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An Investigation of Frame-Core Tube Building Construction Sites on Safety Evacuation

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Abstract: FTBCS safety evacuation of frame-core tube buildings on construction sites (FTBCS) is one of the most challenging evacuation scenarios conceivable. This investigation proposes a practical calculation method and examines the parameters' influence on safety evacuation in frame-core tube building construction sites. Firstly, the characteristics of constructors from 30 FTBCS in China are analyzed. After an investigation of 23,230 constructors, it was found that constructors have unique properties in gender ratio, age composition, and occupational age. Female constructors account for about 10%, and aged constructors account for 0.28%. Constructors within five years of occupational age account for about 26.39%. Evacuation speeds on different working faces including frames and core tubes are tested, and the decline coefficients of 0.80 and 0.70 are taken consideration into the evacuation model. Then, an exclusive evacuation time algorithm that is appropriate for FTBCS is proposed. Multiple parameters' influence on safety evacuation is researched by numerical simulation. With a 5.0% growth of female gender ratio, aged constructors, and constructors within five years of occupational age, the average movement distance is increased by 10.32 m, 0.67 m, and 11.19 m, respectively. The age composition ratio and occupational age ratio mainly affect the evacuation process by evacuation speed and path programming, respectively, and the leading influencing factors are not distinct in their gender ratio effects. Optimization of construction layout can reduce the evacuation time from the horizontal direction plane effectively, and then relieve clustering and crowding on platforms.

Keywords: frame-core tube building construction site (FTBCS); characteristics of constructors; safety evacuation; evacuation time; VR test

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1. Introduction

Building construction is an important part of the construction industry, with an overall effect on the national economy, and whose influence cannot be ignored.

A frame core-tube structure is a typical high-rise building structure with a widespread application because of its satisfactory performance in stability [1]. Building construction sites have many properties different from the completed building [2,3]. The location of the safety evacuation is becoming more and more extensive and detailed [4–11]. Construction control and management is an important part of construction management [12–14], and all projects should be given enough attention. Programming the safety evacuation on a construction site is a mandatory national regulation in China [15,16]. The construction duration of most frame-core tube buildings is longer than 24 months, and the probability of encountering emergency circumstances is also increased with the growth of construction duration [17]. From Figure 1, it can be seen that the frame-core tube building has a large work quantity. All of the construction equipment, including the instruments and storage yard are placed in FTBCS, and hence the working face area is reduced. Evacuation paths for constructors become complicated with confined spaces. FTBCS transforms with progress schedule, and this will reduce constructors' familiarity with the environment.



Figure 1. Frame-core tube building in construction.

It has been found that velocity-step width, velocity-step length, velocity-stepping time, and the relationship between the step length and step frequency for different groups have considerable differences and are affected by evacuee gender, age, height, and state of health [9,10,18]. Children [19], aged people [20], disabled people, and patients [21–23] are studied on the classification to identify the factors that inhibit the implementation of safety evacuation in each group. Evacuee behaviors show great differences under the influence of personality, age, gender, and other factors inhibiting the implementation of safety evacuations. A safety evacuation has a trend of delicacy management. The construction industry suffers the largest number of deaths [24–28]. There are hundreds of constructors losing their lives annually due to injuries and fatalities on the working face. To minimize the high number of constructors' injuries and fatalities, numerous practices that range from behavioral to engineering safety approaches have been implemented in construction over the last few decades. High-risk factors in construction sites and optimal construction layout for evacuating are becoming emerging trends [29–31]. Constructors are a special group with a high-risk occupation, and their characteristics affecting a safety evacuation are worth studying in detail to improve safety performance in the construction industry.

With a rapid increasing in quantity and construction duration, a safety evacuation of FTBCS is important to improve safety performance in the construction industry. In this research, the authors place emphasis on the special characteristics in FTBCS and the particularity of the constructors. A methodology diagram is shown in Figure 2. Firstly, the characteristics of constructors are collected, analyzed, and summarized by survey research, including gender ratio, age composition, and occupational age. Evacuation speeds on different working faces are tested by VR equipment and the BIM model, and reduction coefficients on different working faces are given. Secondly, an exclusive evacuation time algorithm is proposed, and the proposed algorithm of evacuation time study is concerned with the particular FTBCS. Then, a visual numerical analysis evacuation modal with different working faces is built based on the Pathfinder platform. Finally, the safety evacuation process of FTBCS is analyzed, and multiple parameters' influence on safety evacuations are researched, including gender ratio, age composition, occupational age, working face, and construction layout.

In the investigation of multiple parameters' influence, the first is the creation of a safety evacuation model in Pathfinder with the characteristics of constructors and the exclusive evacuation time algorithm. The second is the implementation of the evacuation process with representative scenarios, residence constructor variation in key locations, evacuation time, and average distance of movement. Multiple parameters' influence on safety evacuation are researched, including gender ratio, age composition, occupational age, working face, construction layout, and then reason and degree of influence on safety evacuation are calculated and summarized.

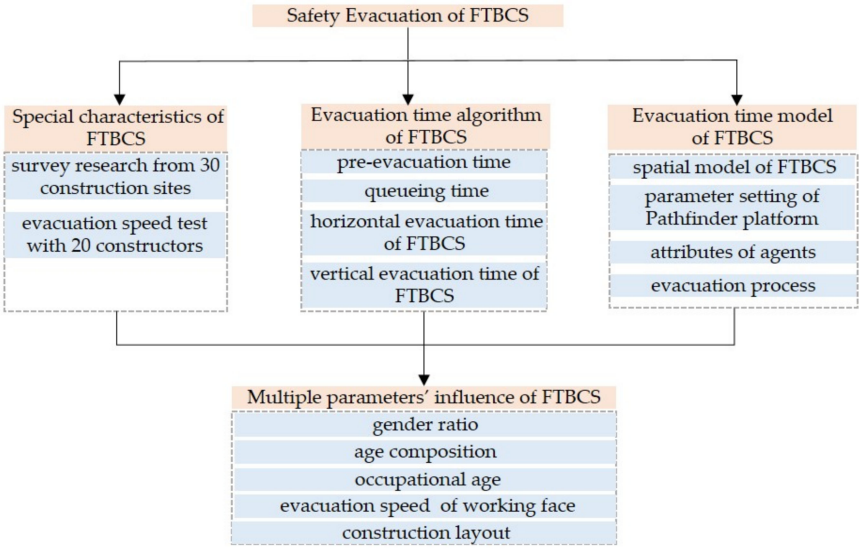
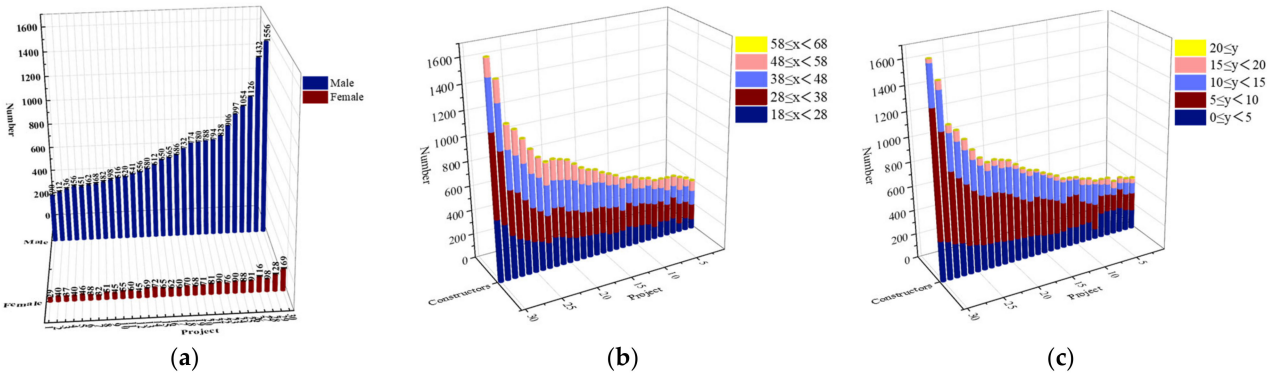


Figure 2. Methodology diagram.

2. Survey Research of Construction Site

According to the investigation of the critical factors affecting evacuation performance [32–35], the efficiency of evacuation performance depends not only on the physical characteristics of the buildings, but also on the pedestrian characteristics in an emergency situation. Data collection techniques can influence the validity and reliability of the research, and constructors' data are obtained by departments of project management from thirty frame-core tube buildings with 23,230 constructors in China. The construction site implements the constructors' real name access control system; thus, the information related to the constructors' gender, age, occupational age, and profession are recorded and collected by the department of project management. Results of survey research from thirty construction sites including constructors' gender, age composition, and occupational age are given in Figure 3.



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

Figure 3. Results of survey research from 30 FTBCS in China. (**a**) Gender of constructors; (**b**) age composition of constructors; (**c**) occupational age of constructors.

The deep influencing factors, which are factors that should be paid more attention in order to decrease the delay in the pre-evacuation time, include age, gender, education level, and actions at the recognition and response stage [36–38]. Pedestrian behaviors also show great heterogeneity under the influence of personality, age, gender, and other factors. From Figure 3a, it can be detected that the number of male constructors is considerably higher than the number of female constructors in FTBCS. According to the comprehensive calculation, the male and female ratio of constructors in the surveyed construction site is 10.23:1, and hence it can be roughly estimated that the male ratio of constructors in the

construction site is taken as 90.0% in the following computational model. From Figure 3b, it can be calculated that constructors aged between 18~28 years old, 28~38 years old, 38~48 years old, 48~58 years old, and 58~68 years old account for 26.39%, 31.62%, 26.86%, 14.84%, and 0.28% respectively. It could be detected that constructors are mainly younger adults and middle-aged on account of the physical labor with strong intensity in the construction industry. People over 60 years old are taken as aged in the simulation. The percent is too small, and hence the aged in the computational model is insignificant. From Figure 3c, it can be calculated that the occupational age of constructors between 0~5 years old, 5~10 years old, 10~15 years old, and 15~20 years old account for 25.46%, 44.81%, 24.20%, 5.34%, and 0.19% of the total, respectively. Actions and choices to a certain extent are affected by occupational age relating to familiarity with FTBCS. Occupational age is reflected by the familiarity with exits and obstacles in the following computational model. Different evacuation measures should be seriously taken according to pedestrian characteristics in order to increase the success rate of occupant evacuation. By analyzing the results of survey research from 30 FTBCS in China, it was found that the pedestrian characteristics are considerably different from other evacuation environments, including residential buildings, hotels, schools, hospitals, commercial buildings, stations, and tunnels. Therefore, pedestrian characteristics should be paid more attention to in order to speed up evacuation.

The evacuation speed of constructors is directly affected by the working faces with an emergency situation in the construction site [12,26,29]. VR equipment and the BIM model are considered valuable in most safety evacuation studies with easier alternatives to experiments [8,22,29,30,39–43], and the author has confirmed that experiments with VR equipment and the BIM model are reasonable proxies of the evacuee's performance under emergency scenarios in the existing research [41]. The evacuation speed of constructors is tested by VR equipment and the frame-core tube building BIM model with twenty constructors, and the test is shown in Figure 4. The evacuation of the constructor starts with an alarm bell, and evacuation distance and evacuation time are recorded and calculated. Constructors are tested in three different scenarios, including a core tube working face, frame working face, and the completed floor, and the scenarios of core tube and frame working faces are also shown in Figure 4.

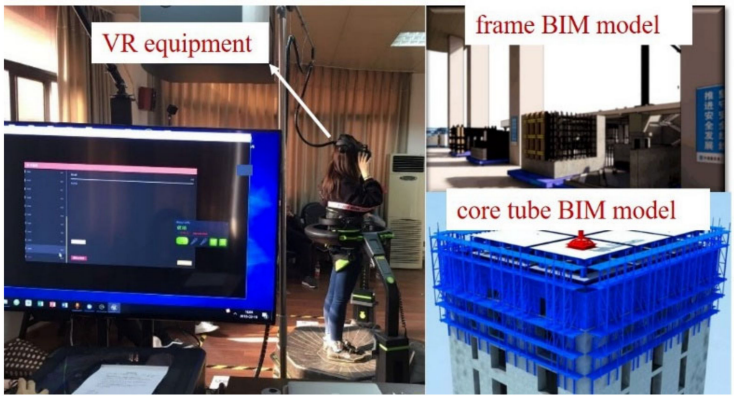


Figure 4. Evacuation speed test with VR equipment and BIM model.

It has been demonstrated that feelings, emotions, social influence, and cognition are all factors influencing the evacuation speed [35,37,39]. There is some difference between an emergency situation and the test of feelings, emotions, social influence, and cognition. The evacuation speed of the constructor is affected by the working face, which can be summarized from the results in Table 1. Evacuation speed in the core tube is the slowest, and evacuation speed on the floor is the fastest. As the sample number of the constructors is not sufficient, a reduction coefficient is introduced to obtain the evacuation speed in different working faces. The average value evacuation speed in the completed floor, frame, and core tube working faces are 1.654 m/s, 1.363 m/s, and 1.217 m/s, respectively, with

reduction coefficients of 0.824 and 0.735. As the consideration of feelings and emotions of the constructors is relatively relaxed, evacuation speed in the test exceeds the actual situation. As a consequence, the reduction coefficient is taken as 0.80 and 0.70 in the following Pathfinder model.

Table 1. Results of evacuation speed in different working faces.

Constructor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Floor (m/s)	1.65	1.78	1.95	1.55	1.45	1.56	1.77	1.89	1.59	1.54
Frame (m/s)	1.52	1.53	1.6	1.33	1.22	1.25	1.5	1.53	1.31	1.23
Core tube (m/s)	1.33	1.25	1.38	1.25	1.19	1.21	1.25	1.34	1.19	1.22
Constructor	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Floor (m/s)	1.6	1.72	1.59	1.61	1.57	1.62	1.43	1.84	1.72	1.65
Frame (m/s)	1.29	1.38	1.28	1.29	1.26	1.31	1.21	1.48	1.38	1.35
Core tube (m/s)	1.13	1.23	1.16	1.14	1.08	1.18	1.12	1.32	1.11	1.26

3. Establishment of Exclusive Evacuation Modal

The safety evacuation model for constructors mainly contains three parts, including constructors' evacuation of working in a core tube, constructors' evacuation of the external frame, and evacuation of the core tube stairwell.

3.1. Evacuation Time of Constructors in the m Floor of Core Tube

According to the design of FTBCS, there are generally two entrances to the stairwell in the core tube, with only one in the unilateral case, and the entrance and its surrounding area belong to the dangerous area. In order to avoid crowding and congestion in evacuations, the evacuation strategy is set as the single row of constructors passing through after the constructors receive the evacuation warning. The evacuation time required for any construction area personnel to completely evacuate the construction area (the last person to enter the stairwell) is shown in Equation (1) as pre-evacuation time, queueing time, horizontal evacuation time on the working face, and vertical evacuation time of the frame-core tube building.

$$T_m = \max[t_{i,m}] = \max\left[t_{i,m}^{p} + t_{i,m}^{s} + t_{i,m}^{q} + t_{i,m}^{v}\right] \tag{1}$$

$$t_{i,m}^{s} = \frac{D_{j,m}\, L_{i,m}}{v_{i,ms}} \tag{2}$$

$$t_{i,m}^{v} = \frac{d_m}{n_m v_{i,md}} \tag{3}$$

T_m is evacuation time of all constructors on the m floor. $t_{i,m}^{p}$ is the pre-evacuation time of the constructor. $t_{i,m}^{q}$ is queueing time of the constructor. $t_{i,m}^{s}$ is the horizontal evacuation time on working face. $t_{i,m}^{v}$ is the vertical evacuation time of the constructor walking down the stairs. $D_{j,m}$ is the delay factor on the working face, j is the number of working faces, and m is the number of floors. n is the number of evacuation queues when the constructor walks down the stairs. $v_{i,m}$s, and $v_{i,md}$ are the walking velocity of the i constructor in the horizontal and vertical distances. d_m is the stair length in each floor. $L_{i,m}$ is the horizontal distance of the i constructor on the m floor from the working face to the stairwell. When there are a large number of constructors on the working face, two teams of evacuated constructors on both sides of the entrance may meet at the exit. Δt is the time increment in the safety evacuation. Δt_n is the n'th the time increment. $f_{(m,out)}$ is the outflow rate in the stair exit. $f_{(m,in)}$ is the inflow rate in the stair exit. The free flow time t_0 is Δt_λ. There are two statuses

of constructors in the stair exit, including evacuation without queuing and evacuation with queuing. The outflow rate in the stair exit can be expressed in Equation (4).

$$f_{(m,out)}(\Delta t_n) = \begin{cases} K\rho(\Delta t_n), \ \Delta t_n > \Delta t_\lambda \\ = 0, \ \Delta t_n \leq \Delta t_\lambda \end{cases} \tag{4}$$

$\rho(\Delta t_n)$ is the arrival rate of constructors in the n'th the time increment. K is the service rate, and the principle of FIFO (first input first output) is taken. According to the pedestrian flow conservation law in safety evacuations, the accumulated constructor inflow is equal to the accumulated constructor outflow. Hence, the variation rate of queuing length can be expressed in Equation (5).

$$q(\Delta t_{n+1}) = q(\Delta t_n) - f_{(m,out)}(\Delta t_n) + f_{(m,in)}(\Delta t_{n-\lambda}) \tag{5}$$

$q(\Delta t_n)$ is variation rate of queuing length in the n'th the time increment. The variation rate of queuing length of the constructor can be expressed in Equation (6).

$$q(\Delta t_{n+1}) = \begin{cases} 0, \ n \in (0, \ \lambda) \\ -K\left(\partial^{-1}(q(\Delta t_n))\right) + \rho(\Delta t_{n-\lambda}), \ n > \lambda \end{cases} \tag{6}$$

When there is no queuing, $q(\Delta t_n)$ is equal to 0, and q the can be given in Equation (7), and then Equation (8) can be derived.

$$q = \partial(\rho) \tag{7}$$

$$\rho = \partial^{-1}(q) \tag{8}$$

When the initial queuing length is 0, $q(\Delta t_\lambda)$ is equal to 0. Equations (9) and (10) can be derived.

$$f_{out}(\Delta t_n) = K\rho(\Delta t_n), \ n > \lambda \tag{9}$$

$$\tau(\Delta t_n) = \Delta t_\lambda + K\rho(\Delta t_n)^{-1} q(\Delta t_{n+\lambda}) n \in (0, \mathrm{N} - \lambda) \tag{10}$$

Queuing time of constructors can be given in Equation (11).

$$t^q_{i,m} = \tau(\Delta t_n) = \Delta t_\lambda + K\rho(\Delta t_n)^{-1} q(\Delta t_{n+\lambda}) \tag{11}$$

3.2. Evacuation Time of Constructors in the (m − k) Floor of Frame

Both evacuation time of constructors in the working face ((*m − k)* floor of frame) and upper working face ((*m – k − 1)* floor) are taken into consideration. Evacuation time in the (*m − k)* floor can be expressed in Equations (12)–(15).

$$T_{m-k} = \max[t_{i,m-k}] = \max\left[t^p_{i,m-k} + t^s_{i,m-k} + t^q_{i,m-k} + t^v_{i,m-k}\right] \ m > k \tag{12}$$

$$t^s_{i,m-k} = \frac{L_{i,m-k}}{v_{i,(m-k)s\prime}} \tag{13}$$

$$t^v_{i,m} = \frac{d_{m-k}}{n_m v_{i,md\prime}} \tag{14}$$

$$t^q_{i,m-k} = \tau(\Delta t_n) = \Delta t_\lambda + K\rho(\Delta t_n)^{-1} q(\Delta t_{n+\lambda}) \tag{15}$$

Evacuation time for all constructors in the frame-core tube building can be expressed in Equation (16).

$$T = \max[T_m, T_{m-k}] \tag{16}$$

4. Numerical Simulation and Model Validation

The Pathfinder platform is widely used in evacuation simulation on account of its flexible properties' setting according to the emergency situation [44–54]. SFPE (Society of fire protection engineers) mode and Steering model are the main movement modes in Pathfinder. Pathfinder is an agent-based evacuation platform with continuous physical space. Individuals in the Pathfinder have various attribute settings to approximate reality, which is propitious to reflect the characteristics of the constructors. In accordance with different scenarios, Pathfinder can provide the possibility of modeling the exact architecture space with details of dimensions and proportions, which is propitious to reflect the particular characteristics of FTBCS.

4.1. Spatial Modeling

The frame-core tube building of Xishan Wanda Plaza in B-domain is taken as the engineering background in this research. The construction duration is 875 days. According to the construction schedule, the construction progress of the core tube is five floors faster than that of the outer frame. The working face of the frame is set as a reference level with 0.0 m. The stair width is 1.2 m and the working face of the core tube is 2.5 m in width and 27.0 m in length. The core tube building has an area of approximately 484 m^2, with two stairs. The lengths of the corridors to stairs are 10.5 m and 3.0 m, respectively. The frame building has an area of approximately 2356 m^2, with two stairs. The FTBCS with fifteen standard layers is built according to the drawing. The spatial model of FTBCS and key dimensional parameters are shown in Figure 5.

The walking speed is influenced by the working face of the constructors, and hence the working faces are distinguished and marked with different colors, and are shown in Figure 5. The concrete and climbing frame working faces of the core tube building are represented by gray and red, respectively. The working face of the frame building is represented by orange and the completion areas are represented by purple. There are three floors of core tube working faces and one-floor working face building in construction, and obstacles are displayed on both the core tube building and the frame building. The constructors are arranged on the working faces of the building.

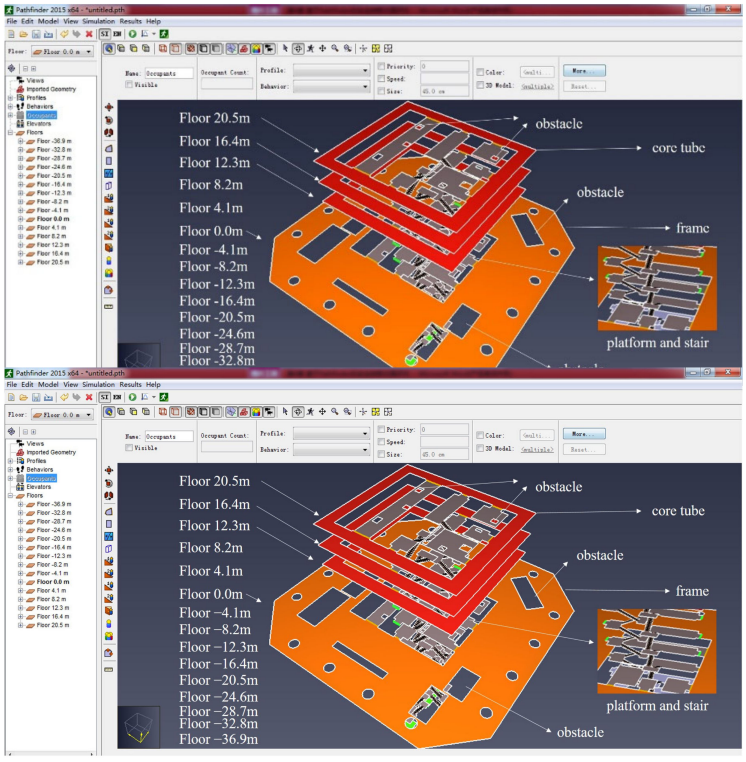


Figure 5. FTBCS model in Pathfinder.

4.2. Parameter Setting

The value of the comprehensive evacuation time of constructors is obtained by Formula (16). Agent is a mobile robot that can be adapted to heterogeneous environments and can be defined by an inputting parameter. The Pathfinder software is an agent-based egress simulator. It uses a combination of steering behaviors and physical constraints to simulate large-scale occupant behavior and evacuation times based on the movement of individual occupants or agents. The software will automatically adjust and calculate the instantaneous speed corresponding to evacuation space density and the position of the agents. Results of survey research from thirty frame-core tube buildings with 23,230 constructors are applied in setting agent attributes and behavioral characteristics in Pathfinder, including ratio and range of age, gender ratio, reaction time, and walking speed in different working faces. The reaction time of the agent is relevant to the occupational age of the constructors. Attributes of agents set in Pathfinder are shown in Table 2. The parameter classification in reference [55] is applied as a similar classification of agents. The floor walking speeds of the agents are the reference of walking speeds in different working faces used in the evacuation model, with the reduction coefficients in Section 2 taken into consideration.

Table 2. Attributes of agents [55].

Agent Type	Shoulder Width (m)	Body Thickness (m)	Height (m)	Transfer Passage (m/s)	Stairs Down (m/s)	Stairs Up (m/s)	Platform (m/s)	Floor (m/s)	Working Face(m/s)	
									Frame	Core Tube
Male	0.5	0.26	1.75	1.39	0.95	0.75	1.56	1.58	1.26	1.11
Female	0.44	0.27	1.65	1.22	0.83	0.66	1.41	1.43	1.14	1.00
Aged	0.45	0.3	1.6	1.06	0.4	0.52	1.15	1.17	0.94	0.82

4.3. Evacuation Process in Construction

Constructors are informed of the emergency situation by an alarm bell in the construction site, and all constructors receive the warning at the same time, without considering the delay of warning. The damage of FTBCS, the influence of visibility, and the influence of construction machinery collapse are not taken into consideration. The evacuation process of FTBCS is shown in Figure 6, including the pre-evacuation period and evacuation period.

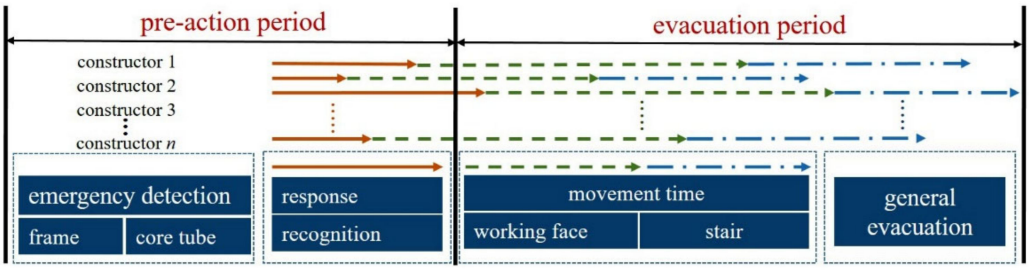


Figure 6. Evacuation process of FTBCS.

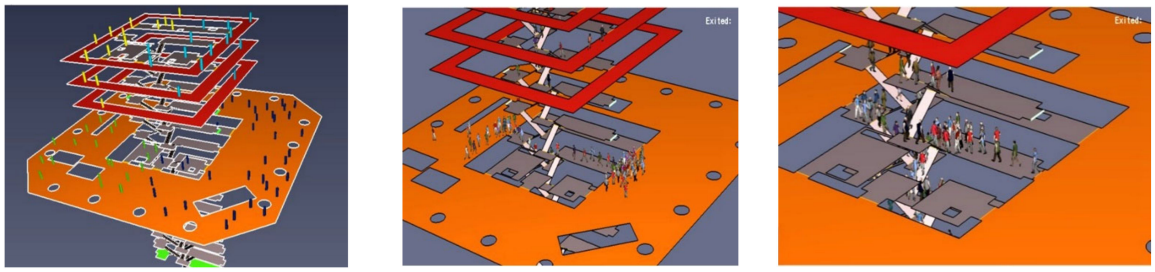
Constructors working in the frame and core tube receive the warning at the same time. The time of response and recognition is represented by the orange arrow, and it depends on the gender, age, and occupation age setting in the attributes of agents. The movement time is represented by the green and blue arrows, and it depends on the attributes of agents, number of constructors, and the working face of the constructors. The horizontal evacuation time is represented by the green arrow, and the vertical evacuation time is represented by the blue arrow. There is no damage and collapse until the last constructor evacuates the frame working face, and the evacuation time in Section 5 includes the pre-evacuation and evacuation periods.

5. Analysis of Different Parameters

In order to find the parameters' influence on the safe evacuation of FTBCS, different agent parameters are given in the Pathfinder model. The number of constructors is 150, with 30 constructors on the core tube working face and 120 constructors on the frame working face. The gender ratio of constructors in the survey research is 90%:10%, the variable delta is taken as 5.0% and five working conditions are given to find the gender ratio's influence on safety evacuation. The age composition of constructors in the survey research proves that the aged could be neglected, as the proportion is 0.28%. In order to find the age composition's influence on safety evacuations, the variable delta of aged constructors is taken as 5.0% in male constructors and five working conditions are given. Constructors with work experience of more than five years are taken as specialized workers. Occupational age is relevant to the strategy, and specialized workers are likely to choose the nearest exit rather than environment pathfinding, and the percentage is 75%:25% in the survey research. The influence of working face speed is reflected by evacuation speed in the floor, frame, and core tube. Evacuation speeds of the frame and core tube working faces are taken as the same as the floor evacuation speed in order to find the influence. In order to find the parameters' influence on safety evacuation, the working condition closest to reality is analyzed, and the constructor parameters are given in Table 3. The evacuation process of constructors in Pathfinder is shown in Figure 7, and the variations of constructor numbers on different platforms in evacuation are given in Figure 8.

Table 3. Constructor parameters in analysis of construction layout's influence.

Agent Property	Category	Proportion
Gender	Male and female	90%:10%
Size and speed	Male, female parameters in Table 2	90%:10%
Strategy	Nearest exit, environment pathfinding	75.0%, 25.0%
Pre-action time	Open	Uniform distribution [0 s, 120 s]



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

Figure 7. Evacuation process of constructors in Pathfinder. (**a**) distribution of constructor; (**b**) the arched pedestrian flow; (**c**) the last constructor enters into platform.

Three representative scenarios in the evacuation process of constructors in Pathfinder could be seen from Figure 7. The distribution of the constructors is given in Figure 8, with 26, 4, and 2 constructors on core tube working faces (Floor 20.5 m, Floor 16.4 m, and Floor 12.3 m), and 118 constructors on the frame working face (Floor 0.0 m). The phenomenon of clustering and crowding appears on the stairs on the platform in the frame working face about 60.0 s after the evacuation, and this phenomenon on the left side of the building is more serious than on the right side. This phenomenon does not exist in the core tube working face, and FPC and SPC in Figure 8 also can reflect this phenomenon. The first constructors arrive at FPC and SPC on 39.0 s and 36.0 s, and then the maximal residence constructor on FPC and SPC is two constructors. It has been found that there are bottlenecks of evacuation on both sides of the platform to the stairs. There is no evacuation bottleneck on the working faces under the situation mentioned. Constructors line up around platforms

to the stairs, and an arched pedestrian flow is formed when a certain amount of constructors arrives at evacuation exits in the frame working face, and this phenomenon is shown in Figure 7b. When constructors hear the alarm bell, they flood to evacuation exits after the pre-action time. Evacuation exits on a frame working face are too narrow for all constructors' to evacuate immediately and, hence, the crowd retention phenomenon comes into being. Crowd density at the evacuation exit is increased by the crowd retention phenomenon gradually, and FPF and SPF in Figure 8 can reflect this phenomenon. When the crowd density reaches a certain equilibrium value, an arched pedestrian flow structure will be formed, which is closed to the outside. Maximal residence constructors on FPF and SPF are 35 constructors and 18 constructors. At this moment, the constructor cannot pass through the evacuation exit from the arched pedestrian flow. The arched pedestrian flow gradually fades away with the evacuation process. The phenomenon of clustering and crowding appears on the platform, continuing to the end, and this phenomenon is shown in Figure 7c. From the evacuation process of constructors in Pathfinder, it also can be assumed that FPF and SPF are the key platforms that should be paid attention to.

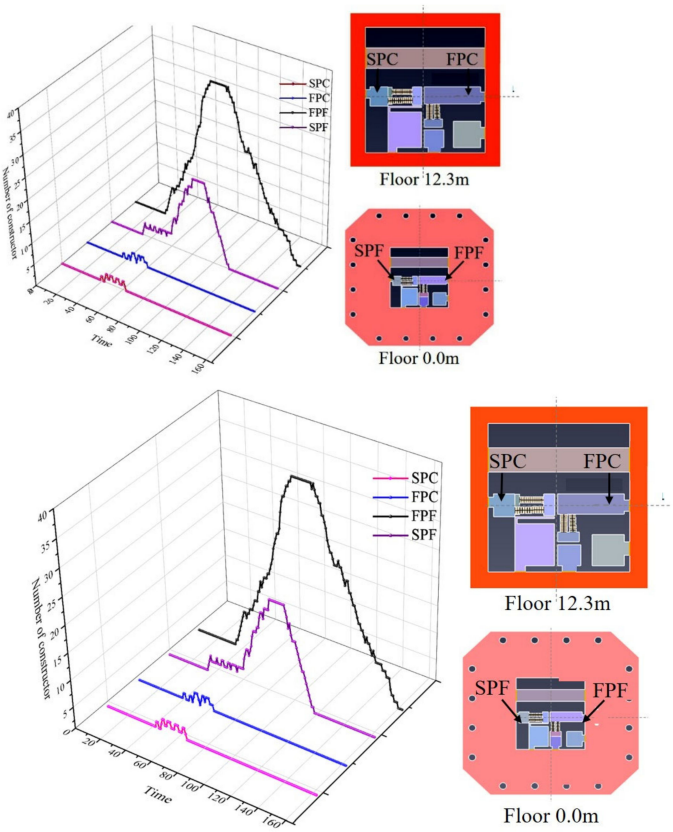


Figure 8. Number of the constructor on different platforms in evacuation. FPF (first platform of frame working face), SPF (second platform of frame working face), FPC (first platform of core tube working face), and SPC (second platform of core tube working face).

5.1. Gender Ratio

The gender ratio of constructors has a particular characteristic wherein the male constructor accounts for up to 90%. While this particular characteristic is not be studied in the existing research, in order to find the gender ratio's influence on safety evacuations, five working conditions are analyzed by taking the gender ratio as a variable; the constructor parameters are given in Table 4. The evacuation process of constructors is shown in Figure 9, and the number of constructors that remain in the frame-core tube building.

Evacuation times are 100%:0%, 95%:15%, 90%:10%, 85%:15%, and 80%:20% gender ratios are 198.7 s, 218.3 s, 271.5 s, 313.8 s, and 331.9 s. With a 5.0% growth of female gender

ratio, the evacuation time is delayed 33.3 s on average, and the standard deviation is 14.96. The average distances of movement of 100%:0%, 95%:15%, 90%:10%, 85%:15%, and 80%:20% gender ratio are 66.56 m, 71.83 m, 86.52 m, 96.17 m, and 107.83 m, respectively. With a 5.0% growth of the female gender ratio, the average distance of movement is increased by 10.32 m with a 3.42 standard deviation, and the evacuation time will be exaggerated without considering the gender ratio in the construction site. The evacuation time of the last fifteen constructors has a great change in the different five working conditions, and it increases with the growth of the female gender ratio.

Table 4. Constructor parameters in analysis of gender ratio's influence.

Agent Property	Category	Proportion
Gender ratio	Male and female	100%:0%, 95%:15%, 90%:10%, 85%:15%, 80%:20%
Size and speed	Male and female parameters in Table 2	100%:0%, 95%:15%, 90%:10%, 85%:15%, 80%:20%
Strategy	Nearest exit, environment pathfinding	75.0%, 25.0%
Pre-action time	Open	Uniform distribution [0 s, 120 s]

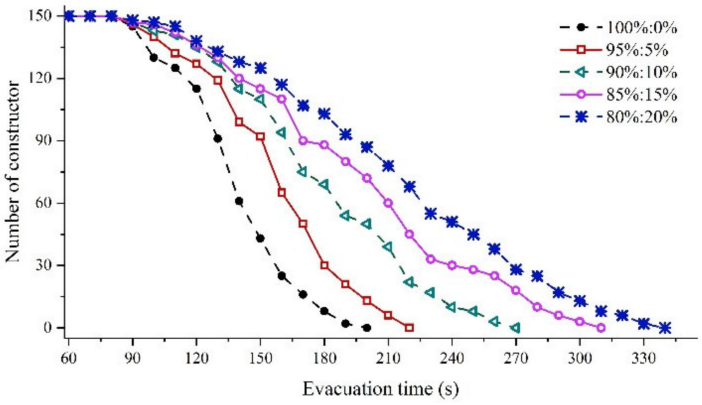


Figure 9. Evacuation process of constructors with different gender ratios.

5.2. Age Composition

According to the survey research, the aged could be neglected, representing only a 0.28% proportion of the constructors. The male constructor takes the principal percentage with 90%, and hence the variation of the age can be taken as the variation of the male constructor. In order to find the age composition's influence on safety evacuations, five working conditions are analyzed by taking the age composition ratio as a variable, and the constructor parameters are given in Table 5. The female constructor takes 10.0% in all five conditions. The evacuation process of constructors is shown in Figure 10.

Table 5. Constructor parameters in analysis of age composition's influence.

Agent Property	Category	Proportion
Gender ratio	Male and female	90%:10%
Size and speed	Male and aged parameters in Table 2	90%:0%, 85%:5%, 80%:10%, 75%:15%, 70%:20%
Strategy	Nearest exit, environment pathfinding	75.0%, 25.0%
Pre-action time	Open	Uniform distribution [0 s, 120 s]

Evacuation times are 90%:0%, 85%:5%, 80%:10%, 75%:15%, and 70%:20%, and age composition ratios are 271.5 s, 323.8 s, 347.6 s, 365.4 s, and 382.2 s. A low portion of the aged in the construction site is conducive to decrease the delay in the evacuation. With a 5.0% growth of aged constructors, the evacuation time is delayed 27.68 s on average, and the standard deviation is 14.46. The average distances of movement of 90%:0%, 85%:5%, 80%:10%, 75%:15%, and 70%:20% age composition ratio are 86.52 m, 87.75 m, 88.33 m,

88.78 m, and 89.23 m, respectively. With a 5.0% growth of aged constructors, the average distances of movement are increased by 0.67 m on average, and the standard deviation is 0.32. It is found that the average distance of movement has a small change with the age composition ratio. It can be speculated that there is not much evacuation time wasted pathfinding with the aged increasing.

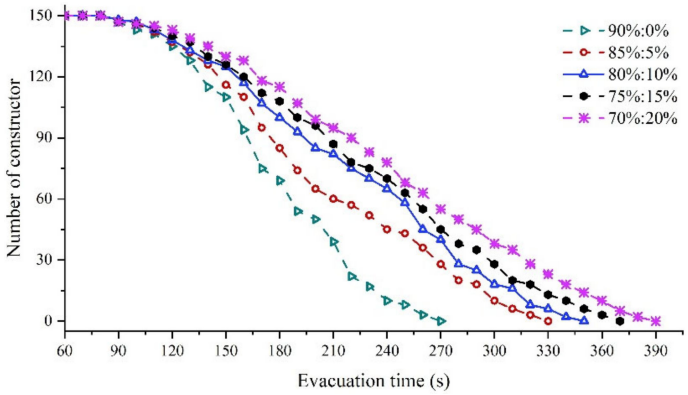


Figure 10. Evacuation process of constructors with different age composition ratios.

5.3. Occupational Age

In order to find the occupational age's influence on safety evacuations, strategy choices with different percentages are taken as the variation, and the constructor parameters are given in Table 6. The evacuation process of constructors is shown in Figure 11.

Table 6. Constructor parameters in analysis of occupational age's influence.

Agent Property	Category	Proportion
Gender ratio	Male and female	90%:10%
Size and speed	Male, female parameters in Table 2	90%:10%
Strategy	Nearest exit, environment pathfinding	65.0%:35.0%, 70.0%:30.0%, 75.0%:25.0%, 80.0%:20.0%, 85.0%:15.0%
Pre-action time	Open	Uniform distribution [0 s, 120 s]

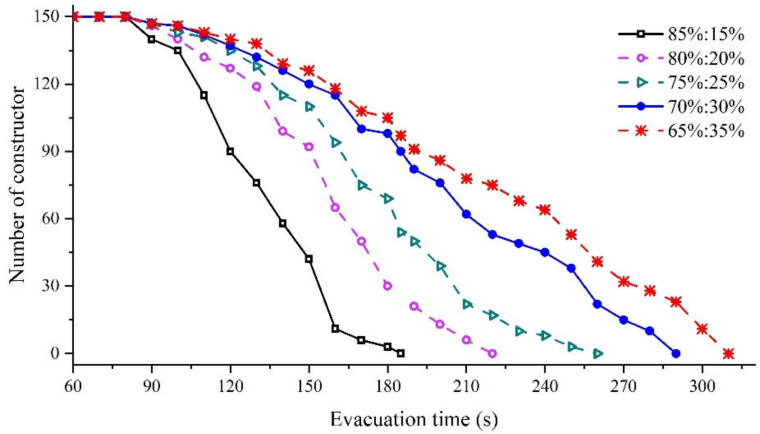


Figure 11. Evacuation process of constructors with different occupational age ratios.

Evacuation times are 90%:0%, 85%:5%, 80%:10%, 75%:15%, and 70%:20%, and occupational age ratios are 184.6 s, 211.3 s, 271.5 s, 289.9 s, and 309.2 s. With a 5.0% growth of constructors within five years of occupational age, evacuation time is delayed 32.63 s on average, and the standard deviation is 17.1. Average distances of movement of 85%:15%, 80%:20%, 75%:25%, 70%:30%, and 65%:35% of occupational age ratios are 55.13 m, 71.67 m, 86.52 m 91.79 m, and 99.87 m, respectively. With a 5.0% growth of increasing of constructors

within five years of occupational age, average distances of movement are increased by 11.19 m on average, and the standard deviation is 4.66. With the identical percentage change of gender ratio, age composition ratio, and occupational age ratio, influences on evacuation time and average distances of the movement have visible differences. The age composition ratio mainly affects the evacuation process by evacuation speed. The occupational age ratio mainly affects the evacuation process by path programming, and the leading influencing factors are not distinct in the gender ratio effect.

With a 5.0% growth of the female gender ratio, aged constructors and constructors within five years of occupational age, the average evacuation time is increased by 33.3 s, 27.675 s, and 31.15 s; hence the change ratio of evacuation time is 12.27%, 10.19%, and 11.47%, respectively. The gender sensitivity coefficient, aged constructor sensitivity coefficient, and occupational age sensitivity coefficient on evacuation time are 2.454, 2.038, and 2.294. With a 5.0% growth of female gender ratio, aged constructor sand constructors within five years of occupational age, the average movement distance is increased by 10.32 m, 0.67 m, and 11.19 m, respectively; hence, the change ratio of movement distance is 11.9%, 0.77%, and 12.93%. The gender sensitivity coefficient, aged constructor sensitivity coefficient, and occupational age sensitivity coefficient on movement distance are 2.38, 0.154 and 2.586, respectively. It can be seen that the sensitivity order of evacuation time is gender, occupational age, and aged constructor, and the sensitivity order of movement distance is occupational age, gender, and aged constructors.

5.4. Working Face Speed

The evacuation speed is distinguished by gender and age in the agent property and distinguished by location in the spatial model, including transfer passage, stairs up and down, floor, frame, and core tube working face. Evacuation speeds in frame and core tube working faces are the unique property in the construction site, and the influence is researched by two different working conditions in Table 7.

Table 7. Constructor parameters in analysis of working face's influence.

Agent Property	Category	Proportion
Gender ratio	Male and female	90%:10%
Size and speed	Male, female parameters in Table 2	90%:10%, working face speed is equal to floor speed
Strategy	Nearest exit, environment pathfinding	75.0%, 25.0%
Pre-action time	Open	Uniform distribution [0 s, 120 s]

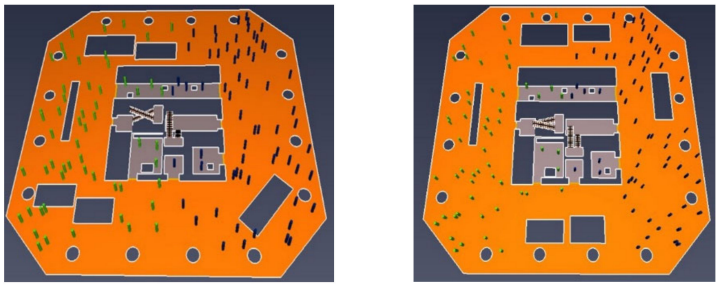
With consideration of evacuation speed difference on different working faces, the average distance of movement is 86.52 m and the evacuation time is 271.5 s. The average distance of movement is 85.79 m and the evacuation time is 216.98 s. It can be speculated that there is a relatively large difference in evacuation time rather than the average distance of movement with the working face's influence.

5.5. Construction Layout

Construction equipment, instruments, and storage yards will impede the safe evacuation on the working face, affecting the path selection of constructors. Obstacle avoidance is needed in safe evacuations. The obstacles' location in the frame working face is optimized. There are two optimization principles: (1) Construction equipment, instruments, and storage yards should be placed parallel to or perpendicular to FTBCS. (2) The geometric center should be on the same line as far as possible. The construction layouts are shown in Figure 12.

The pathfinder model under two kinds of construction plane layout is analyzed. It is found that the evacuation time is 271.5 s when the construction layout of the frame working face is not optimized. With the optimization of the construction layout, the evacuation time is 214.3 s, with 26.7% descending. It is also found that the average distance of movement on the frame working face is 54.12 m. In order to analyze the evacuation process

quantitatively, the number change of constructors on the platforms of frame working face is given in Figure 13.



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

Figure 12. Construction layout of frame working face. (**a**) construction layout without optimization; (**b**) construction layout with optimization.

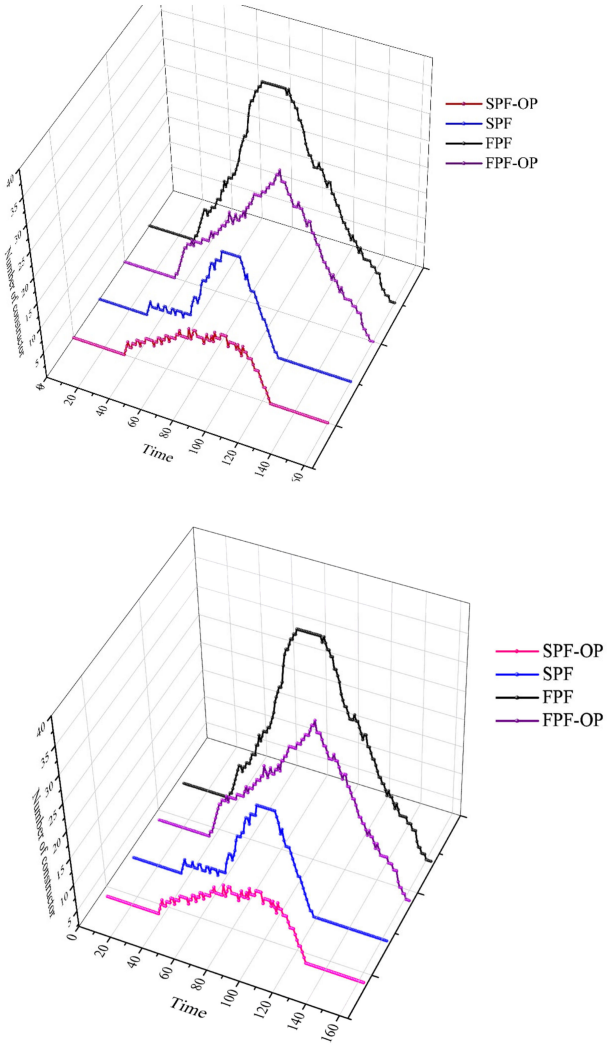


Figure 13. Number of constructors on FPF and SPF platforms with different construction layouts. FPF (first platform of frame working face), SPF (second platform of frame working face), FPF-OP (first platform of frame working face with optimization of construction layout), and SPF-OP (second platform of frame working face with optimization of construction layout).

From Figure 13, it can be seen that the largest number of residence constructors in FPF and SPF are 35 and 18 constructors, respectively, when the construction layout of the frame working face is not optimized. With the optimization of the construction layout, the largest

number of residence constructors in FPF and SPF is 28 and 11 constructors, respectively, with 25.0% and 18.2% descending, respectively. The phenomenon of clustering and crowding on the platform has been relieved with the optimization of the construction layout. The largest number of residence constructors continues to be 16.0 s and 9.0 s before the declining of residence constructors in FPF and SPF without optimization of the construction layout. The number of residence constructors reaches peak value and then falls down gradually in SPF-OP, where there is no peak duration. The largest number of residence constructors continues to be 4.0 s before the decline of residence constructors in SPF-OP. It can be speculated that the constructors on the frame working face can be evacuated quickly from the horizontal direction plane, and then complete the stair evacuation quickly. Evacuation times in FPF and SPF are reduced, and hence clustering and crowding on the platform have been relieved. In the actual evacuation, it also can reduce stampede accidents greatly caused by clustering and crowding.

5.6. Suggestions

From the parameter analysis above, the following measures could be taken to improve the safety evacuation in FTBCS. The occupational age ratio mainly affects the evacuation process by path programming, and the leading influencing factors are not distinct in the occupational age ratio effect. In FTBCS, safety education and construction instruction (SECI) should be emphasized in order to improve the path programming of constructors. Optimization of construction layout (OCL) can relieve clustering and crowding on platforms and reduce the evacuation time effectively; Hence, optimization principles should be taken. The effects are given by a side-by-side comparison in Table 8.

Table 8. Side-by-side comparison with suggested improvements.

Evacuation Parameters	Without Improvement	SECI Improvement	OCL Improvement	Percentage
Evacuation time	271.5	184.6	214.3	−32.0%
Movement distance	86.52	55.13	54.12	−36.3%

The location in FTBCS is suggested as the first sequence because of the decline coefficients evacuation speeds on different working faces. In the simulation, clustering and crowding phenomena were discovered by the evacuation process, and the sequence of the activities recommended for safety evacuations is shown in the flowchart in Figure 14.

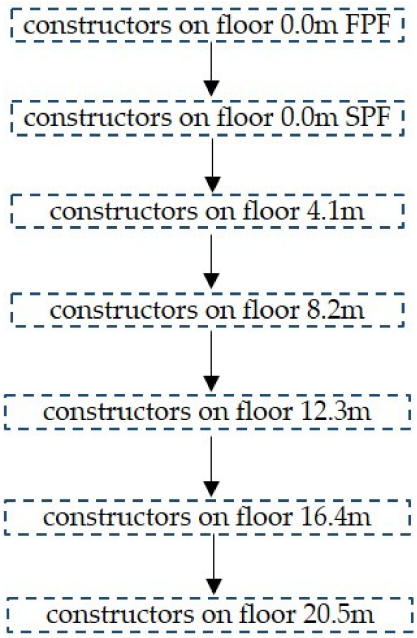


Figure 14. Sequence recommended for safety evacuation.

6. Conclusions

This research contributed to the improvement of safety evacuations of frame-core tube buildings in construction. The following conclusions are drawn:

(1) Constructors have unique properties in gender ratio, age composition, and occupational age. The male and female ratio of the constructor in the surveyed construction site is 10.23:1. Constructors aged between 18~28 years old, 28~38 years old, 38~48 years old, 48~58 years old, and 58~68 years old account for 26.39%, 31.62%, 26.86%, 14.84%, and 0.28%, respectively. The occupational age of constructors between 0~5 years old, 5~10 years old, 10~15 years old, and 15~20 years old account for 25.46%, 44.81%, 24.20%, 5.34%, and 0.19%, respectively. In FTBCS, the male and female ratio of the constructor can be roughly estimated to be 90% and 10% in the safety evacuation model, and the aged constructors can be ignored. The occupational age of constructors shows a major difference in FTBCS, which will affect the evacuation time and evacuation strategy.

(2) The evacuation speeds for constructors in FTBCS have been reduced because of complications within confined spaces. Reduction coefficients of 0.80 and 0.70 can be taken as reduction coefficients of evacuation speeds on frame- and core tube working faces in FTBCS, respectively. Without consideration of evacuation speeds on the working face, the evacuation time will be short-calculated.

(3) In the numerical simulation of the evacuation process, the arched pedestrian flow and crowd retention phenomenon appear on the platforms of the frame working face. It is determined that FPF and SPF are the key platforms that should be paid attention to in FTBCS.

(4) The increasing percentage of female constructors, aged constructors, and constructors of fewer occupational ages will exaggerate the evacuation time and average distance of movement, but there is some difference in the influence. The age composition ratio mainly affects the evacuation process by evacuation speed. The occupational age ratio mainly affects the evacuation process by path programming, and the leading influencing factors are not distinct in the gender ratio effect.

(5) Construction equipment, instruments, and storage yards should be placed parallel to or perpendicular to FTBCS, and the geometric center should be on the same line as far as possible in construction layout optimization. Optimization of construction layout can relieve clustering and crowding on platforms and reduce the evacuation time effectively. The main reason is constructors on the frame working face can be evacuated quickly from the horizontal direction plane with less obstacle avoidance, and then complete the stair evacuation quickly.

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