Research on Multi-exit Laboratory Safe Evacuation

Hao Wang, Ling Wu, Songtao Wang

***Abstract*—Safety accidents frequently occur in university laboratories, making the evacuation of students from multiple exits a critical issue. In order to address this concern, we utilized the AnyLogic software to simulate a university laboratory environment. By quantifying the degree of awareness, representing safety education, safety training, and familiarity, we enhanced the expected speed within the primary social force model. Expanding on this foundation, we investigated various exit layouts and conducted experiments to develop an optimization scheme that evenly distributes exit locations and improves exit width. The objective of this approach was to resolve the problem of imbalanced utilization rates in multi-exit laboratories. The simulation results demonstrate that increased awareness not only enhances students' expected speed but also reduces evacuation time. Moreover, by implementing appropriate exit spacing and width settings, we were able to not only evenly distribute students but also alleviate congestion at exits, effectively resolving the issue of imbalanced exit utilization.**

***Index Terms*—Social force model, Multi-exit laboratory, Safe evacuation, Anylogic simulation**

I. Introduction

University laboratories are environments where researchers and students conduct scientific experiments and generate new knowledge. However, they are also environments where hazards exist and accidents occur [1]. Unfortunately, since 2001, many accidents have occurred in these laboratories in China, leading to fires, explosions, and other disasters. These accidents have harmed the lives and health of many faculty and students. Fig. 1 shows the statistics of 126 laboratory accidents that occurred in universities from 2001 to 2021, which caused 19 deaths and 106 injuries.

Laboratory accidents can include various incidents, such as explosions, fires, poisonings, electrical hazards, mechanical hazards, and others [2]. Table I presents the 125 laboratory accidents that occurred from 2001 to 2021.The analysis reveals that explosions and fires are the dominant types of laboratory accidents in universities, accounting for about 82% of the total. The other types of accidents, such as poisonings and electrical hazards, are less frequent, but they are very serious and fatal.

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Considerable research has been conducted to develop and improve the theory and methods of simulating personnel evacuation, leading to significant advancements. Currently, prominent microscopic models used in emergency evacuation include the social force model, lattice gas model, cellular automata model, and Agent-based model. Helbing et al. [3] proposed a characterization of human behavior that consists of three forces: driving force, attraction among individuals, and repulsion between individuals and the environment. These three forces interact to determine how people behave and they are called social forces.

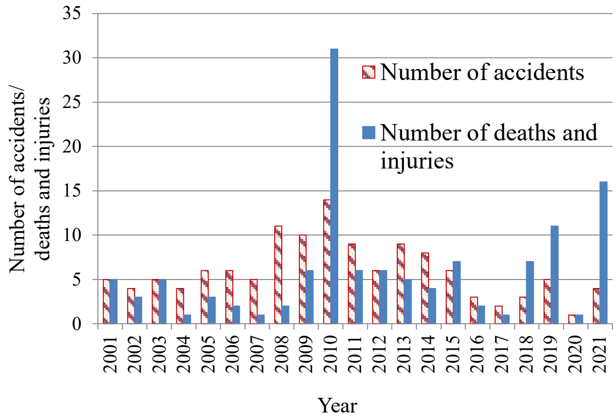

Fig. 1. Summary of laboratory accidents in universities

TABLE I
TYPES OF LABORATORY ACCIDENTS IN UNIVERSITIES

Types	Number of Accidents	Number of Deaths	Number of Injured	Total
Explosions	38	11	46	57
Fires	65	5	38	43
Poisonings	11	1	13	14
Electrical hazards	6	2	5	7
Mechanical hazards	3	0	2	2
Others	3	1	1	2
Explosions	38	11	46	57

Extensive research has been conducted on evacuation behavior in emergency situations such as fires, explosions, and the dispersion of toxic gases in the late 20th and early 21st centuries. Mabrouk et al. [4] applied the social force model to examine the impact of different approaches on pedestrian interactions, as well as the relationship between crowd movement speed and crowd density. Cao et al. [5] modified the social force model by addressing the issues of "see-through" and "overlapping" phenomena in the model. They also introduced a parameter to account for pedestrians' psychological emotions. Based on the social force theory, Xiong et al. [6] introduced the concept of perceived distance for pedestrians, while reflects how far they perceive themselves from others and the environment. This concept enables the integrating psychological attributes into the social force model, and reduces the deviations caused by intelligent human behaviors. They also proposed the concept of pedestrian detour effects, which describes how people adjust their paths to avoid obstacles or congestion, and used the AnyLogic software to simulate the effects of these factors on the evacuation time, detour distance, and crowd density at exits under two different scenarios. Subsequently, evacuation experiments were conducted to validate the reliability of their model.

The scenarios of emergency evacuation can be classified into indoor and outdoor settings. In indoor environments, such as enclosed spaces, the crowd is more diverse and the space is more limited, which can result in overcrowding and stampede incidents. Therefore, it is vital and difficult to evacuate people quickly and safely in these situations. Numerous scholars have performed simulation studies to investigate various aspects of emergency evacuation in indoor settings.

One notable study by Zheng et al. [7] simulated the process of crowd evacuation during a fire and found that unfamiliarity with the environment significantly impedes the evacuation. Another study by Xing et al. [8] investigated how the crowd's familiarity with a large supermarket in Changzhou and their choice of evacuation routes affect the evacuation speed. Meanwhile, Guo et al. [9] studied the effects of indoor pedestrian zone width, guide signs, and exit passageway distribution on crowd evacuation in shopping malls. Lastly, Li et al. [10] examined the influence of internal spatial layout and dynamic information within classrooms on student evacuations.

Zhong et al. [11] used the Beijing airport terminal as a case study to investigate how evacuation guidance, customs inspection obstacles, seating arrangements, and structural columns affect the evacuation process. Du et al. [12-15] identified several factors that can affect the emergency crowd evacuations, such as the number of exits, the pedestrians' familiarity with the site, the width of the stairs, the number of gates, and the characteristics of the pedestrians. Moreover, Liu et al. [16] introduced the concept of exit cost, which measures the effort and time required to reach an exit, and used simulations to analyze pedestrian behavior when selecting exits among multiple exit options in public indoor settings. Additionally, Hassanpour et al. [17-18] proposed a multi-exit multi-speed evacuation algorithm and an optimized allocation model for multiple exits. Furthermore, Han et al. [19] developed a novel route-planning algorithm based on Dijkstra's algorithm, which is a renowned algorithm for finding the shortest path between two points.

The above mentioned studies have contributed to the understanding and improvement of the safety of crowd evacuation in indoor environments. In another word, researchers aim to enhance the efficiency and effectiveness of evacuation strategies by studying factors such as the environment familiarity, route selection, spatial layout, and dynamic information

Despite the significant modifications made to the social force model by numerous researchers, few studies have taken into account comprehensive factors that affect pedestrian speed, such as educational background, safety training, and safety education. In addition, most of the research focus on the evacuation of public spaces, such as supermarkets, subway stations, and cinemas, and neglects the evacuation of places that have dense obstacles and crowded conditions, such as laboratories, stadiums, and dormitory buildings. Furthermore, there is no satisfactory solution for the problem of evacuating people in indoor settings that have multiple exits.

To address these issues, this study employed Anylogic to model and simulate fire emergency evacuations in a university laboratory. Factors, such as safety training, safety education, and familiarity with the environment were incorporated into the social force model to adjust the actual crowd speed. Additionally, we classified the students into familiar and unfamiliar groups, and determined the optimal ratio between them. In order to address the problem of imbalanced utilization of exits during multi-exit emergency evacuations, the strategy to modify the layout and structure of the exits were put forward. Then the effectiveness of the proposed model was validated through an optimization scheme. Hence, this study provides a scientific foundation for developing indoor emergency evacuation plans with multiple exits, thus achieving a logical diversion of students, alleviating exit congestion, and enhancing evacuation efficiency.

II. Modeling

A. The Original Social Force Model

The social force model is based on the principles of Newtonian mechanics and assumes that each individual is a particle that is subject to multiple forces. These forces consist of a driving force, a repulsive force, and a frictional force. The driving force is the main force that motivates individuals to move towards their desired destination, which is usually the nearest exit. The repulsive force is the force that results from the collision or avoidance of other individuals or obstacles. The frictional force is the force that arises from the contact or sliding of individuals or obstacles. These forces determine the acceleration and movement of each individual in a two-dimensional plane. The social force model can be expressed by the following equation:

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = \frac{m_i(v_i^0(t)e_i^0(t) - v_i(t))}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_w f_{iw} \quad (1)$$

in which $m_i(v_i^0(t)e_i^0(t) - v_i(t))/\tau_i$, f_{ij}, f_{iw}, and m_i, are the driving force, repulsive force, frictional force, and the mass of the individual, respectively. Where v_i^0 and $v_i(t)$ represent the target velocity and the actual velocity of the individual respectively. Additionally, $e_i^0(t)$ represents the expected direction of movement, and τ_i represents the adaptation time.

The mutual force f_{ij} between individuals consists of both frictional and repulsive forces, and can be written as

$$f_{ij} = (A_i \exp(\frac{r_{ij}-d_{ij}}{B_i}) + kg(r_{ij} - d_{ij}))n_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t t_{ij} \quad (2)$$

where A_i, B_i, k, κ are constants. A_i is the strength of the repulsive force between individuals, B_i represents the minimum distance between individuals to produce the repulsive force. $r_{ij}=r_i+r_j$, represents the sum of radii between individuals. $d_{ij}=\|r_i-r_j\|$, represents the distance between the center of mass of individuals. $n_{ij}=(n_{ij}^1,n_{ij}^2)=(r_i-r_j)/d_{ij}$ is the normalized vector between individuals. $g(x)$ is a function: when the individuals are in contact with each other, $g(x)=x$, otherwise, $g(x)=0$. $t_{ij}=(-n_{ij}^2,n_{ij}^1)$, representing the direction of the tangent line between individuals. Finally, $\Delta v_{ji}^t=(v_j-v_i)\cdot t_{ij}$, represents the relative velocity in the direction of the tangent line between individuals.

The force between an individual and an obstacle is represented as f_{iw}, which encompasses both repulsive and frictional forces. The model of f_{iw} can be expressed by

$$f_{iw}=(A\exp(\frac{r_i-d_{iw}}{B_i})+kg(r_i-d_{iw}))n_{iw} + \kappa g(r_i-d_{iw})(v_i\cdot t_{iw})t_{iw} \quad (3)$$

where d_{iw}, n_{iw}, v_i, and t_{iw} represent the distance between the individual and the obstacle, the normalized vector from the obstacle to the individual, the actual velocity of the individual, and the direction of the tangent line between the individual and the obstacle, respectively. The parameters of the social force model are presented in Table II.

TABLE II
PARAMETERS OF THE SOCIAL FORCE MODEL

Parameter	Value	Unit
m_i	80	kg
τ_i	0.5	s
A_i	2×10^3	N
B_i	0.08	m
k	1.2×10^5	$Kg\cdot s^{-2}$
κ	2.4×10^5	$kg\cdot m^{-1}\cdot s^{-1}$
r	0.4	m

B. Modeling Process

This study used AnyLogic (version 8.8.1) software to create a realistic virtual model of the laboratory and the students, and to implement the social force model and the evacuation process. The flowchart of the evacuation process was shown in Fig. 2. Based on the Pedestrian Library in AnyLogic, a laboratory class was modeled in four steps.

Step 1 Environment modeling.

The actual laboratory environment was simulated by using the walls, lab benches, chairs, entrances and exits as obstacles. Fig. 3 displayed these relationships visually, where the numbers ①, ②, ③, and ④ represent exit 1, exit 2, exit 3, and exit 4, respectively. Exit 1 and exit 4 are the normal exits, while exit 2 and exit 3 are the emergency exits.

Step 2 Design of the student evacuation flow chart.

The study determined the number of students and identified the evacuation routes. By using the controls in the AnyLogic Pedestrian Library to design the flow chart for student evacuation (as depicted in Fig. 4), an effective evacuation plan was established.

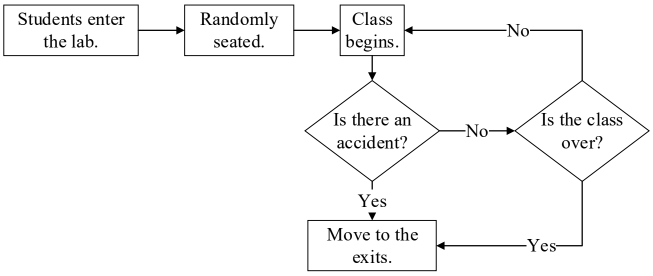

Fig. 2. Flow chart of student evacuation

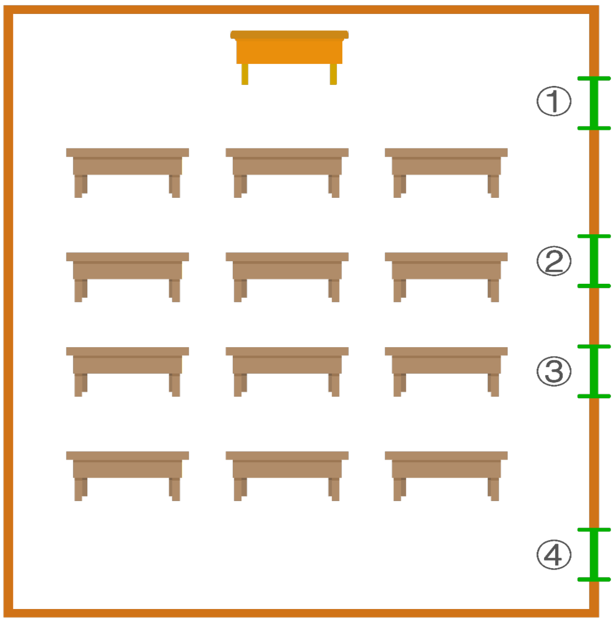

Fig. 3. Environment modeling of the laboratory

Step 3 Setting student parameters.

The parameters of the number of evacuated students, shoulder width, and walking velocity were adjusted to improve the realism of the model.

Step 4 Execution of the simulation model.

Different simulation results were obtained by running the model with different parameter settings, and analyzed the reasons for the variations in simulation outcomes.

C. Parameter Setting

The allocation of space for students was determined by the dimensions of their shoulders and chests. A statistical analysis was conducted based on the Human Dimensions of Chinese Adults [20] which found that the shoulder width of adult individuals in China typically varies from 40 cm to 50 cm. In the simulation, the diameter of students was randomly generated within the range of 0.4 m to 0.5 m.

Number of evacuees. The maximum number of students for a laboratory class was set to 51 in the PedSource property, according to the maximum laboratory capacity of 50 students and 1 teacher. According to the GB 50016-2014 Code for Fire Protection Design of Buildings, the crowd density in an ordinary building should not exceed one person per square meter. If the crowd density exceeded this limit, there was a

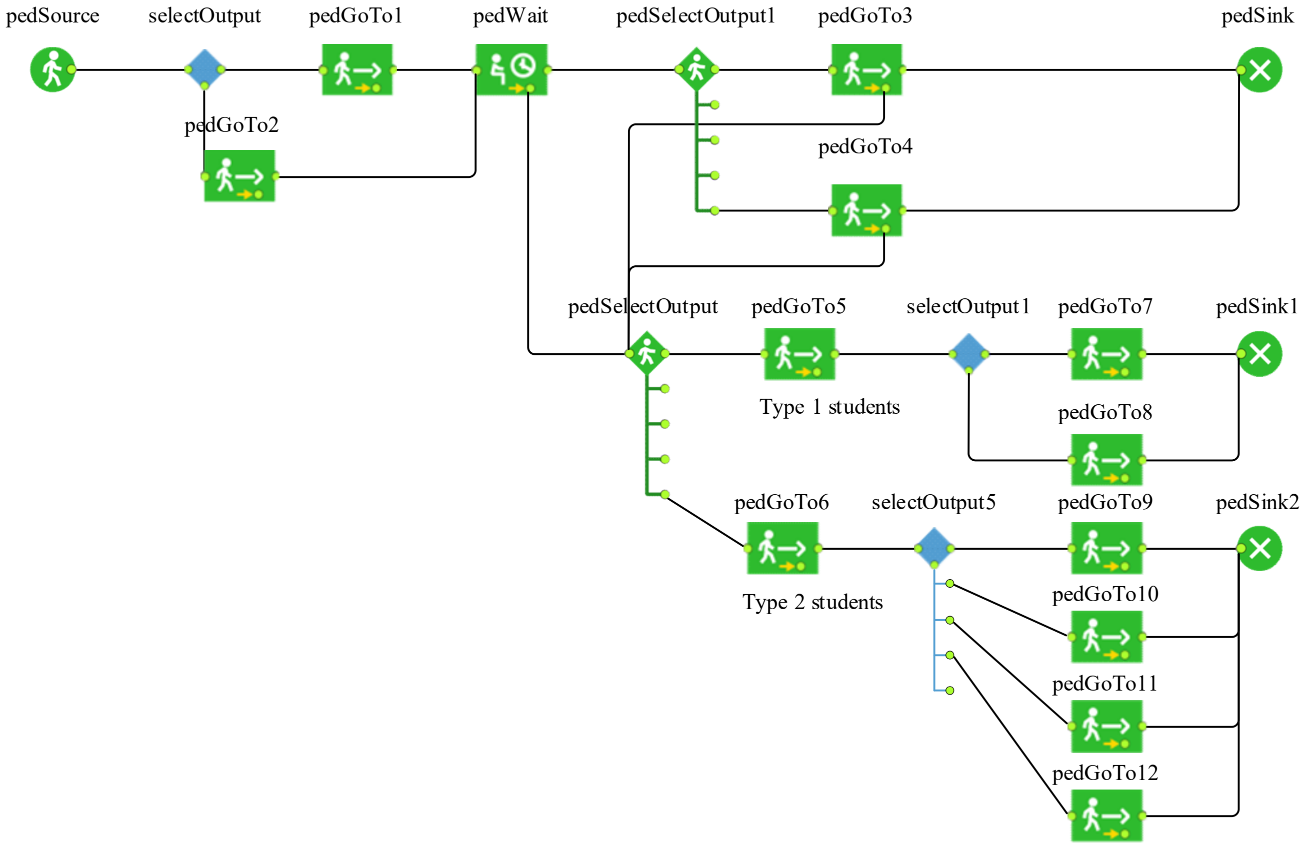

Fig. 4. Flow chart of student evacuation

high risk of causing a stampede accident. Then, the laboratory area was set to 120m^2, which can accommodate up to 120 students and teachers. Therefore, the study complied with the regulatory requirements by setting maximum number specified in the PedSource property significantly lower than the maximum value mandated by the Code for Fire Protection Design of Buildings.

Walking velocity was a crucial factor to consider in emergency evacuation situations. To determine the average walking velocity of evacuees with diverse characteristics, extensive research has been reviewed and the findings are presented in Table III [21]. Jia et al. [22] conducted a questionnaire survey focusing on the gender distribution among university students, revealing a male-to-female ratio of 6:4 in universities. Given that the majority of students were young adults, a maximum walking velocity of 1.486 m/s was calculated d for evacuation purposes using the formula (1.51 × 0.6 + 1.45 × 0.4). Additionally, the AnyLogic software incorporated a default initial speed between 0.3 m/s and 0.7 m/s.

TABLE III
AVERAGE WALKING VELOCITY OF THE EVACUEES

Young adults	Young adults	Middle-aged	Middle-aged	Minors & Seniors
Male	Female	Male	Female	
1.51m/s	1.45 m/s	1.47 m/s	1.39 m/s	1.0 m/s

III. IMPROVEMENT OF THE ORIGINAL SOCIAL FORCE MODEL

A. Improved Social Force Model Added with the Level of Awareness

Over the past two decades, researchers have made numerous modifications to the social force model. However, these adjustments have overlooked significant factors, such as safety training and education, resulting in a neglect of the impact of subjective awareness on evacuation velocity. Those who have received safety training are more familiar with the layout of the room and the distribution of entrances and exits when asked to evacuate a room with complex spatial arrangements and various obstacles. This familiarity ultimately facilitates their evacuation process by enabling them to navigate efficiently through the space and select appropriate emergency exits. To demonstrate the impact of safety education and training on students during the evacuation process, this study introduces a new parameter, called awareness level C, into the equation used to calculate the actual velocity of students. The actual velocity of students during the evacuation was determined based on the maximum and minimum evacuation velocities of students.

The level of awareness was assessed on a scale of 0 to 1. The findings demonstrated that increased safety education and training among students were associated with higher levels of awareness, leading to faster evacuation speeds and less time spent locating exits. The modified actual velocity, v_i can be expressed as

$$v_i = v_{\min}(1-c) + c \times v_{\max} \tag{4}$$

which combines the adjusted actual velocity v_i and the level of awareness C. The minimum and maximum evacuation velocity of the crowd are represented as $v_{\min}$ and $v_{\max}$, respectively. It is should be noted that an individual's walking velocity varies depending on their mental state. In a relaxed state, the average walking velocity is approximately 0.6 m/s, which increases to 1.0 m/s in a normal state. Under stressful conditions, individuals typically walk at speeds no greater than1.5 m/s. For the purpose of this research, which aimed to investigate students' behavior during emergency evacuations, a minimum evacuation velocity of 1.0 m/s and a maximum of 1.486 m/s were set for students.

B. Effectiveness Verification of the Improved Social Force Model

In the event of an accident during an experimental university class, students must promptly identify and proceed to the nearest safety exit for evacuation. The evacuation timing begins when the accident occurs and concludes when all students have safely evacuated from the laboratory, signifying the completion of the entire simulation process. The effectiveness of the enhanced social force model was verified by calculating and comparing evacuation times with the original model. Two groups of students were categorized: one group familiar with all exits and the other group only acquainted with commonly used exits. The first group was familiar with the regular exits, specifically exit 1 and exit 4. In contrast, the second group of students had knowledge of both the regular and emergency exits, including exit 1, exit 2, exit 3, and exit 4.

In order to reduce simulation errors, each value of C was simulated ten times and the average value was calculated. The correlation between the evacuation time and the level of awareness among the two student groups was then determined, as depicted in Fig. 5.

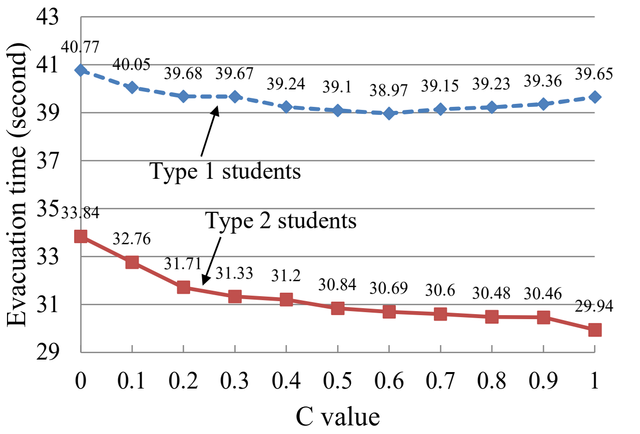

Fig. 5. Correlation between level of awareness and evacuation time among the two types of students

As depicted in Fig. 5, the second group of students, who know all the exits, have a faster and smoother evacuation as their awareness level increases. For example, at C = 0, the evacuation time was 33.84 seconds, while at C = 1, it dropped to 29.94 seconds, a substantial reduction of 3.9 seconds. However, the first group of students exhibited an inflection point in their evacuation time. In the range of C from 0 to 0.6, an elevation in the awareness level leads to a faster evacuation. Surprisingly, at C = 0.6, the evacuation time reached its minimum of 38.97 seconds. However, for C values between 0.6 and 1, the evacuation time rises gradually, following the "fast is slow" evacuation pattern. Specifically, at C = 1, the evacuation time was 39.65 seconds, which was 1.12 seconds shorter than at C = 0. Comparing the evacuation timeline charts between the two groups of students revealed that the awareness level can enhance the effectiveness of the social force model. Furthermore, the students' familiarity with their surroundings helps them evacuate faster evacuation to safe areas during emergencies.

The above results show a correlation between evacuation time and the parameter C in the range of 0 to 0.6.The minimum evacuation time was observed at C = 0.6. This study further investigates the evacuation process for both types of students, with their respective C values set at 0.6. For instance, a sample group consisting of 51 students from a laboratory class was selected. The student population was divided into two types: one represented by a proportion denoted as P, and the other by 1-P. we aimed to obtain accurate results by evacuating different proportions of students and measuring the corresponding evacuation time to ensure accuracy, we conducted ten repetitions of the experiment using the same P-value and calculated the resulting average values. The analysis of the results shown in Fig. 6 shows that as the value of P increases, the evacuation time initially decreases but later begins to increase. Notably, at P = 0.2, indicating that the first type of students accounted for 20% of the total, the evacuation time reached its minimum. Therefore, it can be concluded that effective minimization of evacuation time can be achieved when 80% of the students have received safety education and training.

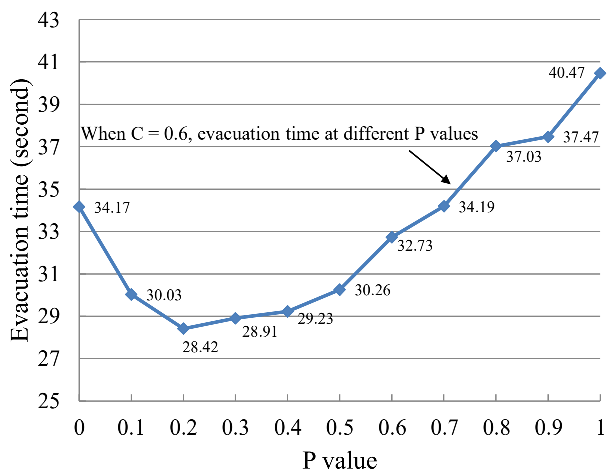

Fig. 6. Evacuation times at different P values

This study presents comprehensive analysis of the reasons behind the phenomenon and compares the number of students evacuated from each exit and the corresponding evacuation time at different probabilities (P = 0 and P = 0.2). To ensure accuracy, the average evacuation time for each probability is calculated by conducting ten repetitions of the experiment. The results are presented in Fig. 7 and Fig. 8. When P = 0, the evacuation process took approximately 32.15 seconds. The majority of students were evacuated through exit 2, which also had the longest evacuation time. In contrast, exits 1 and 4 had the fewest evacuees, with exit 4 showing the earliest flattening of the evacuation time trend in the line chart. However, when P = 0.2, the evacuation time decreased to approximately 27.12 seconds. Upon comparing Fig. 7 and Fig. 8, it can be observed that both the number of students and the time required for evacuation from exit 1 have significantly increased. This increase effectively reduced the evacuation pressure at exit 2, resulting in an overall decrease in evacuation time.

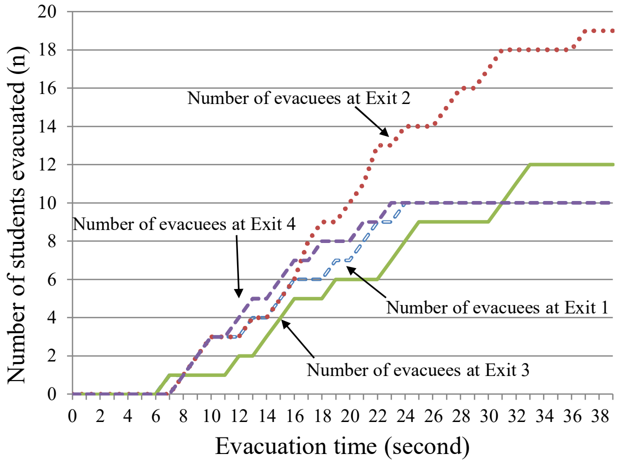

Fig. 7. Statistical graph of evacuated students (P = 0)

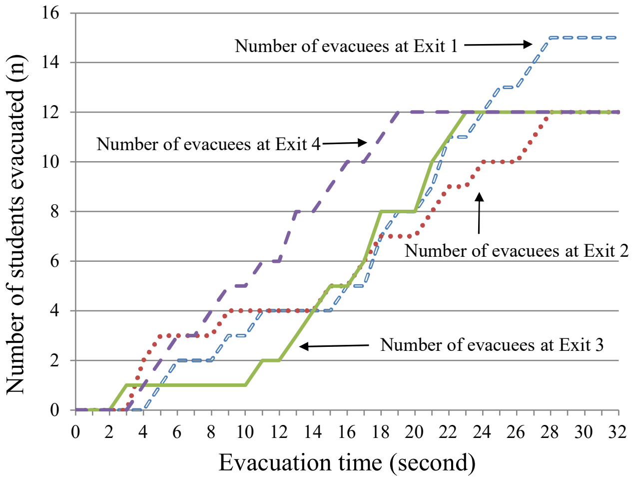

Fig. 8. Statistical graph of evacuated students (P=0.2)

IV. Optimized Solution for Unbalanced Utilization of Exits

During the evacuation process, students frequently experience a heightened state of panic caused by their lack of familiarity with their surroundings. Consequently, their actions become rushed and disoriented, leading to the inability to effectively locate and utilize all available emergency exits. This imbalanced use of exits can have a significant impact on the overall efficiency of the evacuation procedure. Based on this analysis, this paper proposes two potential solutions: repositioning both the inlet and outlet, as well as adjusting the width of the outlet. These suggested measures aim to facilitate a more logical diversion and ultimately reduce the time needed for evacuation.

A. Analysis of Simulated Evacuation with Different Exit Spacing

To assess the influence of exit spacing on student evacuation, this study employs two simulation approaches: centralized placement of emergency exits and an average distribution of all exits, as depicted in Fig. 9 and Fig. 10. To ensure accuracy, the identical spacing was tested ten times to determine the average value. The resulting data include the overall evacuation time and the number of evacuees at each exit for both scenarios.

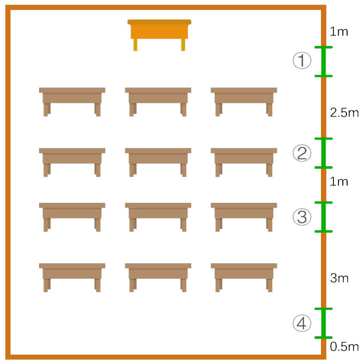

Fig. 9. Centrally distributed emergency exits

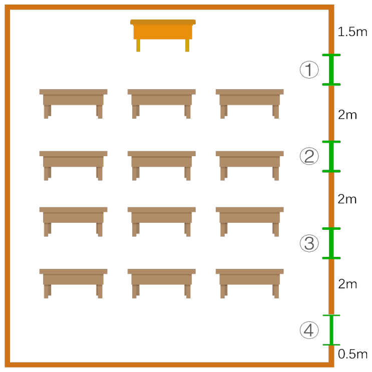

Fig. 10. Evenly distributed all exits

Fig. 11 illustrates the effect of central emergency exits on evacuation dynamics. The results indicate an uneven utilization pattern between common exit 1 and exit 4, as well as between emergency exit 2 and exit 3 when the emergency exits are located in the center. Notably, exit 3 and exit 4 experienced a substantial concentration a high concentration of evacuees, resulting in crowd congestion and a prolonged evacuation time of 32.18 seconds.

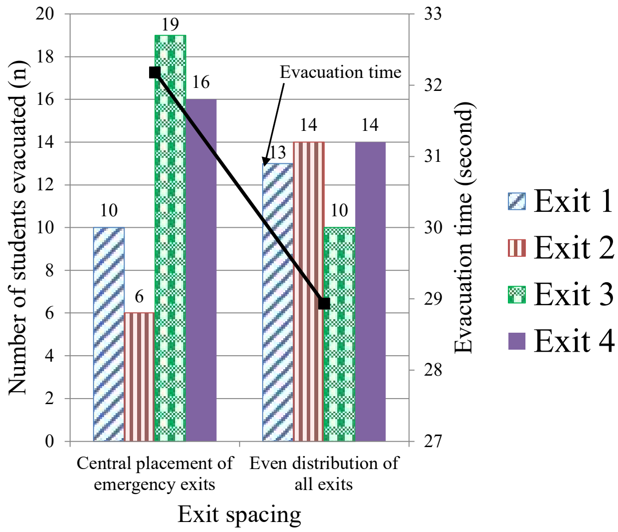

Fig. 11. Number of evacuees and evacuation time at each exit for the two types of exit spacing

Nevertheless, by distributing the exits evenly across the evacuation area, the congestion problem at exit 3 and exit 4 was resolved. This revised arrangement ensured that each exit had a similar level of utilization, leading to a more equitable evacuation process. As a result, the evacuation time decreased significantly to 28.93 seconds.

These findings emphasize the importance of distributing emergency exits properly to enable efficient and secure evacuations. By ensuring balanced utilization, a more effective evacuation process can be achieved, resulting in improved overall safety and reduced evacuation times.

B. Analysis of Simulated Evacuation with Different Exit Width

To examine the impact of exit width on the student evacuation process, this study implemented three simulation scenarios incorporating distinct exit widths: 1 meter, 1.2 meters, and 1.5 meters. To ensure rigorous analysis, we conducted ten iterations of the test for each exit width, calculated the average values, and determined the evacuation time for each scenario. This meticulous approach facilitated a comprehensive analysis of the relationship between the width of the exits and evacuation efficiency.

As depicted in Fig. 12, the evacuation time decreased progressively as the exit width increased. The recorded evacuation times were 28.93 seconds, 24.76 seconds, and 23.01 seconds, respectively, showing a gradual downward trend. Importantly, the number of evacuees at each exit remained relatively consistent throughout the evacuation process.

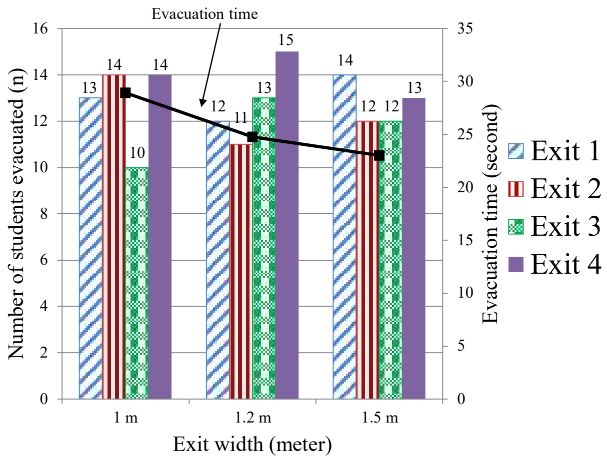

Fig. 12. Number of evacuees and evacuation time at each exit for three exit widths

The comparison of exit widths and exit spacing provides evidence that increasing the appropriate exit width can alleviate crowd congestion and reduce evacuation time. Furthermore, adjusting the spacing between exists allows for a more even distribution of exits, which effectively address the issue of imbalanced exit utilization caused by narrow spacing and concentrated distribution. Achieving an equitable distribution of exits enables individuals, including students, to evacuate through the nearest exit, thus ensuring a balanced distribution of evacuees across all exits and ultimately reducing overall evacuation time. Ensuring the appropriate exit width and spacing is crucial in mitigating the problem of uneven exit utilization.

V. Conclusions

This study presents a comprehensive investigation into an evacuation simulation study carried out at a university laboratory. An improved enhanced social force model is proposed by incorporating a measure of consciousness to enhance the accuracy of pedestrian expected speed. The study has yielded several crucial findings, which are outlined below:

1) The impact of awareness on evacuation time: Research findings demonstrate that enhancing pedestrian awareness significantly reduces evacuation time. There is a clear inverse relationship between awareness and evacuation time. Pedestrians with higher levels of awareness tend to make quick decisions and respond promptly during emergency situations, thereby enhancing the overall speed of evacuation.
2) The influence of unfamiliar students on evacuation time: The study highlights that when the percentage of students unfamiliar with the environment reaches 20% of the total number of evacuated students, the evacuation time is minimized. The results indicate that having unfamiliar students present can improve evacuation efficiency by following familiar students and facilitating a quicker evacuation process.
3) Optimization of exit width and position: Proper adjustment of exit width and allocation of exit positions are crucial. This approach ensures a balanced distribution of evacuees across exits, resulting in enhanced evacuation efficiency. Optimization of both exit width and position helps prevent congestion, facilitating a smoother evacuation process.

Although this study has produced valuable findings in the field of indoor multi-exit emergency evacuation, it has limitations. For example, the experiment did not consider factors, such as panic emotions and spontaneous grouping that may arise during the evacuation process, which could potentially affect the actual evacuation outcomes. Therefore, future research should thoroughly examine more realistic scenarios, including the impact of emotional contagion on the evacuation process. Furthermore, we plan to conduct research on larger-scale emergency evacuations on a larger scale, such as those involving multiple floors or buildings.

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