and consider the heterogeneity among them. This kind of model can quantitatively, and often time visually, characterize the non-linear relationship between agents and reflects the self-organizing phenomenon. The most wide used microscopic models are the cellular automata model and the social force model. As it is necessary to consider the interactions between students and their psychological factors play an important role under the classroom evacuation scenario, the social force model was chosen to carry out the simulation and Anylogic is used to aid with visualizing the analyzing process.

2.2 Applications of Computational Models in Campus Evacuation Simulation and Plan Optimization

Lim Eng Aik(2011) implemented a modified version of Cellular Automata in simulating classroom evacuation behavior, through which he combined a probabilistic neural network in simulating the decision-making process of the evacuees. This study applied PNN, which is an classifier model based on Bayesian decision-making on estimate probability density function with Gaussian distribution, to classify the position of neighboring cell the is suitable to be move into. It successfully reproduce people's evacuation behavior near the exist, for which the agents tend to select the exit that is the closest, but will choose the alternative exit when the density if too high. This result can reflect that individuals may not choose the most effective way of evacuating when there are multiple exits and has shed lights on classroom exits design. Liu et al.(2015) implements Netlogo in simulating the campus evacuation behavior and provide insights on architectural designs of schools. Combined with AutoCAD and ArcGIS, they first draw the basic outlines for different classroom layouts and then transform the file from polygons into rasters, and then the file has been read by Netlogo. As Netlogo is only capable of drawing simple geometric graphs, this method largely eliminates this draw back and offer accurate simulation. This study conclude that classroom with two exists significantly decreases the evacuation time than the ones with only one exit, certain remedial measures are necessary to be taken if school can't avoid the layouts with only one exit. Delcea et al.(2020) conducted a evacuation simulation involving 18 students aged 19-21, the experiment was conducted in both a traditional and a collaborative classroom, with empirical measurements of various aspects, such as speed, obstacle navigation, and ad-hoc guidance. Based on the field observations, an agent-based model was created, calibrated, and used for further simulations. This highly configurable model was adapted to five types of collaborative classroom configurations, and their evacuation time efficiency was hierarchized, with the exit door position as a given factor. The impact of jumped and bypassed obstacles, as well as volunteer guidance, on evacuation time was analyzed. This study concludes that the evacuation time in a collaborative classroom with a single exit door was on average, 6.02% shorter than in a non-collaborative classroom. Furthermore, the presence of two evacuation doors in a collaborative classroom, coupled with proper desk placement, can reduce the evacuation time by up to 36.51% compared to a single-door scenario. Zhang et al.(2008) conducted an analysis of video recordings which revealed typical evacuation characteristics including variable velocity, queuing, and exit monopolization. Based on these observations, this study improved the multi-grid model by incorporating pre-movement time, variable velocity, and adding a new update procedure. Further analysis of the pre-movement time distribution showed evacuation times follow a (truncated) normal distribution, varying within 30% of the mean. Furthermore, the experimental egress time was close to the model's minimum, likely due to coordination among participants. This study provides valuable insights for developing applicable egress models and understanding basic evacuation behaviors. Song et al.(2019) implemented a model that considers two key factors affecting the evacuation process, which are room obstacles and the number of pedestrians in each exit area. This study outline the methods for determining pedestrian movement probability and the model's evolution rules, and then design model that can handle evacuation scenarios both with and without obstacles. The room's obstacles are represented by a static floor field calculated using the A-star algorithm. Two simulation experiments and comparative analyses were conducted, and this model was able to accurately reproduce student evacuation experiments. The results of this study highlight the importance of the number of pedestrians in the exit area as a critical factor for evacuation, and demonstrate the effectiveness and superiority of our proposed model.

3.Methodologies

3.1 Social Force Model

The Social Force Model (SFM) is a widely used framework proposed by Dirk Helbing in 1995 for simulating the behavior of pedestrian crowds. It examines the various forces acting upon the

individuals undergoing evacuation, enabling the calculation of the combined force, as well as the acceleration magnitude and direction for each individual (Helbing & Molnár, 1995). By predicting the force state and motion state of the individual at the subsequent time interval, the model can simulate and visualize the trajectory of the agents, thereby facilitating a comprehensive understanding of the evacuation process (Helbing et al., 2000). The social force model is grounded in Newton's second law, and take people's subconscious psychological factors into consideration. These factors, which include the desire to reach a safe exit, the need to maintain personal space, and the tendency to avoid collisions, are mathematically represented and integrated into the model to generate accurate predictions of individual and crowd movement (Helbing et al., 2000). For the six types of common crowd self-organization phenomena, the Social force model has been shown to have a better ability than the other models in simulating five of them (Duives et al., 2013). The application of the social force model in the context of emergency evacuation planning enables researchers and practitioners to anticipate potential bottlenecks (Hoogendoorn & Daamen,2005), the turbulent movement in extremely dense areas (Helbing & Johansson,2007), identify optimal evacuation routes, and develop strategies to mitigate the risk of injury or loss of life (Zheng et al., 2009).
The kinetic equations of the social force model are as follows:

$$m_\alpha \frac{d\vec{\omega}_\alpha}{dt} = \vec{F}_\alpha(t) + \xi, \tag{1}$$

$$\vec{F}_\alpha(t) = \vec{F}^0_\alpha(\vec{v}_\alpha, v^0_\alpha \vec{e}_\alpha) + \sum_\beta \vec{F}_{\alpha\beta}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_\beta) + \sum_B \vec{F}_{\alpha B}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_B) + \sum_i \vec{F}_{\alpha i}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_i, t), \tag{2}$$

In (1):

mα is the mass of individual α, $\vec{\omega}_\alpha$ is the desired velocity of the individual in the current environment, $\vec{F}_\alpha(t)$ is the combined force on the individual, and ξ is a random variable representing the other perturbing forces on the pedestrian in the evacuation.
In (2):
The first term is the individual driving force, the second term is the inter-individual repulsive force, which includes the physical contact force and the psychosocial force, the third term is the repulsive force between the individual and the obstacle, and the fourth term is the combined force of attraction.

3.2 Modeling process based on Anylogic

Anylogic is a comprehensive modeling and simulation software that utilizes Java programming for its pedestrian evacuation model, which is based on a social force model and implemented through discrete event modeling. The software allows for the observation of crowd characteristics, such as speed variations, tendency to distance from others and obstacles, and self-organization of pedestrians. In the past few year, researchers had supported the validity and proved the effectiveness and accuracy of using Anylogic in pedestrian simulation. For example, Gao et al.(2018) examined Anylogic simulation result with the "evacuation time theoretical model calculation", and has concluded that it was consistent with theoretical calculated time. Li et al.(2015) tested Anylogic through the simulation of 2013 Ya'an earthquake, through which the result had showed that it can reconstruct the pedestrian flow and its complex pattern accurately. The Anylogic Pedestrian Library module divides the modeling process into two parts: "environment" and "logic". The "environment" constructs the evacuation environment through wall module, area module, and target line module, enabling the visualization and imaging of the simulated evacuation process. The environment in this study focused on the basic structure in the classroom and the placement of desks and chairs. The "logic" component expresses the different states of pedestrians as flowcharts, it defines the behavior of each agent through a combination of behavioral modules that connect with logic and in association with the environmental parts.

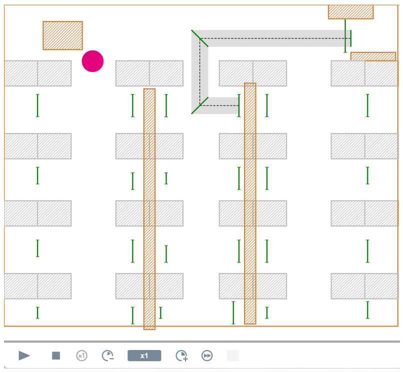
3.3 Parameter Setting in Anylogic

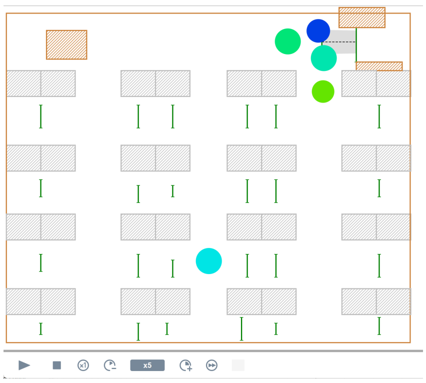
Anylogic required the number of agents, comfort speed, and diameter of individual agents to build the simulation environment. The number of agents is the average class size in the selected high school, which is 30; the comfort speed is set to 0.7~1.3m/s, which is obtained through the literature review combined with field research(Xu et al., 2008); each student is represented as an circle, with the diameter be the maximum shoulder width and is set to 0.357m~0.513m. This statistics is obtained from GB/T 26518-2010, or the current Human dimensions of Chinese minors(Zhang et al., 2011). For the environment setting, 1m is represented by 90 pixels on Anylogic.

3.5 Behavior Rules of Each Agent
The Pedestrian Source module generated agents with predefined parameters, simulating students seated individually within the classroom setting. To accurately represent the distribution of occupants, 30 Pedestrian Source modules were utilized, each positioned adjacent to the desk modules. The Pedestrian Go To module established the target direction for the agents, directing them towards the classroom exit. Each agent terminated at the Pedestrian Sink module, after they have pass the exit of the classroom.

3.**Experiment design**

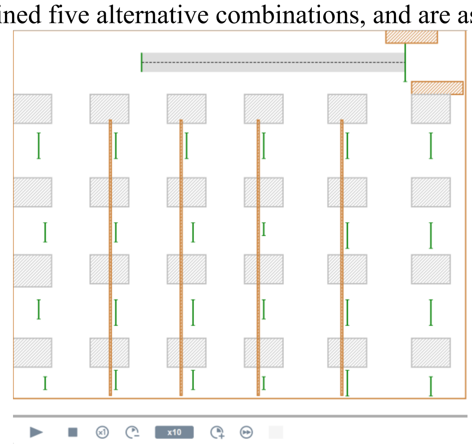
3.1.The Selected Building
The school selected in this study is a high school in Beijing, China. The area of each room is 7.8m*6.37m, each classroom has one door with width 0.69m, and pathway width 0.7m. In every room there are 30 desks and chairs placing in 6 lines, for each desk with a width of 0.66m.
3.2.Designed scenario 1: Simulation on evacuating behavior of pushing chairs
The first designed scenario for this study is to investigate the impact of pushing chairs on evacuating time in classrooms when students sit in pairs. This is the most common desk layouts at schools, and students are often asked to push their chairs in when leaving their seats so that would benefit the others behind, but there lacks scientific prove of the effectiveness of doing so. The designed environment is as shown:

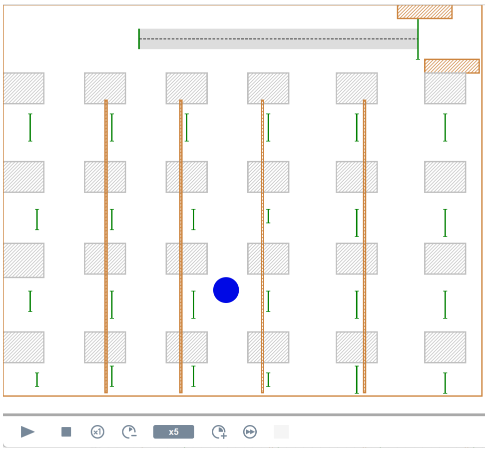

This environment simulates the scenario without pushing chairs


This environment simulates the scenario with chairs pushed in

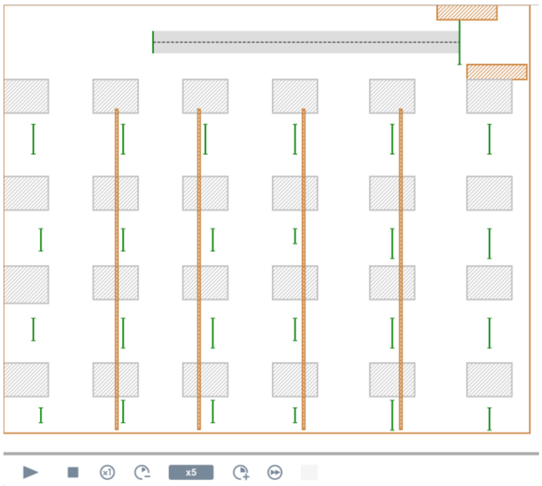
The shaded route added within the environment has a guiding effect on the simulated individuals. This is due to the fact that the simulated individuals appear to swing for a long period of time when the program is running, resulting in distortion. Adding a guiding line would make the model better at simulating the real situation.

3.3.Scenario 2: Simulation on the evacuation behavior of leaving seats from different sides
The second part of the study focuses on investigating the choice of leaving from the left-hand side and the right-hand side. Students may easily get panic under emergencies, thus they may not listen to the instructions of the teachers and leading to collisions or even stampede while steping out of their seats. This designed scenario examined five alternative combinations, and are as shown as follow:

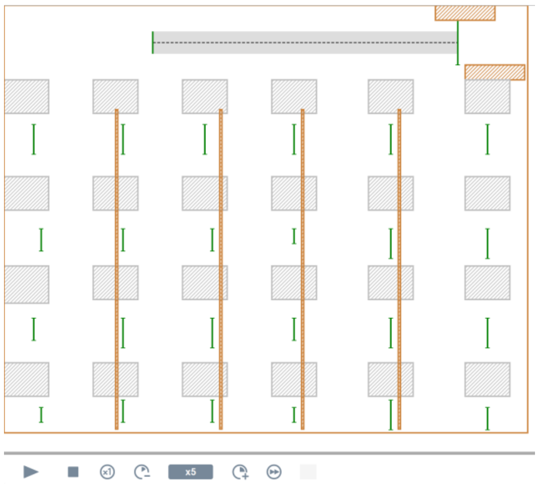

With one roll of students leaving from the left-hand side and the others from the right-hand side



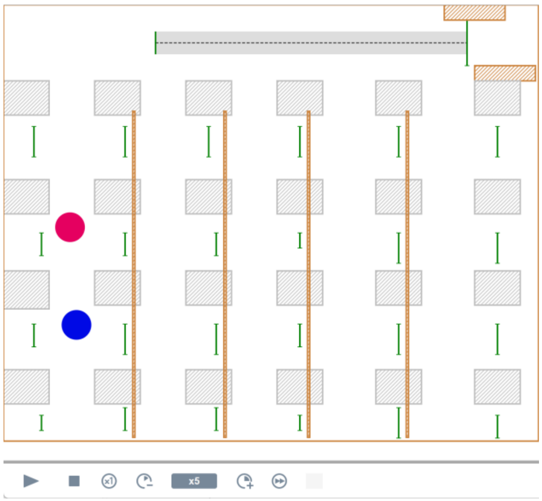
With two rolls of students leaving from the left-hand side and the others from the right-hand side



With three rolls of students leaving from the left-hand side and the others from the right-hand side



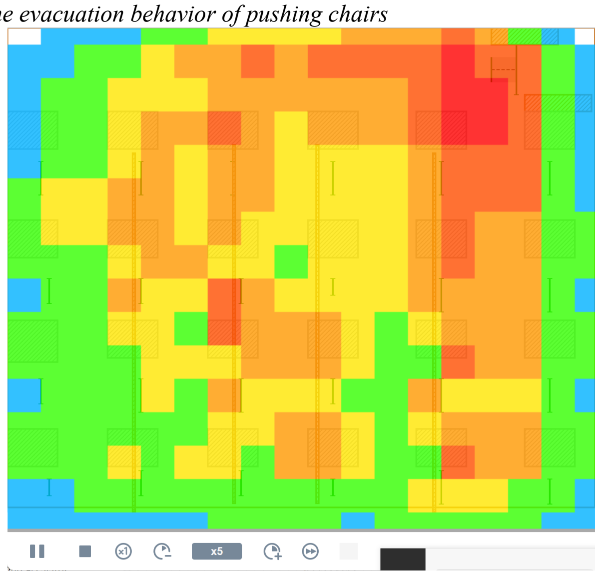
With four rolls of students leaving from the left-hand side and the others from the right-hand side



With one roll of students leaving from the right-hand side and the others from the left-hand side

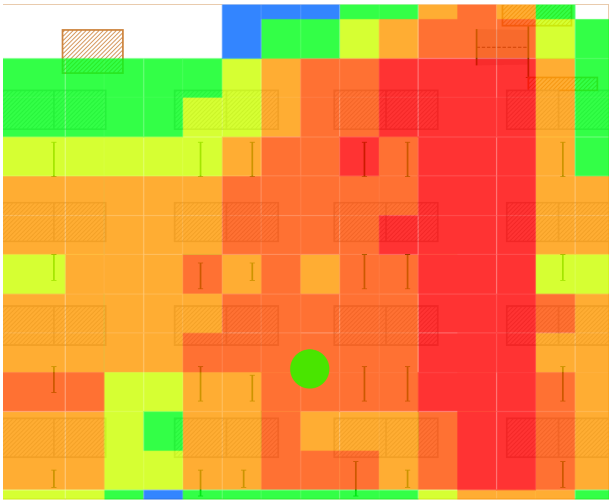
4.Data Analysis

4.1.Simulation result on the evacuation behavior of pushing chairs



The density map under the condition with out chairs pushing in

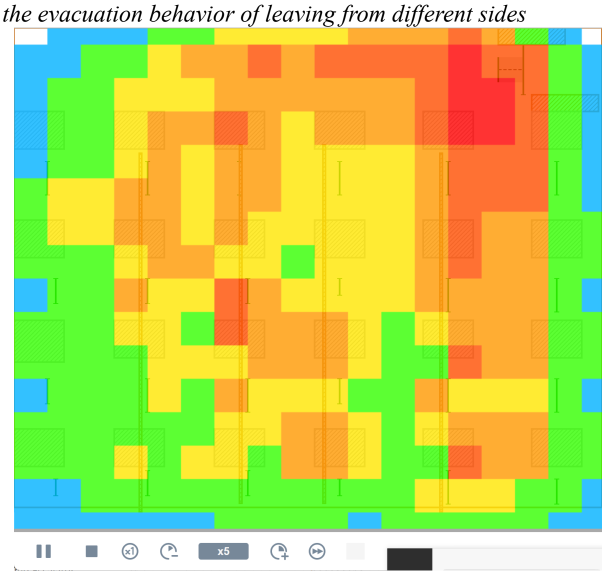
Due to the obstacle of chairs, all evacuees form a clear three-branch flow soon after leaving their seats, and the most crowded place for evacuation is reflected in the density map as the lateral area in the front half of the classroom. After several simulations, the average time was at 74.15 seconds.



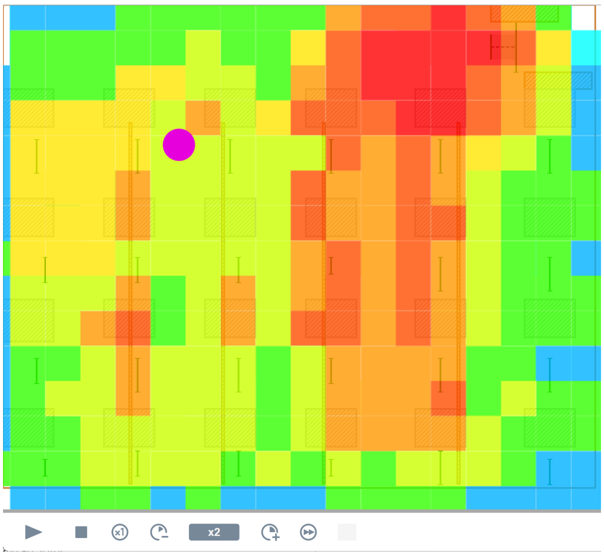
The density map under the condition with out chairs pushing in

Since there is no obstacle of chairs, all evacuees will choose to cross the classroom diagonally after leaving their seats to take the shortest path to approach the exit, resulting in a large number of people gathering in a short time near the exit. The most congested place for evacuation occurred in the right half of the classroom in the vertical area. After several simulations, the average time was 100.55 seconds.

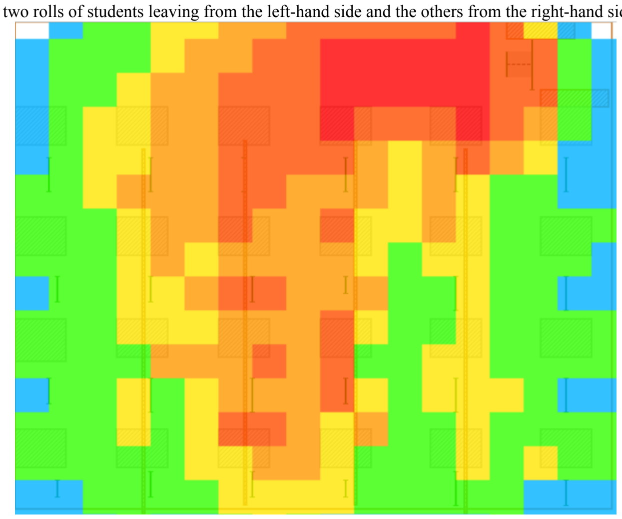
4.2.*Simulation result on the evacuation behavior of leaving from different sides*



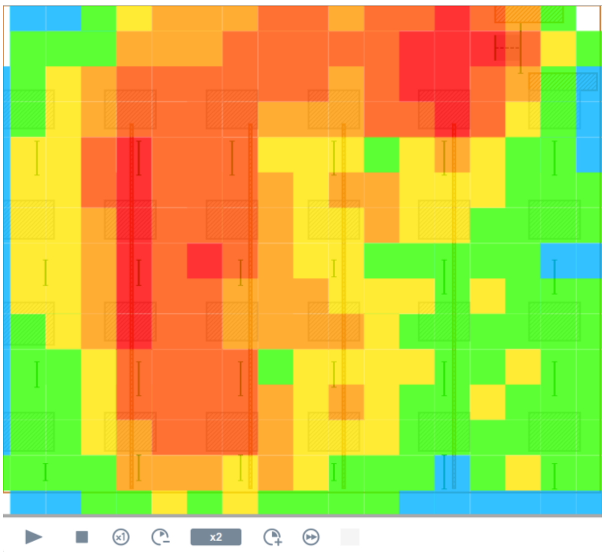
With one roll of students leaving from the left-hand side and the others from the right-hand side takes 45.55s



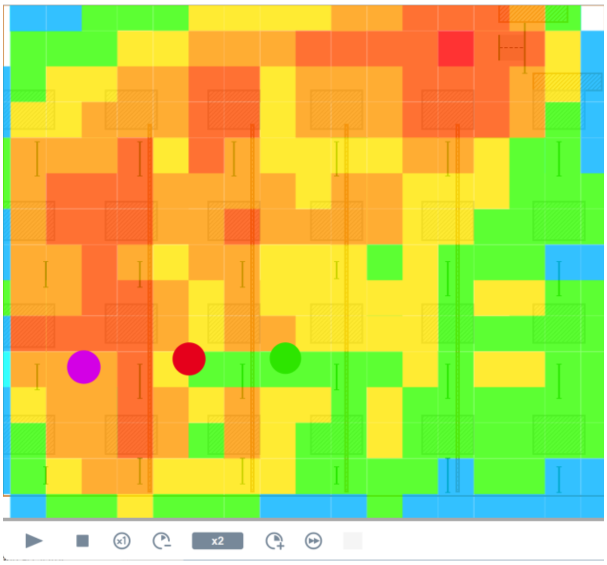
With two rolls of students leaving from the left-hand side and the others from the right-hand side take 48.55s



With three rolls of students leaving from the left-hand side and the others from the right-hand side takes 47.30s



With three rolls of students leaving from the left-hand side and the others from the right-hand side takes 46.55s


With one roll of students leaving from the right-hand side and the others from the left-hand side takes 41.59s

5.Conclusion

After six times of repeating tests, the result in simulating the evacuation behavior of pushing chairs suggest that the conventional approach of pushing classroom seating to create additional routes for students during evacuations will lead to a concentration of individuals at the exit, thereby increasing the risk of stampede and congestion. In contrast, leaving the chairs out during evacuation to force students to walk in lines will minimize the time spent blocking the exit and turns our to be the more effective strategy for enhancing evacuation efficiency and reducing evacuation time. The result in investigating the evacuation behavior of choosing the side to leave the seats concludes that despite the relatively consistent evacuation times across the five schemes, a closer examination of the data reveals a subtle yet significant advantage to allowing larger groups of students to exit the classroom from the same side. This observation is particularly noteworthy in the context of optimizing the evacuation process. A visual analysis of the density maps suggests that the concentration of individuals decreases more significantly when the group with the largest number of students exits the classroom first or last, with the latter scenario exhibiting a more substantial reduction in density. These findings underscore the importance of strategic group management during evacuations, highlighting the potential benefits of coordinated exit strategies in reducing congestion and improving overall evacuation efficiency.

7.Limitations

The advantage of using the social force model is that it could accurately reflect the self-organization behavior of the crowds, and it provide complex analysis of the individual decision-making process as well as the interaction between individuals. However, the main drawback is that it is computational expensive, thus errors more occur with visualizing the trajectories of the agents. During the simulation agents will occasionally be overlapping, oscillating, or even stop between two tables or at the exit when encountering another agents. While the introduction of guiding lines helped alleviate some of these problems, there still needs improvements on the algorithm.Furthermore, minor errors may occur in the virtual time of each simulation results, due to the manual measurement of classroom dimensions and parameters, as well as the hand-built environment on Anylogic instead of uploading a precise floor plan, which may not accurately reflect the real-time evacuation process. However, despite these limitations, the simulations can still be reasonably compared and conclusions drawn, as they are conducted under the same conditions and thereby yielding effective results. For future researches, a more comprehensive campus evacuation plan could be analyzed through adding factors such as corridor flow, stairwell crowd behavior, and evacuation floor sequences to optimize evacuation efficiency and minimize risks.

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