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Research on the Influence of Narrow and Long Obstacles with Regular Configuration on Crowd Evacuation Efficiency Based on Tri-14 Model with an Example of Supermarket

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Abstract: Regular shelves configuration forms unique characteristics of internal obstacles in a supermarket. It is crucial to study the crowd evacuation affected by obstacles during accidents or disasters in supermarkets as assembly occupancies. Based on the Tri-14 model, this paper studied the influence of safety exit designs and shelves' configuration on the crowd evacuation efficiency with different densities in a supermarket through parameters and images. The results mainly indicate that: (1) The evacuation distance of farthest grid (D_{fg}) is the key factor to determine the total evacuation time of a low-density crowd. (2) For a high-density crowd, the closer the proportion ratio of the number of evacuees choosing each exit is to that of designed strand numbers of crowd flow at each exit, the higher the evacuation efficiency and average utilization efficiency of exits get; the scattered arrangement of exits will not necessarily lead to improving evacuation efficiency. Shelves' configuration could lead to the extension of D_{fg}, but the change may reduce evacuation time instead, especially when forming effective advanced-gathering zones. (3) Under appropriate conditions, the impact of shelves' configuration on evacuation efficiency can be negligible. This study has certain guiding significance for obstacle configuration and architectural design in large public gathering places.

Keywords: cellular automata model; shelves configuration; crowd density; safety exit; evacuation time and efficiency

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1. Introduction

With the rapid economic development and continuous improvement of living standards, people's demand and consumption of commodities are increasing daily. As one of the important circulation places of goods and materials, the supermarket has been developed by leaps and bounds. In the light of the Classification of Retail Formats (GB/T 18106-2021), the supermarket is a retail form that meets the needs of consumers in daily life by mainly selling foods and daily necessities [1]. According to the New Development Trend Report of Chinese Trade Circulation Industry in 2021, as of April 2021, there were about 920,000 supermarkets and convenience stores in China, with an average annual growth rate of more than 30% from 2015 to 2020 [2]. The rapid growth of supermarkets not only meets people's demand for goods, increases the economic interests of the country, but also enriches people's activity space, and adds modern flavor to the city.

The method of selling by open-shelf display is widely used and shelves are usually arranged neatly and regularly in supermarkets, which makes it easy for customers to select commodities and can help owners to save labor. Simultaneously, the large number of fixed high shelves form unbridgeable long and narrow obstacles that are equal to the walls in general buildings in the perspective of a crowd evacuation, which is quite different from other types of building places. The evacuation passageways are formed between the shelves, or between the shelves and walls. The vast majority of pedestrians have to reach the safety exits only by detour due to the restrictions of the shelves, which greatly changes their evacuation path and prolongs their actual evacuation distance compared to the condition of no shelves. In addition, a high-density crowd during business hours on holidays and a large variety and number of goods with high fire loads are common in supermarkets, which may bring great difficulties to crowd evacuation and fire safety in case of fire or other emergencies.

In recent decades, the studies of crowd evacuation in assembly occupancies have attracted more and more attention and become one of the hot research directions in the field of urban public security because it may cause great casualties and social impacts in the event of accidents [3–8]. At present, crowd evacuation is a complex problem involving multiple disciplines. The traditional research methods of it mainly include direct observation, photo-video, animal experiments, and crowd evacuation drills [9–17]. However, due to the rapid development of computer technology and inherent defects of traditional methods, computer simulation has become the main development direction in this field because it has obvious advantages in parameter setting, result prediction, optimal design, and evacuation research in large-scale and complex scenes [8,18–21].

In recent years, many scholars have conducted many relevant studies on the safety crowd evacuation in supermarkets. Wei, X.G. et al. took the family group as the research object and simulated the evacuation in a supermarket according to the observed data and found that the larger the group, the longer the evacuation time of the crowd [22]. Li, C.Y. et al. chose the food oil area of a supermarket as the ignition point, carried out the numerical simulation of different fire scenarios, obtained the locations and times of internal evacuation exits of bigger evacuation pressures and where the persons were trapped easily, and quantitatively analyzed key positions for firefighters to guide the evacuation and to search for and rescue people [23]. Liu, J. constructed the evacuation model of supermarkets in a fire environment according to the personnel evacuation characteristics, studied the influence of different factors on the evacuation time, and used the improved ant colony algorithm to explore the optimal path for fire rescue [24]. In view of the actual situation of fire evacuation in large-scale supermarkets at present, Zhang, Y. studied and optimized three evacuation route planning algorithms, verified the feasibility of each algorithm, analyzed the advantages and disadvantages of each algorithm, and concluded that the Dijkstra algorithm was the best algorithm for fire evacuation route planning in large-scale supermarkets [25]. Wang Z.J. used FDS+EVAC to establish the evacuation model, analyzed the fire prevention and evacuation performance of the supermarket according to the evacuation results, and finally put forward the corresponding recommendations aiming at the deficiency of safe evacuation in the supermarket [26]. Cao S. C. et al. investigated the evacuation process from a supermarket under good and limited visibility by a group of experiments and questionnaires, proposed a multi-grid model to simulate pedestrian evacuation, and studied the effect of obstacles on evacuation time with and without obstacles inside by simulations [27].

In addition, many scholars have studied the influence of obstacles on the evacuation process in recent years. Wu, H., Luo, Q., and Sun J. studied the impacts of obstacles with different locations, shapes, lengths, widths, and distances from the exits in the corridors on crowd evacuation by experiments and simulations [28–30]. Liu, H. et al. built a corresponding social-psychological model based on the "non-adaptive" behavior theory of a panic crowd, introduced the model into the evacuation simulation process by quantified parameters related to the theory, and on this basis, studied the influence of different shapes, sizes, and layouts of obstacles on evacuation efficiency and crowd congestion [31]. Cao, Y.Y. proposed an optimization method of obstacle layout based on MA-ES, and finally obtained the obstacle layout with the best crowd evacuation effect [32]. Lv, H. and Yi, P. studied the influence of the shape, size, position, and layout of obstacles placed in front of exits during emergency evacuations [33,34]. Aiming at the classroom scene, based on experimental, observational, or simulation methods, Gao, R., Yue, H., Zang, Y., and

Wang, K. studied the impacts of exit location, exit width, indoor obstacle layouts, aisle width, aisle orientation, aisle number, and human–obstacle interaction on evacuation time and path [35–38]. Wang, J.H. et al. studied the effect of adding an obstacle with different sizes and positions in front of a 30○ corner exit on an evacuation through simulation and experimentation, and found that the beneficial effect of an obstacle on evacuation depends on the size and the distance to the exit [39]. Based on the experiment and simulation, Zhao, Y.X. et al. observed that the evacuation efficiency was actually quite sensitive to the geometrical parameters of obstacles, that the average evacuation time in human experiments could be reduced by a suitable layout of obstacles, and that the panel and double-pillar obstacles could better improve the evacuation efficiency compared to a single-pillar obstacle [40]. Sticco, I.M. et al. performed numerical simulations to analyze two different types of vestibules, and found that the three parameters, including the walls' friction coefficient, the distance from the obstacle to the exit door, and the space between the two panels, controlled the vestibule's density, which subsequently affected the evacuation flow [41]. Li, L. et al. employed an arch-formation-based obstacle optimization approach to get the suitable characteristics of obstacles in an evacuation scene, and used the radial pressure which could represent the strength of arch formation to build a new fitness function [42]. However, Shiwakoti, N. et al. presented a critical review on the performance of an obstacle near an exit, and found that although there was a general consensus on the beneficial effect of an obstacle, there was a large uncertainty on the situations in which the positive effect of the obstacle could be observed, and there was no clear established relationship between the exit width, obstacle distance, and obstacle size/shape [43].

Through literature analysis, it can be seen that the studies on supermarket evacuation mostly focus on crowd characteristics, algorithms, and environment, and most of them aim at a specific supermarket scenario. Meanwhile, most of the research on the impact of obstacles on the evacuation focuses on algorithm innovation and optimization. In addition, the selected evacuation scenes in the relevant articles mostly focus on obstacles near the exits and at the passageways of the buildings, or the patterns of indoor obstacle arrangements and building scales in the research are quite different from those in supermarkets. There are few relevant research results that combine the narrow and long characteristics of shelves to discuss evacuation path and efficiency and have a certain degree of universality in supermarkets.

In order to solve the above problems, based on the Tri-14 model and with a view to the features of shelves' configuration in supermarkets, this paper systematically analyzed the influence of safety exit designs and shelves' configuration on evacuation efficiency with different crowd densities by computer simulation technology. This paper, which took a supermarket scene of 42 m $\times$ 42 m that conformed to the requirements of the Code, for example, obtained the crowd evacuation processes and parameters under the condition of different crowd densities by setting numbers and configurations of shelves and available numbers and locations of safety exits. Through parameter analysis, a number of instructive and universal evacuation suggestions are obtained, which can provide a certain reference for ensuring and evaluating shelves' configuration in supermarkets and the arrangement of obstacles and architectural design in assembly occupancies with a large scale from the perspective of improving crowd evacuation efficiency.

2. Evacuation Model and Scenario Design

2.1. Introduction to Evacuation Model

Tri-14 is an evacuation model of discrete fine grid based on two-dimensional cellular automaton proposed by Ji [44]. The evacuation simulation software based on Tri-14 model consists of five modules, including the modules of building plan import and modeling, adding pedestrians and setting behavior characteristics, evacuation parameters calculation, visualization of evacuation process and output and processing of related data, which can meet the needs of general research and engineering application.

Different from traditional two-dimensional CA evacuation models, the cellular space is divided into several independent grids of isosceles right triangle which combines the characteristics of triangle and rectangle and makes each cell has more neighbors in Tri-14 model. As shown in Figure 1, black and gray triangular blocks represent object grid and its neighbors in four different positions, respectively. This space division method makes the number of evacuation direction can reach to 14 under barrier-free condition, which increases the degree of freedom of pedestrian evacuation movement behavior and can express the evacuation behavior more accurately. Meanwhile, the Tri-14 model can simulate the phenomenon of pedestrians crowding into the crowd with a smaller insertion angle, which helps to more accurately and truly express the direction choice and behavior characteristics of a high-density crowd evacuation.

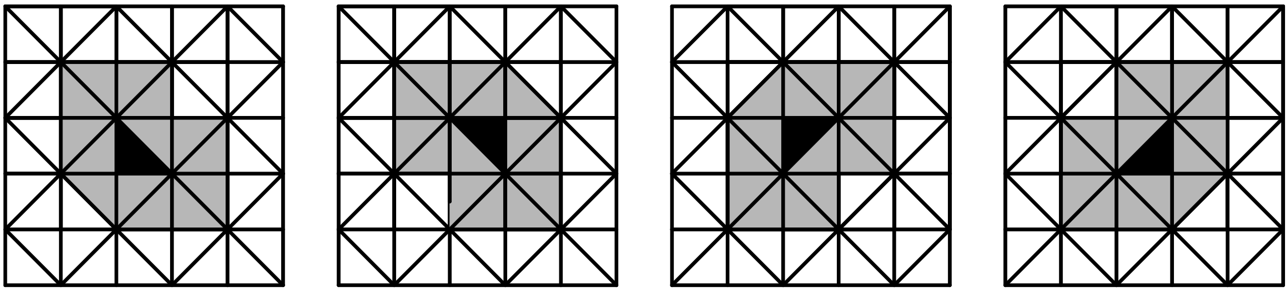


Figure 1. Cellular automaton neighbors of a triangular grid at four positions in the Tri-14 model.

According to the definition of the cells and their neighbors, a three-dimensional array for programming is used in the Tri-14 model to improve the computational efficiency. In terms of evacuation movement, the rules of the local and global moving potential are put forward in the model with the help of electrical ideas in the physical field. On this basis above, the decision rules of pedestrians' paths and movements are formulated. The basic algorithm of the model is similar to that of a classical cellular automaton as shown in Figure 2.

Moreover, there are many practical functions implemented in the Tri-14 model, including changing the size of the cellular grid based on the human body or actual demand, the synchronous dynamic display of calculation and evacuation movement by a pedestrian chart or a density cloud chart, tracing evacuation route, and so on. The model validation works have been carried out in References [44,45] by verifying the arch effect at the bottleneck and the comparison of experimental data and simulation results at an exit in a teaching building and an escalator at a subway station. The related results showed that this model had good simulation reliability and strong adaptability to a high-density crowd evacuation.

2.2. Evacuation Scenario Design

2.2.1. Building Layout

The object of this study is the business hall of an above-ground, single-story supermarket, which is of a fire resistance level of two and equipped with a sprinkler system. The planar shape of the hall is a square of 42 m $\times$ 42 m dimensions with the building area of 1764 m^2. According to China's Code for Fire Protection Design of Buildings (GB50016-2014, 2018 edition) (hereinafter referred to as the Code), it can be determined that the crowd density value of the supermarket hall is 0.6 person/m^2, and the designed minimum total net width of safety exits is 6.877 m based on the number of evacuees (1764 m^2 $\times$ 0.6 person/m^2 = 1058 person) and evacuation width index of one hundred evacuees. Moreover, according to the Code, the straight-line distance from any point in the supermarket hall to the nearest safety exit should not be greater than 37.5 m [46].

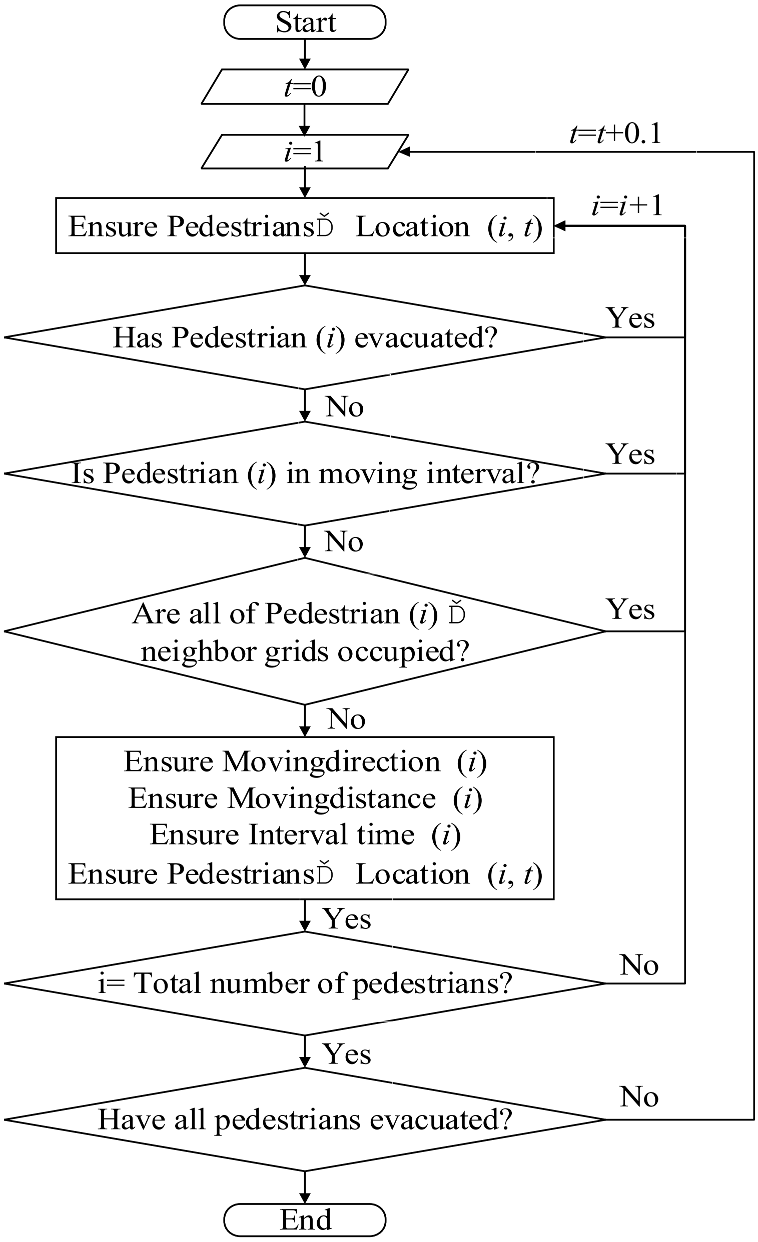
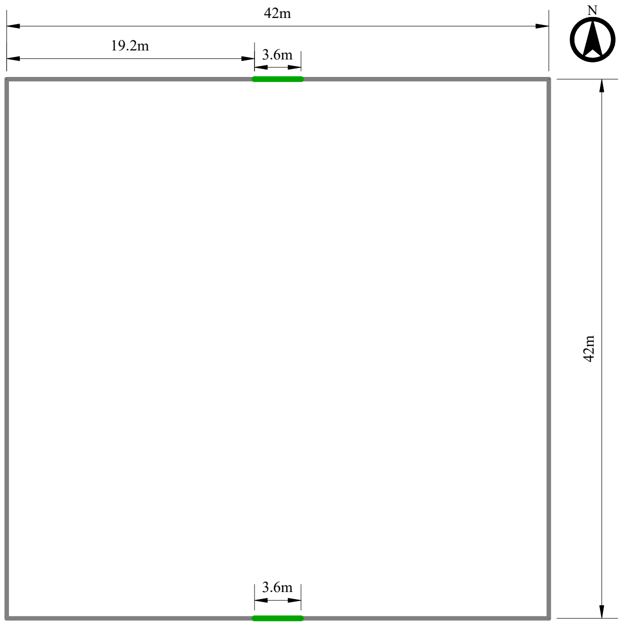


Figure 2. The flow diagram of the basic algorithm for the evacuation movement of the Tri-14 model.

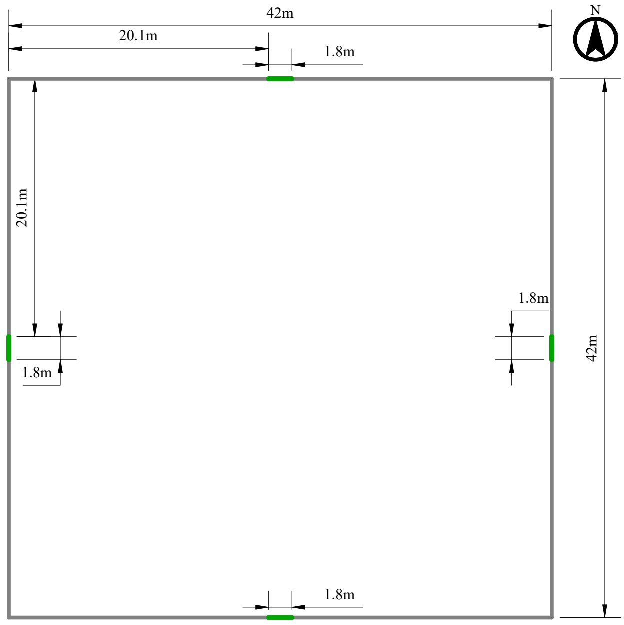
In different building layouts of the supermarket in this series of simulations, the total net widths of the safety exits were all 7.2 m, and the numbers of the safety exits were all no less than 2, and the distances between the farthest point at the supermarket hall and the safety exit under the worst-case condition was 28.5 m, which was less than 37.5 m. The number of safety exits, total and respective net widths of safety exits, and evacuation corridors and safety evacuation distances all met the requirements in the Code. Furthermore, the widths of all shelves in different scenarios were 1.2 m.

In order to achieve the research objectives, the simulations were carried out by replacing the location, number, and respective net width of the safety exits, changing the length of shelves, and blocking one of the safety exits. To illustrate the naming principle of the plane models, the scenario NS3.6-20 is taken as an example, which means that there are two safety exits of 3.6 m located at the north and south side, respectively, and 20 shelves in the supermarket hall. The layouts of safety exits and shelves in 8 different scenarios and the related instructions are shown in Figure 3.



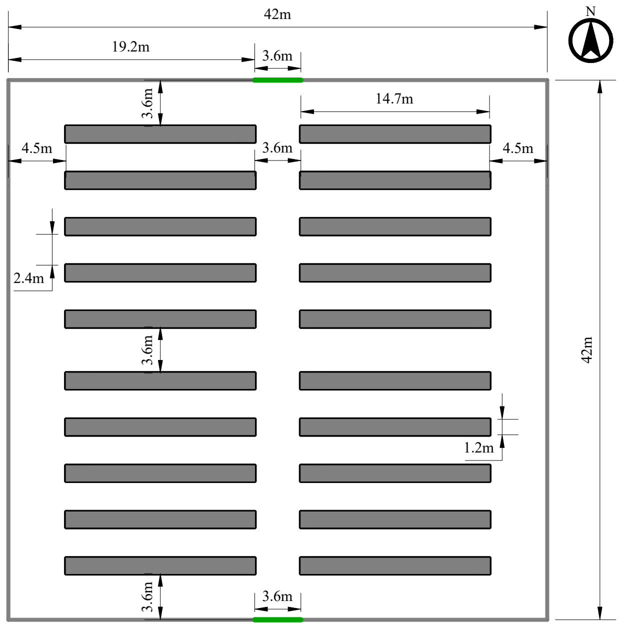
Instruction: There are two safety exits with same widths of 3.6 m located at the central north and central south side, respectively without shelf.

(**a**)



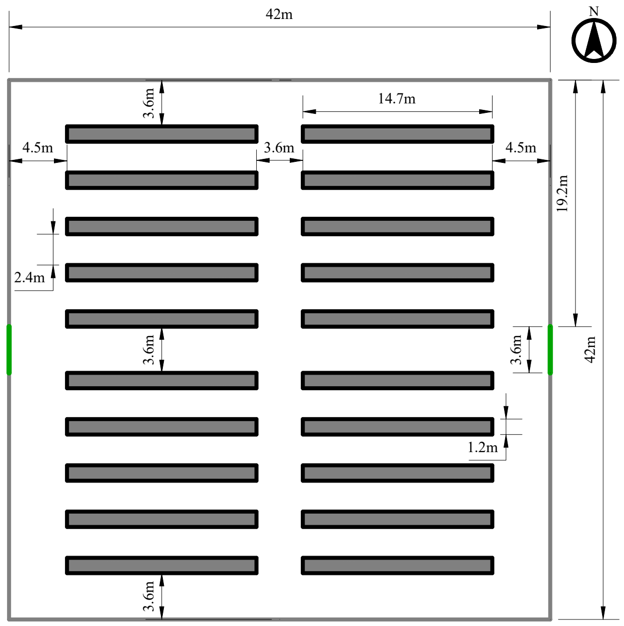
Instruction: There are four safety exits with same widths of 1.8 m located at the central west, central east, central north and central north side, respectively without shelf.

(**b**)



Instruction: There are two safety exits with same widths of 3.6 m located at the central north and central south side, respectively and 20 shelves. The size and position of main aisles, accessory aisles and shelves are shown in above figure.

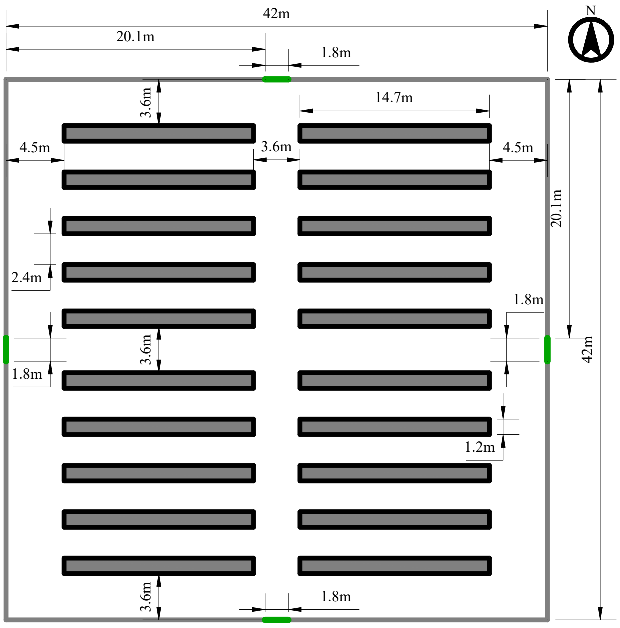
(**c**)



Instruction: There are two safety exits with same widths of 3.6 m located at the central west and central east side, respectively and 20 shelves. The size and position of main aisles, accessory aisles and shelves are shown in above figure.

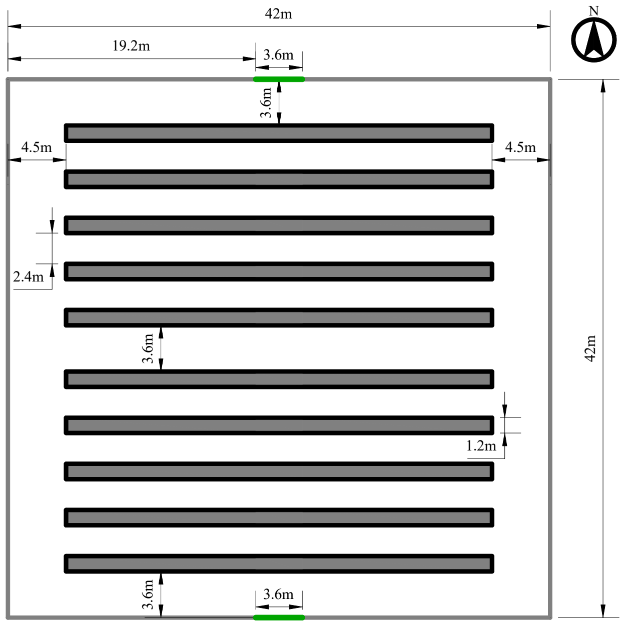
(**d**)

Figure 3. *Cont.*



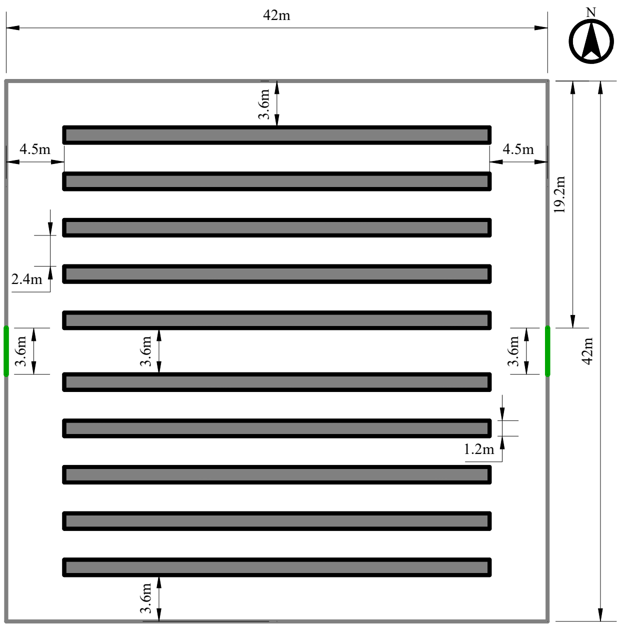
Instruction: There are four safety exits with same widths of 1.8 m located at the central west, central east, central north and central north side, respectively and 20 shelves. The size and position of main aisles, accessory aisles and shelves are shown in above figure.

(**e**)



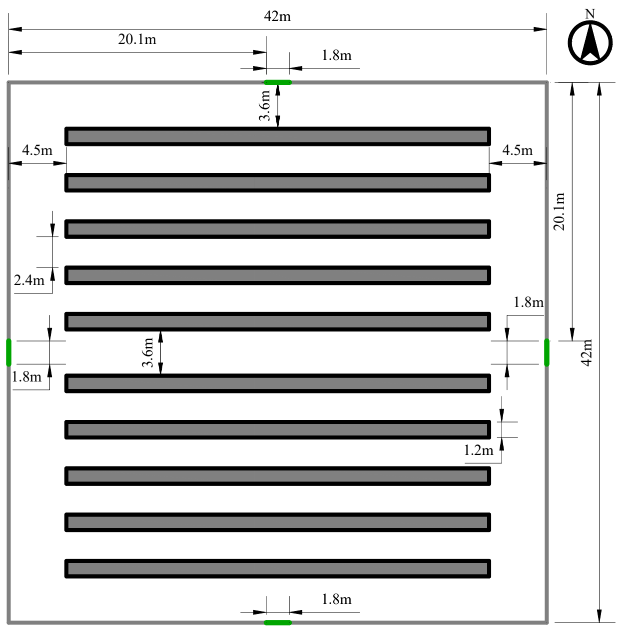
Instruction: There are two safety exits with same widths of 3.6 m located at the central north and central south side, respectively and 10 shelves. The size and position of main aisles, accessory aisles and shelves are shown in above figure.

(**f**)



Instruction: There are two safety exits with same widths of 3.6 m located at the central west and central east side, respectively and 10 shelves. The size and position of main aisles, accessory aisles and shelves are shown in above figure.

(**g**)



Instruction: There are four safety exits with same widths of 1.8 m located at the central west, central east, central north and central north side, respectively and 10 shelves. The size and position of main aisles, accessory aisles and shelves are shown in above figure.

(**h**)

Figure 3. Layout plans of a supermarket hall in different scenarios. (**a**) NS3.6-0, (**b**) WENS1.8-0, (**c**) NS3.6-20, (**d**) WE3.6-20, (**e**) WENS1.8-20, (**f**) NS3.6-10, (**g**) WE3.6-10, (**h**) WENS1.8-10.

2.3. Evacuation Scenario Design

Evacuation Parameters Setting

1. Determination of grid size:

Based on the average shoulder width of the human body and considering the measured value, clothing influence, and interpersonal distance, the two-waist size of the isosceles right-triangular grid was set as 0.6 m in this series of simulations [44,47].

2. Setting a way of adding pedestrians and a principle for pedestrians to choose an exit:

In this series of simulations, the pedestrians were randomly set by a global placement in the full-size space. In view of the fact that the direction of evacuation indication signs in the supermarket was designed based on the shortest path principle, and the assumption that all evacuees would move to the safety exits in accordance with the signs, the principle for pedestrians to choose an exit was performed based on the shortest path.

3. Allocation of the number of evacuees:

In order to explore the influence of the density of pedestrians on the evacuation process, firstly, based on the building area of the supermarket hall and the calculated crowd density of the exhibition hall, which is 0.75 p/m^2 by referring to the Code, a set of data of 1323 evacuees was obtained [46]. Additionally, based on the 1058 evacuees as calculated in Section 2.1, the number of evacuees was successively decreased by a 10% gradient until 106. The allocation of the number of evacuees was shown in Table 1.

Table 1. Allocation of the number of evacuees in the supermarket hall.

Serial Number	1	2	3	4	5	6	7	8	9	10	11
Calculating Crowd Density (p/m^2)	0.75	0.6	0.54	0.48	0.42	0.36	0.3	0.24	0.18	0.12	0.06
Number of Evacuees	1323	1058	952	846	741	635	529	423	318	212	106

4. Attribute configuration of pedestrians.

In order to avoid the influence of different genders, ages, and proportions of evacuees on the simulation results, the pedestrians in this simulation process were all male between the ages of 18 and 26, and the walking speed model was based on the experimental results presented by Xie [48]. The response time of pedestrians was set randomly from 1 to 10 s.

3. Simulation Results and Discussion

3.1. Results and Discussion of Evacuation Data with All Safety Exits Open

In this series of simulations, the average evacuation times of 10 times under conditions of different scenarios and numbers of pedestrians in the supermarket hall are shown in Table A1. Due to the small dispersion degree of data distribution in each group, the results are acceptable considering both the simulation time cost and the reliability of simulation results. The schematic diagram of corresponding data is shown in Figure 4.

The discussion on Figure 4 is as follows.

(1). When the designed crowd density increases from 0.06 p/m^2 to 0.12 p/m^2, the slopes of the line segments in the figure are almost horizontal, namely, the increments of the total evacuation times are small (except for the WENS1.8-10 scenario, which will be discussed separately later). In other words, when the crowd density is very low, the increment of the total number of pedestrians has little effect on the total evacuation time. Combined with the dynamic evacuation images, the reason for the above phenomenon is that in the same scenario (except for WENS1.8-10), when the number of pedestrians is small and the pedestrians are randomly distributed in the whole zone, there will be no crowding phenomenon in the evacuation process, and the interactions between pedestrians in the evacuation process can be almost negligible.

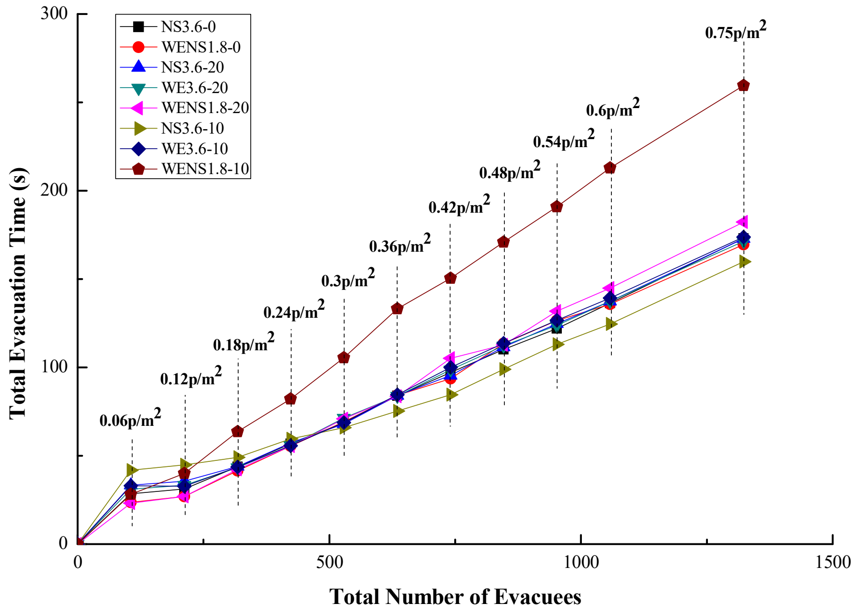


Figure 4. Schematic diagram of average evacuation times under conditions of different scenarios and numbers of pedestrians with all safety exits open.

In view of the moving velocity model and the attribute configuration of pedestrians, theoretically, it shows that the total evacuation time depends on the evacuation time of the pedestrian whose linear walking distance between his initial occupying grid and chosen exit is farthest in the scenario while ignoring the response time. Through the function of replay and path redrawing in the software, the results were consistent with the above conclusion in the vast majority of simulation cases, unless there was a pedestrian who was very close to the farthest pedestrian at t = 0 and his response time was significantly less than the latter. In the same scenario and different simulations, there was little difference in the linear walking distances of the aforesaid farthest pedestrians under the conditions of the same evacuation environment and number of pedestrians. The key determinant of the aforementioned distances is the maximum value of the linear walking distances between the position of each grid and its corresponding safety exit (abbreviated as the evacuation distance of the farthest grid denoted by D_{fg}), and there is a high probability that the farthest grid and its nearby grids are occupied by at least one person under the circumstance that pedestrians are added randomly and the number of them is not ultra-small.

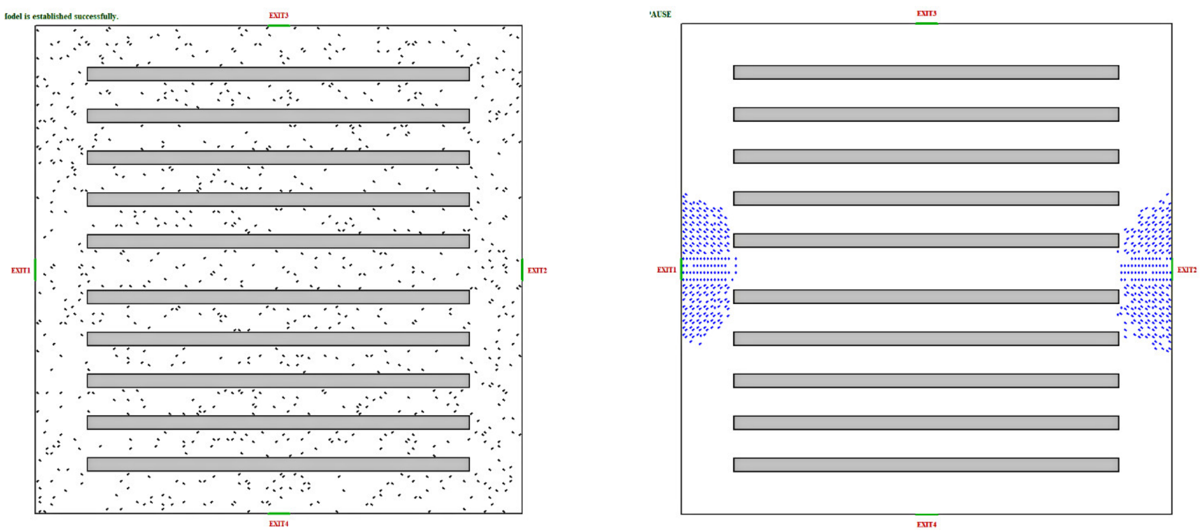
Taking the NS3.6-10 scenario as an example, in the nearby areas of 3.6 m $\times$ 6 m and 3.6 m $\times$ 12 m centered at the farthest grid which is located in the central position of the architectural plan, the distances between the farthest grid and the inner farthest point of the areas are about 3.15 m and 6.26 m, respectively, so that the evacuation moving times calculated by the walking speed are about 2.3 s and 4.5 s, respectively, which are accounting for merely 5.5% and 10.8% of the average total evacuation time under the condition of 106 evacuees, and merely 5.1% and 10% of the average total evacuation time under the condition of 212 evacuees, respectively, without considering the interaction between pedestrians. Moreover, according to probability statistics, the probability of at least one pedestrian occupying the certain nearby area will increase with the total number of pedestrians. In this case, the probability above in the two areas are up to 0.87 and 0.98 when the total number of evacuees are 106 and 212, respectively. D_{fg} is a geometric characteristic parameter of the building space and has nothing to do with the crowd density, so the two total evacuation times are very close.

(2). When the designed crowd density increases from 0.12 p/m^2 successively, the almost-horizontal trend of the line segments disappears, that is, the total evacuation time also increases significantly with the number of evacuees. Combined with dynamic evacuation images, the main cause of the above results is that with the increase of the number of pedestrians, a certain local congestion area (shown in red in the density cloud chart) will appear and be expanded gradually in the process of evacuation, especially near the exits.

(3). When the crowd density is no more than 0.24 p/m^2, the total evacuation times of WENS1.8-20 and WENS1.8-0 scenarios are very close and the two shortest among all scenarios. Combined with the simulation dynamic process, it can be inferred that the reason is that when the crowd density is at a low level and pedestrians are randomly added, the attribute value of D_{fg} affected by the long shelves in the WENS1.8-20 scenario is essentially constant to that with the minimum value in the WENS1.8-0 scenario without shelves. On the contrary, the total evacuation time in NS3.6-10 scenario is the longest because of its maximum value of D_{fg} under the same condition.

(4). When the initial crowd density is no less than 0.18 p/m^2, the total evacuation time of the WENS1.8-10 scenario is the longest, and the absolute differences of the total evacuation time between it and the other scenarios are growing with the increase of the number of pedestrians. Through the analysis of the evacuation dynamic image, the main reason is that, due to the shelves' configuration, the number of pedestrians choosing south and north exits is far less than that of choosing west and east exits under the principle of shortest path. The net evacuation widths of the four exits are equal so that the designed strand numbers of the crowd flow are consistent. The obvious ratio difference between the number of pedestrians choosing each exit and the designed strand numbers of crowd flow at each exit leads to the reduction of utilization efficiency of safety exits at the south and north side and the gathering of a large number of evacuees near the east and west exits, making evacuation time of WENS1.8-10 to be the longest among all scenarios.

Taking an evacuation process of 846 pedestrians, for example, 674 pedestrians chose the west and east exits (EXIT1 and EXIT2), and 172 pedestrians chose the north and south exits (EXIT3 and EXIT4). As shown in Figure 5, at t = 46 s, a large number of pedestrians gathered near EXIT1 and EXIT2, while the pedestrians choosing EXIT3 and EXIT4 had just all evacuated, and the widths of EXIT3 and EXIT4 were not utilized in the following time in combination with the exported data files and dynamic images. In this scenario, the reason why there is a significant increase in evacuation time when the crowd density increases from 0.06 p/m^2 to 0.12 p/m^2, which is different from other scenarios, is that a crowd gathering near the exits also will occur just under the condition of low initial crowd density caused by the above-mentioned obvious ratio difference.



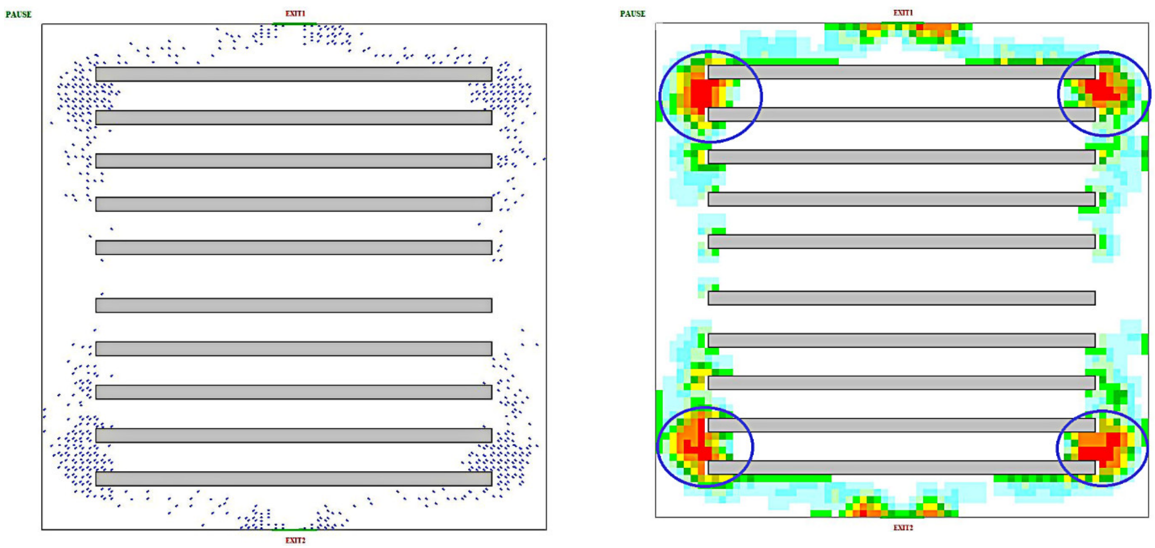
(a) (b)

Figure 5. Evacuation schematic diagram of the WENS1.8-10 scenario at (**a**) t = 0 and (**b**) t = 46 s under the condition that the total number of pedestrians is 846.

To sum up, from the perspective of evacuation safety under high-density crowd conditions, the shelves' configuration in the WENS1.8-10 scenario is the most unfavorable plan among all scenarios.

(5). When the initial crowd density is no less than 0.30 p/m^2, the total evacuation time of NS3.6-10 is minimum among all scenarios. It is worth noting that although the narrow and long shelves' configuration leads to the maximum D_{fg} in the NS3.6-10 scenario, it also makes the total gathering area of a high-density crowd (shown in red in Figure 6) show reduction and dispersion compared with other scenarios with the same number of pedestrians, which is helpful to improve the crowd evacuation efficiency and reduce the total evacuation time according to the simulation results. In addition, the location of the two exits in this scenario makes the number of pedestrians choosing the exits close under the principle of shortest path, that is, the proportion ratio of people choosing each exit is similar to that of the designed strand numbers of crowd flow at each exit.

As shown in Figure 6, for example, taking the total number of pedestrians was 846, and when at t = 20 s, obvious gathering areas of a high-density crowd appeared near the corner positions of the evacuation passage at the end of the two shelves at the south and north side, which are marked with blue ellipses in Figure 6(a-2), and there was only small-scale gathering at EXIT1 and EXIT2 near the south and north exits. Along with time, the gathering areas of the high-density crowd at the end of shelves gradually decreased, and that near EXIT1 and EXIT2 gradually increased. Until t = 60 s, the former basically disappeared, and at t = 70 s, the latter reached the maximum. In addition, the number of pedestrians who chose EXIT1 and EXIT2 for evacuation was 415 and 431, respectively, which were close to each other. In this paper, the red area marked with blue ellipses in Figure 6(a-2) is named as "advanced-gathering zone", and it means the gathering area of high density not near the exits whose size is greater than that near the exits in the early stage of the evacuation process, and the two kinds of gathering areas do not form the overlap or cross in the whole evacuation process; namely, there is a certain distance between the two kinds of gathering areas.



(a-1) **(a-2)**

Figure 6. *Cont.*

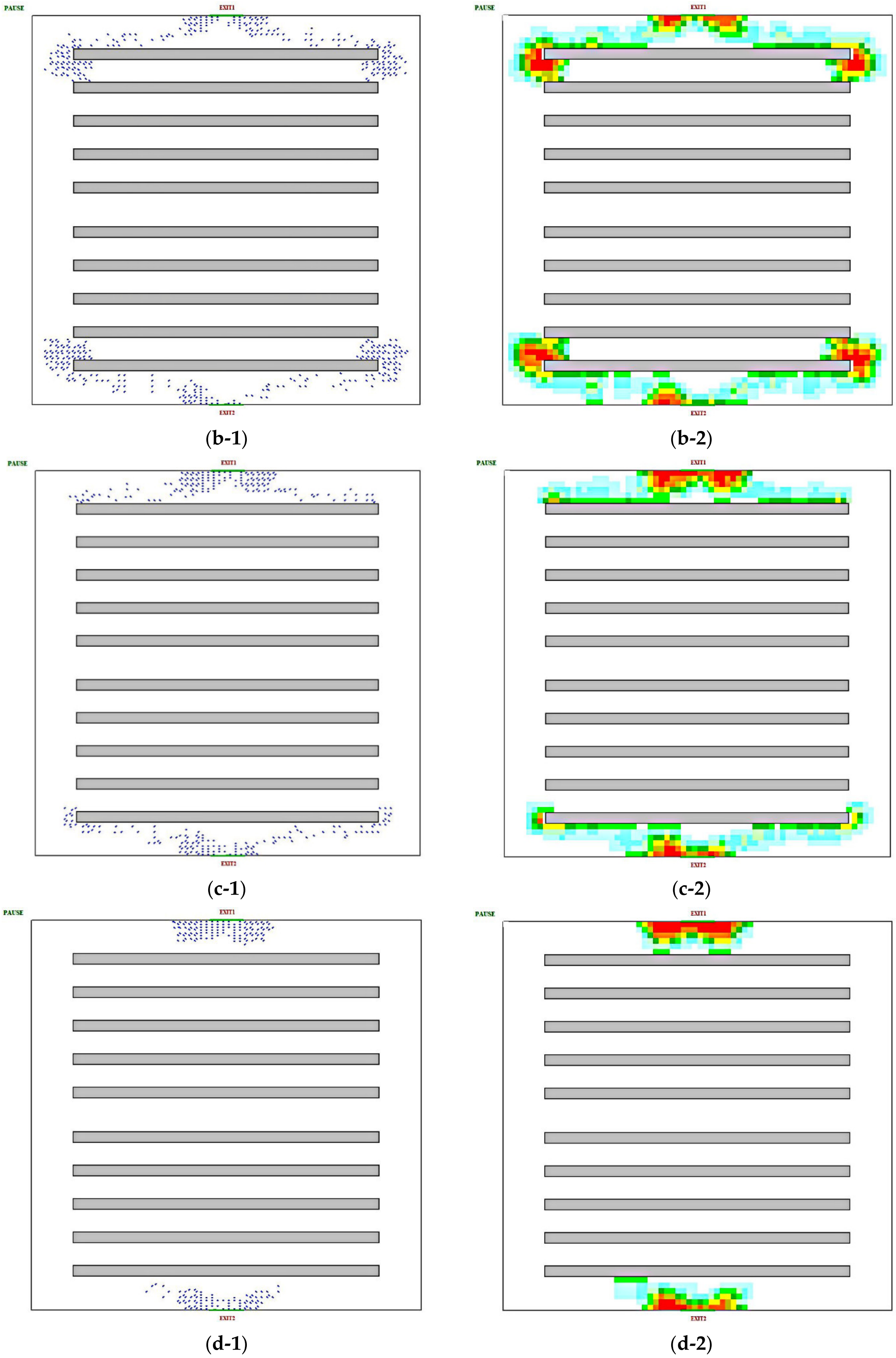


Figure 6. Evacuation schematic diagram of the NS3.6-10 scenario when the total number of pedestrians is 846. (**a-1**) t = 20 s, (**a-2**) t = 20 s (density cloud chart), (**b-1**) t = 40 s, (**b-2**) t = 40 s (density cloud chart), (**c-1**) t = 60 s, (**c-2**) t = 60 s (density cloud chart), (**d-1**) t = 70 s, (**d-2**) t = 70 s (density cloud chart).

In the NS3.6-10 scenario, except for the pedestrians whose line segments between their starting positions and their corresponding chosen exits did not intersect the shelves, the rest had to go through the advanced-gathering zone to reach exits. Due to the existence of the shelves in these positions, the rest of the pedestrians had to swerve, and the calculated crowd density increased, which made their walking speeds significantly reduced when moving to the gathering zone. As a result, there was obvious large-scale congestion in the early stage of evacuation when the number of personnel in the whole area was large. The total net width of passageways in the advanced-gathering zones in this scenario was greater than that of safety exits, and there was a certain distance between the zones and the exits, all of which made the gathering speeds at the exits become slower and pedestrians' flow at the exits become higher than other scenarios in the early stage of the evacuation process. Therefore, according to this case, when the crowd density is higher, although the shelves' configuration leads to the increase of the average actual evacuation walking distance and D_{fg} value, it also helps to form "advanced-gathering zones" in the crowd evacuation path, which is beneficial to improve the evacuation efficiency on the contrary.

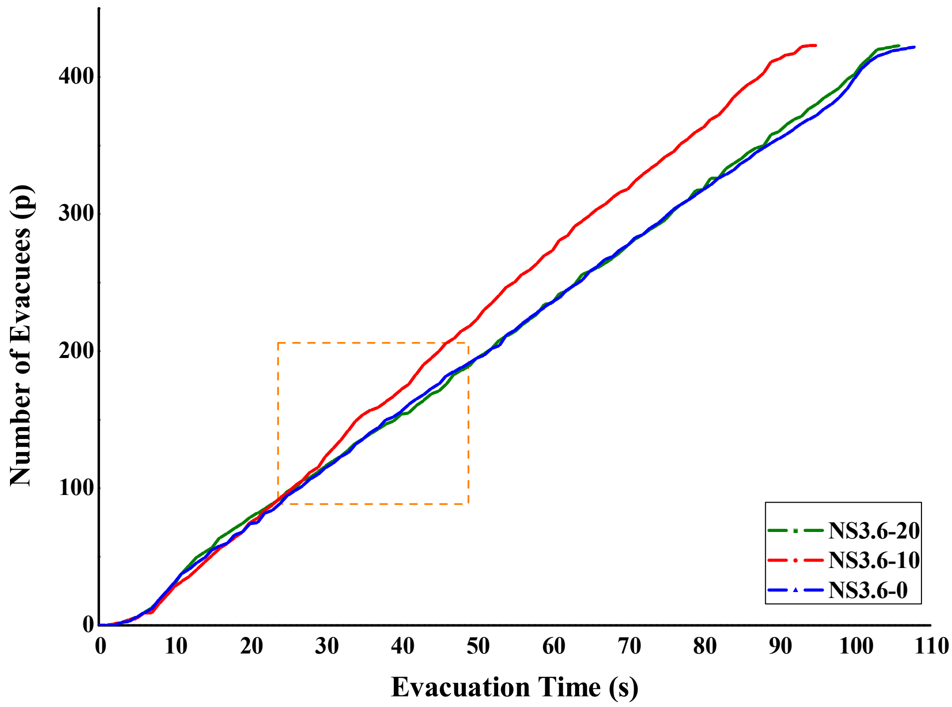
In order to avoid the error caused by the difference of the numbers of evacuees choosing the south and north exits, the simulations were carried out based on the fact that the number of evacuees choosing the north exit EXIT1 was 423, which is half of 846. The schematic diagram of the numbers of evacuees at the north exit position of the NS3.6 series in three scenarios is shown in Figure 7. It can be seen that the change trend of NS3.6-0 and NS3.6-20 curves is basically the same. From about t = 30 s to 35 s in the early stage of evacuation, the curve slope of NS3.6-10 increases significantly compared with that of NS3.6-0 and NS3.6-20 shown in the partial enlarged detail in Figure 7b of the rectangular area formed by the yellow broken line in Figure 7a. The above effect is the fundamental reason for the improvement of evacuation efficiency in the "advanced-gathering zone".

As shown in this example, from the perspective of evacuation safety under high-density crowd conditions, the shelves' configuration in the NS3.6-10 scenario is the most favorable plan among all scenarios.

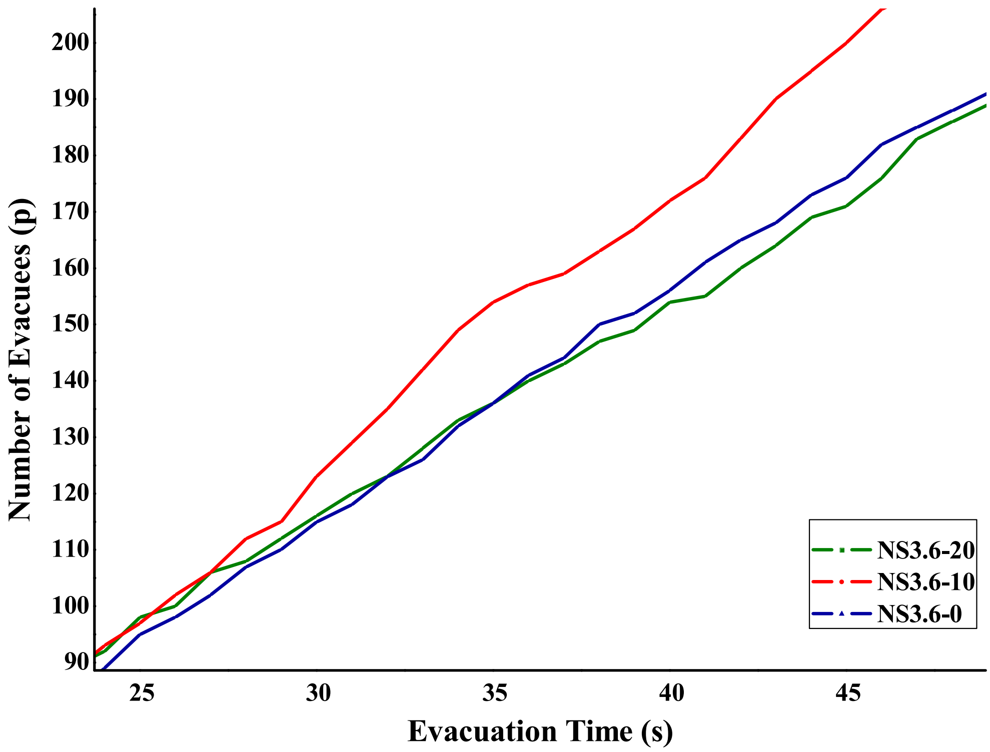
(6). Compared with the scenarios of WENS1.8-0 and NS3.6-0 without shelves, except for the above NS3.6-10 and WENS1.8-10 scenarios, the shelves' configuration has little impact on the total evacuation time when the crowd density exceeds 0.18 p/m^2. This suggests that if the shelves' configuration cannot make an obvious ratio difference between the number of pedestrians and designed strand numbers of crowd flow at each exit or form advanced-gathering zones, crowd gathering is the most significant factor influencing the total evacuation time, and the effect on the increase of D_{fg} by shelves' configuration can be ignored.

3.2. Results and Discussion of Evacuation Data under an Exit Failure Condition

Considering the unfavorable condition of an exit failure caused by fire, smoke, management, or any other unknown factors, the average evacuation times of 10 times under conditions of different scenarios and numbers of pedestrians are shown in Table A2, and the corresponding schematic diagram is shown in Figure 8 in this series of simulations (the results of equivalent scenarios are omitted). The naming principle of the plane models is the same as the description in Section 2.2.1, which means that if the name contains one letter and three letters, the total net width of the remaining exits is 3.6 m and 5.4 m, respectively. The method of pedestrians choosing the exits is also based on the shortest path principle.



(**a**)



(**b**)

Figure 7. Schematic diagram of the change of the number of evacuated people with time at the north exit in the scenarios of NS3.6 series. (**a**) Full evacuation time display diagram, (**b**) partial enlarged detail of rectangular area formed by the yellow broken line in (**a**).

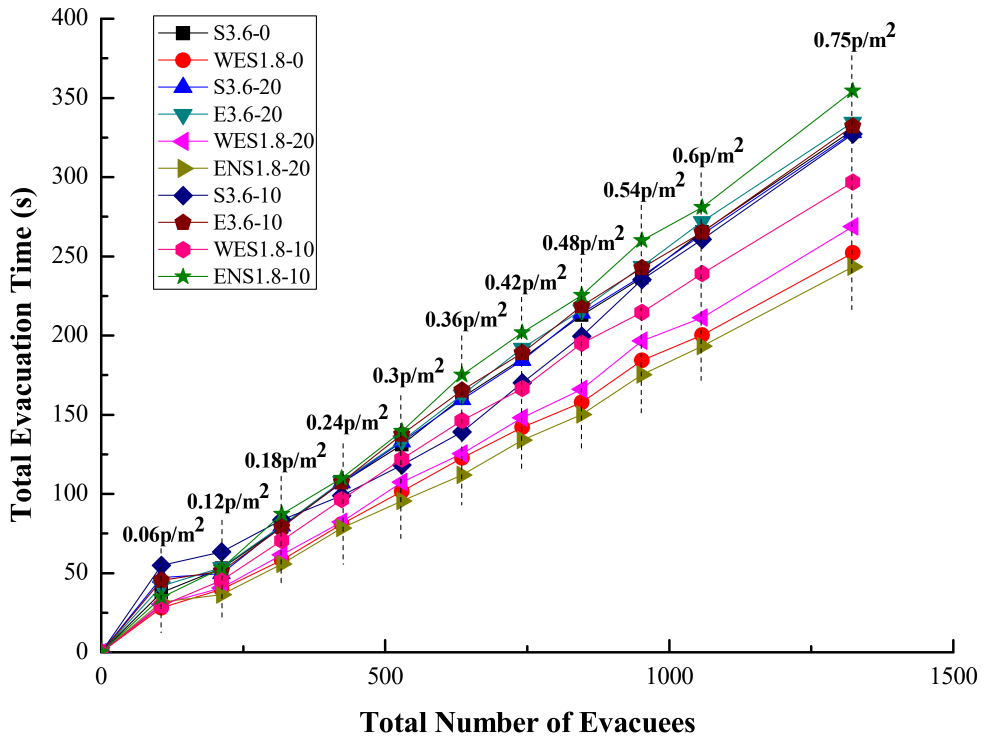


Figure 8. Schematic diagram of average evacuation times under conditions of different scenarios and numbers of pedestrians with a safety exit failure.

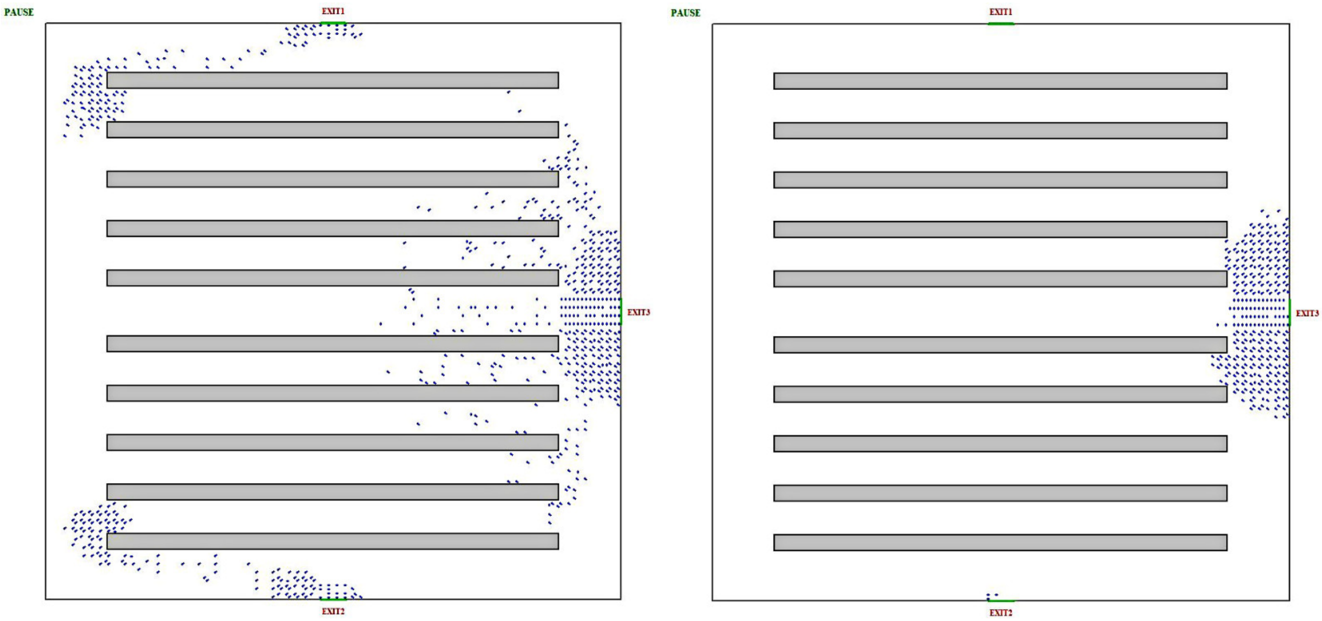
The discussion on Figure 8 is as follows.

(1). When the crowd density changes from 0.06 p/m^2 to 0.12 p/m^2, the change of evacuation times is significantly lower than that between the later changes of higher crowd density as shown by the significant slope difference of the line segment between two points in Figure 8, the reason for which is mentioned in Section 3.1 (1).

(2). When the initial crowd density is no more than 0.12 p/m^2, the total evacuation time of the S3.6-10 scenario is the longest, and WES1.8-0, WES1.8-20, ENS1.8-20, and WES1.8-10 are the four scenarios with the shortest total evacuation times. In combination with the simulation image process, it can be known that this is for the reasons described in Section 3.1 (2).

(3). When the initial crowd density is no less than 0.18 p/m^2, the total evacuation time of the ENS1.8-10 scenario is the longest. The main reason is that there is a big ratio difference between pedestrians choosing each exit and the designed strand numbers of crowd flow at each exit (1:1:1 in this case), which leads to a decrease in the utilization efficiency of some exits and is consistent with the description about WENS1.8-10 scenarios in Section 3.1 (3).

Taking an evacuation process with the total number of 846 pedestrians as an example, the number of pedestrians choosing the north, the south, and the east exits were 188, 191, and 467, respectively, and the total evacuation time was 226.5 s. The real-time moving diagrams of evacuation at t = 20 s and t = 70 s are shown in Figure 9a,b, respectively. Combined with the exported data file, it can be seen that pedestrians choosing the north EXIT1 and the south EXIT2 were all evacuated at t = 66 s and t = 71 s, respectively, and there were 323 pedestrians still gathering at the east EXIT3 at t = 71 s, leading the evacuation widths of EXIT1 and EXIT2 to be not utilized after that.



(**a**) (**b**)

Figure 9. Evacuation schematic diagram of the ENS1.8-10 scenario at t = 20 s and t = 46 s under the condition that the total number of pedestrians is 846. (**a**) t = 20 s, (**b**) t = 70 s.

In addition, it is worth noting that even though the total net width of the remaining exits in the ENS1.8-10 scenario was 5.4 m, which was larger than that in scenarios (S3.6-0, S3.6-10, E3.6-10, S3.6-20, E3.6-20) with a total net width of the remaining safety exit of 3.6 m, the actual evacuation width in the later stage was only 1.8 m, which led to the undesirable result that its total evacuation time was the longest. Therefore, considering the failure of one exit and from the perspective of evacuation safety under high-density crowd conditions, the shelves' configuration of the ENS1.8-10 scenario changing from the original WENS1.8-10 scenario is worst among all scenarios.

(4). When the initial crowd density is no less than 0.18 p/m^2, the total evacuation times in the scenarios with the total remaining exit net widths of 3.6 m (S3.6-0, S3.6-10, E3.6-10, S3.6-20, E3.6-20) are very close, which indicates that under this condition, the extension effect of average evacuation distance or D_{fg} caused by the shelves' configuration in this paper has little influence on the total evacuation time of the crowd, which is consistent with the situation described in Section 3.2 (6).

(5). When the initial crowd density is no less than 0.12 p/m^2, among the scenarios of the total remaining net widths of exits that are 5.4 m, except for the ENS1.8-10 scenario which is discussed in Section 3.2 (3), the total evacuation times in the three scenarios, including ENS1.8-20, WES1.8-0, and WES1.8-20, are all longer than the scenarios with the total remaining exit net widths of 3.6 m under the same number of pedestrians. When the initial crowd density is higher than 0.36 p/m^2, the total evacuation time in WES1.8-10 scenario is longer than that in all the rest scenarios with the total remaining exit net widths of 3.6 m. The foregoing results show that when the initial crowd density is higher and the ratio of pedestrians choosing each exit and of designed strand numbers of crowd flow at each exit are close to a certain extent, the increase in the strand numbers of crowd flow of available exits which can be expressed as the increase of the total evacuation net widths of available exits in this case (because the increase of the total evacuation net widths is a necessary but not sufficient condition for the increase in the strand numbers of crowd flow of exits) is the dominant factor that reduces the total evacuation time.

(6). When the initial crowd density is no less than 0.12 p/m^2, ENS1.8-20 is the scenario with the shortest total evacuation time among all scenarios because the net width of the remaining safety exits is the largest value of 5.4 m, and the ratio of the number of pedestrians choosing each exit is the closest to that of the strand number of crowd flow at each exit among all scenarios.

A concept of "average utilization efficiency of exits" (η), which is defined as the ratio of the sum of evacuation time at each available exit to the product of the number of available exits and the total evacuation time under multiple exit conditions, is put forward as an evacuation result parameter to represent the difference in the evacuation time of each exit in a building in this paper. The specific calculation formula of η is calculated as:

$$\eta = \frac{\sum\limits_{i=1}^{n} t_i}{n \times t_{\max}} \tag{1}$$

where n is the number of available exits ($n \geq 2$), t_i is the evacuation time at i'th exit (s), and $t_{\max}$ is the total evacuation time (s).

The larger the above value of η gets, the closer the evacuation time of all exits are, which is reflected in the reduction of the total evacuation time and the duration of the gathering phenomenon of the crowd, so as to reduce the risk of crowd stampede to a certain extent.

Taking the evacuation processes with a total number of 846 pedestrians in each scenario as examples, relevant parameters with total evacuation net widths of 5.4 m of available exits are shown in Table 2.

Table 2. Relevant parameters with total evacuation net widths of 5.4 m of available exits under the condition that the total number of evacuees is 846.

Scenario Name	Original Scenario Name	Number of Evacuees and Evacuation Time				Total Evacuation Time	η
		At West Exit	At East Exit	At North Exit	At South Exit		
ENS1.8-20	WENS1.8-20	×	216 102 s	323 149 s	307 135 s	149 s	86.4%
WES1.8-0	WENS1.8-0	322 158 s	310 151 s	×	214 101 s	158 s	86.5%
WES1.8-20	WENS1.8-20	344 171 s	330 161 s	×	172 79 s	171 s	81.3%
WES1.8-10	WENS1.8-10	398 201 s	369 179 s	×	79 35 s	201 s	68.8%
ENS1.8-10	WENS1.8-10	×	467 227 s	191 66 s	188 71 s	227 s	53.5%

According to the data in Table 2, under the condition that the net width of each exit is equal, that is, the designed strand number of crowd flow at each exit is the same, the total evacuation time depends on the evacuation time at the exit with the largest number of pedestrians evacuated. Due to the size of human shoulder width, a small increase in the evacuation net width will not necessarily lead to an increase in the strand number of crowd flow at the exit. Therefore, if the strand number of crowd flow is used to represent the evacuation ability of the safety exit, it can be considered that the total evacuation time depends on the evacuation time of the exit with the maximum ratio of the number of pedestrians evacuated to the strand number of crowd flow.

The average utilization efficiencies of the ENS1.8-20 and WES1.8-20 scenarios changing from the WENS1.8-20 scenario are significantly more than those of the ENS1.8-10 and WES1.8-10 scenarios changing from the WENS1.8-10 scenario based on Table 2. The reason is that the ratio of the number of evacuees choosing each exit and of the designed strand number of crowd flow at the corresponding exit in the first two scenarios are much closer than that in the last two scenarios, making η significantly larger than the last two.

The distribution ratios of the number of evacuees at three exits of the WES1.8-0 and ENS1.8-20 scenarios are very close, resulting in the fact that the total evacuation time and the average utilization efficiency η of them are also very close and the two differences between the two scenarios are only 9 s and 0.01%, respectively. Combined with the evacuation image, the reason why the total evacuation time of the ENS1.8-20 scenario is slightly less than that of the WES1.8-0 scenario is that the shelves' configuration leads to the extension of the average evacuation distance and D_{fg} in the ENS1.8-20 scenario, thus weakening the gathering effect at the exit to some extent, including the appearance of the time and size of the gathering area.

By comparing the last two columns of data in Table 2, the rule that can be obtained is that under the condition of a high crowd density, the total evacuation time and the average utilization efficiency of the exits show a negative correlation trend; that is, the shorter the total evacuation time is, the higher the average utilization efficiency of exits. However, due to the randomness of the initial occupation of pedestrians, this rule is not necessarily applicable when the ratio of the number of evacuees at each exit is very close to that of the designed strand number of crowd flow at the corresponding exit. For example, the trend of the above two parameters does not appear in the ENS1.8-20 and WES1.8-0 scenarios, but the deviation of them is very small.

Considering, therefore, the failure of one exit and from the perspective of evacuation safety under high-density crowd conditions, the shelves' configuration of the ENS1.8-20 scenario whose original scenario is WENS1.8-20 is the optimal configuration scheme among all scenarios.

3.3. Overall Result Analysis and Discussion

Given that the recommended crowd density of the business hall is 0.6 p/m^2 in the Code, the overall result analysis takes this value as the standard; that is, the total number of pedestrians is set as 1058. Under this condition, the relevant result parameters of evacuation simulation in the original and changed scenarios are shown in Tables 3 and 4, respectively.

Table 3. Related evacuation parameters of the original scenarios.

Scenario Name	Total Evacuation Time	Increased Value Relative to the Minimum Total Evacuation Time	Increased Proportion Relative to the Minimum Total Evacuation Time
NS3.6-10	124.6 s	—	—
WENS1.8-0	135.8 s	11.2 s	9.0%
NS3.6-0	136.4 s	11.8 s	9.5%
NS3.6-20	137.4 s	12.8 s	10.3%
WE3.6-20	137.5 s	12.9 s	10.4%
WE3.6-10	139.2 s	14.6 s	11.7%
WENS1.8-20	144.9 s	20.3 s	16.3%
WENS1.8-10	212.9 s	88.3 s	70.9%

Table 4. Related evacuation parameters of the changed scenarios.

Scenario Name	Original Scenario Name	Total Evacuation Time	Increased Value Relative to the Minimum Total Evacuation Time	Increased Proportion Relative to the Minimum Total Evacuation Time
ENS1.8-20	WENS1.8-20	193.3 s	0	0
WES1.8-0	WENS1.8-0	200.3 s	7.0 s	3.6%
WES1.8-20	WENS1.8-20	211.2 s	17.9 s	9.3%
WES1.8-10	WENS1.8-10	239.1 s	45.8 s	23.7%
S3.6-10	NS3.6-10	260.6 s	67.3 s	34.8%
S3.6-20	NS3.6-20	263.9 s	70.6 s	36.5%
E3.6-10	WE3.6-10	265.2 s	71.9 s	37.2%
S3.6-0	NS3.6-0	265.5 s	72.2 s	37.4%
E3.6-20	WE3.6-20	271.9 s	78.6 s	40.7%
ENS1.8-10	WENS1.8-10	281.0 s	87.7 s	45.4%

It can be seen from Table 3 that, without considering the failure of any safety exit and from the perspective of evacuation safety, among the scenarios listed in this paper, NS3.6-10 is the most favorable scenario and WENS1.8-10 is the most unfavorable one. Compared with the former, the increases of absolute value and proportion of evacuation time of the latter are 88.3 s and 70.9%, respectively, and the increased percentages of the evacuation time of the other scenarios are between 10% and 20%.

As can be seen from Table 4, considering the failure of one exit, ENS1.8-20 is the optimal scenario, and WES1.8-20 is the second-optimal one among all the scenarios with shelves. The original scenario of the above two is WENS1.8-20. The increased proportions relative to the minimum total evacuation time of the rest of the scenarios with shelves are all more than 20%, and the ENS1.8-10 scenario whose original scenario is WENS1.8-10 is the most unfavorable configuration scheme.

Based on the data in Tables 3 and 4, it can be seen that WENS1.8-10 is the worst scheme in both cases and should not be used in the actual configuration of shelves. If referring to the available evacuation time of the audience hall in a gymnasium based on the clause explanation in the Code, except for the scenario of WENS1.8-10, the evacuation time of the other scenarios is within 3 min without considering an exit failure, which make the others belong to the safety schemes. In view of this, the shelves' configuration of WENS1.8-20 should be preferred in this example.

4. Conclusions

Based on the case analysis and discussion, the conclusions can be obtained as follows.

(1). When the personnel density is at a very low level, there will be no crowding phenomenon in the crowd evacuation process. At this time, the farthest grid evacuation distance (D_{fg}) in a scenario is the key factor to determine the total evacuation time. The optimization of evacuation efficiency only needs to minimize the attribute value of D_{fg} through shelves' configuration while meeting the actual use requirements.

(2). When the crowd density is at a high level, the closer the proportion ratio of the number of evacuees choosing each exit is to that of the designed strand numbers of crowd flow at each exit, the higher the evacuation efficiency is, and the higher average utilization efficiency of exits gets. At the same time, on the premise of ensuring that all safety exits are available under emergency conditions, and with a certain total net evacuation width, the scattered arrangement of safety exits will not necessarily lead to improving the efficiency of crowd evacuation, because it may result in a larger difference between the two ratios as mentioned above. Therefore, on the basis of meeting the requirements of architectural design, the design of the location and width of each safety exit should be taken into full consideration to match the number of pedestrians in its control area of evacuation.

(3). Because the shelves are usually narrow and long in supermarkets, there is much probability of the extension of D_{fg}. However, when the crowd density is at a high level, the extension effect may actually help reduce the evacuation time instead, especially when forming the effective advanced-gathering zones, which makes the optimization effect of the evacuation efficiency in this way more obvious. The formation of advanced-gathering zones can refer to the shelves' configuration in this article, which makes the total net width of passages become narrow; further, it changes and extends a part of personnel evacuation routes, especially making the walking directions turn, thus causing the behavior of slow movement and advanced gathering of a large number of pedestrians during the evacuation process, and forming the delayed gathering of pedestrians at the location of the safety exits. Therefore, on the basis of meeting the requirements of safety evacuation design, full consideration should be given to the use of effective advance-gathering zones established by long shelves' configuration to improve the evacuation efficiency. Given the complexity of the connection between building space and crowd evacuation, it is a very good method to verify the validity of advance-gathering zones by simulation.

(4). Under the condition of a high-density crowd, if the shelves' configuration does not make the obvious ratio difference between the number of pedestrians choosing each exit and the designed strand number of crowd flow at each exit, and does not form effective advanced-gathering zones, the gathering near the exits is the key factor influencing the total evacuation time, and the impact of shelves' configuration on evacuation time can be ignored. Under such circumstances, the optimization of evacuation efficiency can only be achieved by increasing the width of the exits, which is difficult to realize in the operation period of buildings.

(5). From the point of view of crowd evacuation, the shelves' configuration in the supermarket should be determined comprehensively according to the locations of the exits, the pedestrian flow in different commodity areas, considering the failure of exits or not, the safety margin of evacuation time, and other factors. If there is an irreconcilable conflict between the evacuation optimization design and shelves' configuration, the evacuation efficiency can be optimized by the evacuation indicator direction design or human guidance. In fact, the narrow and long shelves in this paper can be regarded as general uncrossable obstacles, and the relevant conclusions can be used to determine the way of setting obstacles in other types of building spaces.

(6). The limitations of this paper are that the pedestrians' attributes and their evacuation response times are limited, the principle for pedestrians to choose an exit is based on the shortest path, the pedestrians are randomly set by a global placement in the full-size space, and the factors of personnel psychology, familiarity with exits, small group behavior, herd behavior, space occupancy preference of pedestrians, and design bias of crowd density in different areas are not taken into consideration. The influence of the above limitations and factors for crowd evacuation are planned to be further studied in a later work.

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Appendix A

The Appendix A includes the average evacuation times under conditions of different scenarios and numbers of pedestrians without and with an exit failure as shown in Tables A1 and A2, respectively.

Table A1. Average evacuation times under conditions of different scenarios and numbers of pedestrians with all safety exits open.

Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)	Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)
NS3.6-0	1323	173.1	WENS1.8-0	1323	169.5
	1058	136.4		1058	135.8
	952	122.0		952	126.5
	846	110.1		846	113.5
	741	97.1		741	93.7
	635	84.0		635	84.2
	529	68.6		529	69.3
	423	56.8		423	55.5
	318	43.8		318	41.5
	212	31.2		212	27
	106	28.5		106	23.7
NS3.6-20	1323	172.9	WE3.6-20	1323	171.3
	1058	137.4		1058	137.5
	952	124.7		952	123.8
	846	111.5		846	112.3
	741	95.5		741	98.7
	635	84.1		635	83.8
	529	68.0		529	71.3
	423	57.3		423	55.7
	318	44.0		318	43.3
	212	35.6		212	33.4
	106	33.3		106	31.0
WENS1.8-20	1323	182.2	NS3.6-10	1323	159.8
	1058	144.9		1058	124.6
	952	136.8		952	113.1
	846	112.8		846	99.0
	741	105.2		741	84.6
	635	83.6		635	75.3
	529	70.9		529	65.9
	423	55.4		423	59.6
	318	42.2		318	49.1
	212	27.0		212	44.8
	106	23.2		106	41.8

Table A1. *Cont.*

Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)	Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)
WE3.6-10	1323	173.8	WENS1.8-10	1323	259.5
	1058	139.2		1058	212.9
	952	126.6		952	190.9
	846	113.6		846	170.9
	741	100.0		741	150.5
	635	84.5		635	133.2
	529	68.8		529	105.4
	423	55.7		423	82.1
	318	43.7		318	63.7
	212	32.7		212	40.0
	106	33.0		106	28.2

Table A2. Average evacuation times under conditions of different scenarios and numbers of pedestrians with a safety exit failure.

Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)	Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)
S3.6-0	1323	329.7	WES1.8-0	1323	252.1
	1058	265.5		1058	200.3
	952	236.5		952	184.2
	846	212.9		846	157.7
	741	185.5		741	142.1
	635	160.8		635	122.8
	529	131		529	101.6
	423	106.9		423	81
	318	79.1		318	58.3
	212	53		212	39.7
	106	37.8		106	28.2
S3.6-20	1323	328.1	E3.6-20	1323	334.6
	1058	263.9		1058	271.9
	952	237.6		952	243.6
	846	214.1		846	216.1
	741	184.2		741	191.9
	635	159.6		635	162.5
	529	132.7		529	133.4
	423	106.9		423	107.9
	318	79.8		318	79.9
	212	49.6		212	53.4
	106	47.1		106	41.8

Table A2. *Cont.*

Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)	Scenario Name	Total Number of Evacuees	Total Evacuation Time (s)
WES1.8-20	1323	268.7	ENS1.8-20	1323	243.3
	1058	211.2		1058	193.3
	952	196.6		952	175.2
	846	166		846	150.1
	741	148.2		741	134
	635	125.3		635	111.8
	529	107.5		529	95.6
	423	82.2		423	78.4
	318	61.5		318	55.7
	212	40.6		212	36.5
	106	30.4		106	31.7
S3.6-10	1323	327.1	E3.6-10	1323	332.1
	1058	260.6		1058	265.2
	952	235.2		952	242.6
	846	199.5		846	218.6
	741	170.1		741	189
	635	139.1		635	165.4
	529	118.1		529	137.5
	423	98.8		423	107.4
	318	83.5		318	78.9
	212	63.4		212	51.3
	106	54.8		106	45.4
WES1.8-10	1323	296.8	ENS1.8-10	1323	354.4
	1058	239.1		1058	281
	952	214.6		952	259.9
	846	195		846	225.3
	741	166.5		741	201.7
	635	146.3		635	175.1
	529	122		529	139.6
	423	96.4		423	109.8
	318	70.5		318	87.1
	212	45.4		212	53
	106	29.4		106	34.6

References

1. *GB/T 18106-2021*; Classification of Retail Formats. China Zhijian Publishing House: Beijing, China, 2021.
2. China Youth Daily. Available online: https://s.cyol.com/articles/2021-04/26/content_1Ve8Aqul.html (accessed on 26 April 2021).
3. Fang, H.; Lv, W.; Cheng, H.; Li, X.L.; Yu, B.J.; Shen, Z.W. Evacuation Optimization Strategy for Large-Scale Public Building Considering Plane Partition and Multi-Floor Layout. *Front. Public Health* **2022**, *10*, 847399. Available online: https://www.frontiersin.org/articles/10.3389/fpubh.2022.847399/full (accessed on 21 February 2022). [CrossRef] [PubMed]
4. Chang, D.; Cui, L.Z.; Huang, Z. A Cellular-Automaton Agent-Hybrid Model for Emergency Evacuation of People in Public Places. *IEEE Access* **2020**, *8*, 79541–79551. [CrossRef]

5. Bai, X.H. Research on Dynamic Parameter Test and Basic Behavior Simulation of Personnel Evacuation. MA Thesis, China University of Mining and Technology, Xuzhou, China, 2021. [CrossRef]
6. Gao, G.P. Study on behavior characteristics and evacuation environment of evacuation in buildings. Ph.D. Thesis, Wuhan University of Technology, Wuhan, China, 2018. [CrossRef]
7. Yang, L.Z. *Movement Law and Evacuation Dynamics of People in Buildings*; Science Press: Beijing, China, 2012; pp. 1–11.
8. Tian, Y.M.; Zhang, W.; Ma, H.W.; He, X.Y. *Emergency Crowd Evacuation*; Chemical Industrial Press: Beijing, China, 2014; pp. 9, 14–16.
9. Dong, H.R.; Zhou, M.; Wang, Q.L.; Yang, X.X.; Wang, F.Y. State-of-the-Art Pedestrian and Evacuation Dynamics. *IEEE Trans. Intell. Transp. Syst.* **2020**, *21*, 1849–1866. [CrossRef]
10. Najmanova, H.; Ronchi, E. An Experimental Data-Set on Pre-school Children Evacuation. *Fire Technol.* **2017**, *53*, 1509–1533. [CrossRef]
11. Haghani, M.; Sarvi, M.; Shahhoseini, Z. Evacuation behaviour of crowds under high and low levels of urgency: Experiments of reaction time, exit choice and exit-choice adaptation. *Saf. Sci.* **2020**, *126*, 104679. [CrossRef]
12. Chen, J.M.; Wang, J.Y.; Wang, B.B.; Liu, R.; Wang, Q.S. An experimental study of visibility effect on evacuation speed on stairs. *Fire Saf. J.* **2018**, *96*, 189–202. [CrossRef]
13. Seike, M.; Kawabata, N.; Hasegawa, M. Experiments of evacuation speed in smoke-filled tunnel. *Tunn. Undergr. Space Technol.* **2016**, *53*, 61–67. [CrossRef]
14. Poulos, A.; Tocornal, F.; de la Llera, J.C.; Mitrani-Reiser, J. Validation of an agent-based building evacuation model with a school drill. *Transp. Res. Part C Emerg. Technol.* **2018**, *97*, 82–95. [CrossRef]
15. Mu, H.L.; Song, W.G.; Sun, J.H.; Lo, S.M.; Wang, J.H. An Experimental and Numerical Study of Imbalanced Door Choice during an Announced Evacuation Drill. *Fire Technol.* **2016**, *52*, 801–815. [CrossRef]
16. Zuriguel, I.; Olivares, J.; Pastor, J.M.; Martin-Gomez, C.; Ferrer, L.M.; Ramos, J.J.; Garcimartin, A. Effect of obstacle position in the flow of sheep through a narrow door. *Phys. Rev. E* **2016**, *94*, 032302. [CrossRef]
17. Lin, P.; Ma, J.; Liu, T.Y.; Ran, T.; Si, Y.L.; Wu, F.Y.; Wang, G.Y. An experimental study of the impact of an obstacle on the escape efficiency by using mice under high competition. *Phys. A Stat. Mech. Its Appl.* **2017**, *482*, 228–242. [CrossRef]
18. Helbing, D.; Farkas, I.; Vicsek, T. Simulating dynamical features of escape panic. *Nature* **2000**, *407*, 487–490. [CrossRef]
19. Zhao, Y.; Liu, H.; Gao, K.Z. An evacuation simulation method based on an improved artificial bee colony algorithm and a social force model. *Appl. Intell.* **2020**, *51*, 100–123. [CrossRef]
20. Li, Y.; Chen, M.Y.; Dou, Z.; Zheng, X.P.; Cheng, Y.; Mebarki, A. A review of cellular automata models for crowd evacuation. *Phys. A Stat. Mech. Its Appl.* **2019**, *526*, 228–242. [CrossRef]
21. Sharbini, H.; Sallehuddin, R.; Haron, H. Crowd evacuation simulation model with soft computing optimization techniques: A systematic literature review. *J. Manag. Anal.* **2021**, *8*, 443–485. [CrossRef]
22. Wei, X.G.; Yao, H.W.; Li, L.F.; Chen, H.W.; Wang, X.F.; Li, F.F. Research on emergency evacuation in large supermarket based on family group movement observation. *Fire Sci. Technol.* **2020**, *39*, 1075–1078. [CrossRef]
23. Li, C.Y.; Wang, B.S. Personnel evacuation in fire of comprehensive supermarket based on numerical simulation. *Fire Sci. Technol.* **2019**, *38*, 1237–1240. [CrossRef]
24. Liu, J. Research on Group Evacuation Simulation and Fire Rescue Path Planning in Supermarket under Fire Environment. MA Thesis, Anhui University of Technology, Maanshan, China, 2018. [CrossRef]
25. Zhang, Y. Study on the Planning of Fire Evacuation in Large Life Supermarket. MA Thesis, Tianjin University of Technology, Tianjin, China, 2018. [CrossRef]
26. Wang, Z.J. Numerical simulation of fore and evacuation of personnel in a large supermarket. MA Thesis, Anhui University of Science and Technology, Huainan, China, 2017. [CrossRef]
27. Cao, S.C.; Fu, L.B.; Song, W.G. Experimental and modeling study on evacuation under good and limited visibility in a supermarket. *Fire Saf. J.* **2018**, *102*, 27–36. [CrossRef]
28. Wu, H.; Ding, Y.C.; Weng, F.L. Study on the influence of obstacles on personnel evacuation in shopping mall. *Sci. Technol. Innov.* **2021**, *2*, 37–41. [CrossRef]
29. Luo, Q. Effect of obstacle on crowd dynamics in corridors: An experimental and simulation. MA Thesis, Southwest Jiaotong University, Chengdu, China, 2021. [CrossRef]
30. Sun, J. Research on the influence of passageway obstacle on crowd evacuation in shopping mall. MA Thesis, South China University of Technology, Guangzhou, China, 2018.
31. Liu, H.; Jin, W.T. Simulation of the evacuation of different obstacles based on a social-psychological model. *J. Saf. Environ.* **2022**, *22*, 1442–1449. [CrossRef]
32. Cao, Y.Y. Obstacle Layout Optimization Based on Crowd Simulation. MA Thesis, Xidian University, Xian, China, 2020. [CrossRef]
33. Lv, H.; Liu, X.Y.; Wang, Y.L.; Zhou, R. Study on influence laws of obstacle in evacuation exit on evacuation efficiency. *J. Saf. Sci. Technol.* **2020**, *16*, 141–145. [CrossRef]
34. Yi, P.; Zhong, X.R.; Yue, P.K. Influence of obstacles in front of shopping center's exit on emergency evacuation efficiency. *Fire Sci. Technol.* **2020**, *39*, 62–66. [CrossRef]
35. Gao, R. Room evacuation model and its application considering the influence of obstacles. MA Thesis, Southwest Jiaotong University, Chengdu, China, 2018.

36. Yue, H.; Zhang, J.Y.; Chen, W.X.; Wu, X.S.; Zhang, X.; Shao, C.F. Simulation of the influence of spatial obstacles on evacuation pedestrian flow in walking facilities. *Phys. A Stat. Mech. Its Appl.* **2021**, *571*, 125844. [CrossRef]
37. Zang, Y.; Mei, Q.; Liu, S.X. Evacuation simulation of a high-rise teaching building considering the influence of obstacles. *Simul. Model. Pract. Theory* **2021**, *112*, 102354. [CrossRef]
38. Wang, K.; Fu, Z.J.; Li, Y.X.; Qian, S.Z. Influence of human-obstacle interaction on evacuation from classrooms. *Autom. Constr.* **2020**, *116*, 103234. [CrossRef]
39. Wang, J.H.; Li, J.C.; Li, J.; Feng, J.J.; Xu, S.Y.; Liu, J.; Wang, Y. Performance optimization of the obstacle to corner bottleneck under emergency evacuation. *J. Build. Eng.* **2022**, *45*, 103658. [CrossRef]
40. Zhao, Y.X.; Lu, T.T.; Fu, L.B.; Wu, P.; Li, M.F. Experimental verification of escape efficiency enhancement by the presence of obstacles. *Saf. Sci.* **2020**, *122*, 104517. [CrossRef]
41. Sticco, I.M.; Frank, G.A.; Dorso, C.O. Improving competitive evacuations with a vestibule structure designed from panel-like obstacles in the framework of the Social Force Model. *Saf. Sci.* **2022**, *146*, 105544. [CrossRef]
42. Li, L.; Liu, H.; Han, Y.B. Optimal Design of Obstacles in Emergency Evacuation Using an Arch Formation Based Fitness Function. In Proceedings of the 13th CCF Conference on Computer Supported Cooperative Work and Social Computing, Guilin, China, 18–19 August 2018. [CrossRef]
43. Shiwakoti, N.; Shi, X.M.; Ye, Z.R. A review on the performance of an obstacle near an exit on pedestrian crowd evacuation. *Saf. Sci.* **2019**, *113*, 54–67. [CrossRef]
44. Ji, J.W.; Lu, L.G.; Jin, Z.H.; Wei, S.P.; Ni, L. A cellular automata model for high-density crowd evacuation using triangle grids. *Phys. A Stat. Mech. Its Appl.* **2018**, *509*, 1034–1045. [CrossRef]
45. Lu, L.G. Research on High Density Evacuation Simulation Method Based on the Theory of Cellular Automata. MA Thesis, China University of Mining and Technology, Xuzhou, China, 2016.
46. *GB 50016-2014, 2018 edition*; Code for Fire Protection Design of Buildings. China Planning Press: Beijing, China, 2018.
47. Mu, R.R. Analysis on the change of the morphology character of 20–25 years old urban adults in China. MA Thesis, Shanghai University of Sport, Shanghai, China, 2017.
48. Xie, X.L.; Ji, J.W.; Wang, Z.H.; Lu, L.G.; Yang, S.F. Experimental study on the influence of the crowd density on walking speed and stride length. *J. Saf. Environ.* **2016**, *16*, 232–235. [CrossRef]