Pathfinder-Based Simulation and Optimisation of Personnel Evacuation Modelling of a Shopping Mall

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Abstract. This study concerns a simulation and optimisation of the personnel evacuation modelling of a shopping mall in Weiyang District, Xi’an. First, investigations were conducted to determine the human flow rate and occupant distribution during the rush hours to build a queuing theory model. Then, a simulation was implemented with an evacuation simulation software Pathfinder, followed by an analysis to the evacuation status and bottlenecks. On the basis of the evacuation status, proposals were put forward on how to overcome the bottlenecks to achieve the optimal matching among the personnel, emergency staircases and aisles. Finally, the improved scheme was simulated. Compared with time taken by the evacuation before improvement, the time taken was greatly shortened after improvement, proving the feasibility of the scheme. Through the simulation experimentaiton, it was found that evacuation modelling can greatly facilitate research on the evacuation problem in multistoryed shopping malls.

Keywords: occupant evacuation, Pathfinder, evacuation bottleneck, evacuation sign.

1. Introduction
With the rapid development of social economy, the construction of various large-scale shopping malls is becoming commonplace. Large shopping malls are generally built in places with high flow rate of people, and nowadays, various large shopping malls are no longer limited to square and rectangular buildings. The building structures novel and complex. However, the complex building structures may pose great difficulties to occupant evacuation in emergency situations. It brings certain difficulties. Poor evacuation plans will inevitably result in economic losses and casualties.

By reviewing the literatures on personnel evacuation, it was found that most of the studies focused on the impact of group escaping behaviors in emergency, neglecting the differences in individual behaviors in emergency evacuation. In this paper, the research object is a shopping mall located in Weiyang District, Xi’an. Field researches were made to collect data on peak flow rates, building structure, evacuation conditions, followed by the building of a queuing theory model to study the impact of the arrival rate of people in charge of evacuation on the evacuation process. A software named Pathfinder was used to simulate the current situation of evacuation. After analyzing the existing bottlenecks, optimization proposals were put forward to form an optimal evacuation scheme to solve the matching problems between the number of personnel and the number of evacuation staircases. The optimized scheme was then simulated. Compared with the original evacuation plan, the optimized scheme proves feasible. The evacuation signs were relocated for optimization.
2. Data statistics and analysis

2.1. Data collection

The research object selected is a large shopping mall, with a total construction area of 209,000 square meters. It consists of 6 floors above ground and 3 floors underground. The second and third floors underground are used as parking lots, the rest of the floors are used for restaurants, department stores, leisure and recreation.

In this study, a week-long pedestrian flow survey was conducted. It was found that the peak flow of people concentrates on six hours between 11:30-14:30 am and 17:30-20:30 pm, while the daily peak flow of people concentrates on Saturdays and Sundays at the same time. This research is mainly aimed at the first underground and the six floors above the ground.

Although the mall is located at an area not so bustling, it is adjacent to an intersection of traffic, surrounded by residential quarters, next to an office building, with a subway station entrance and exit on the first underground floor, so the flow of people is relatively large. Furthermore, the complex structure of the mall renders it necessary to do research on safe evacuation.

The height of each floor is 6 meters and the width of passages is 2m-12m. The shopping mall has a vast area and a complex building structure. The density of people on the 5th floor is the largest, followed by the 4th floor and the 1st underground floor. Except for the subway exit on the 1st underground floor, the mall has 8 exits, all on the first floor. Obviously, once there is an emergency, large numbers of people will have to withdraw from these exits, leading to congestion and hindering evacuation. The evacuation of people can only be completed though the staircases, so they must be utilized fully.

2.2. Statistics on the number and sizes of evacuation stairs

The number of staircases is shown in Tab.1. Each staircase is two-sectioned, with 1.5m in width and each has 18 steps, with 0.25m in width and 0.33m in height. The size of the landing is 1.5mx3.2m. The evacuation stairs are all of the same size, and there are double stairs in some places. Since the sixth floor is irregular in shape, it has 7 stairs. Each of the other floor has 15 evacuation stairs. Even though there are enough staircases, some staircases are hidden. Still, some evacuation signs are inconspicuous. These factors may add difficulty to smooth evacuation.

| floor | -1 | 1 | 2 | 3 | 4 | 5 | 6 |
|-------|----|---|---|---|---|---|---|
| Number of stairs (a) | 5  | 15| 15| 15| 15| 15| 7 |

Tab. 1 Number of staircases on each floor

3. Modeling

The mall conforms to the M/G/c/c queuing model. Assuming that the probability of n persons in stairs and passages is \( P_n \), the calculation formula is as follows:

\[
p_n = p_r(N = n) = \left( \frac{\lambda(E(T_1))^n}{n! f(n)f(n-1)\ldots f(2)f(1)} \right) P_0
\]

\[ n = 0,1,2,\ldots,c \]

(1)

Where, \( \lambda \) represents the arrival rate of people in stairs and passages, \( E(T_1) \) the expected service time of a passenger, \( f(n) \) the service rate offn passengers in the stairs or passage, \( V_c \) the walking speed of passengers in the stairs or passage. \( P_0 \) is the value of no passengers in the staircase or passage.The calculation formula is as follows:

\[
P_0^{-1} = 1 + \sum_{i=1}^{c} \left( \frac{[\lambda E(T_1)]^i}{i! f(i)f(i-1)\ldots f(2)f(1)} \right)
\]

(2)
The congestion probability of $P_c$ and the output rate of $\theta$ for stairs or passages are calculated as follows:

$$P_c = P_r(N = c) \quad (3)$$
$$\theta = \lambda(1 - P_c) \quad (4)$$

The number of people held by the stairs or passages is calculated according to the human body sizes and the sizes of the stairs or passages. The locations and sizes of the stairs or passages on each floor are nearly the same. In this research, the fifth floor was chosen in calculating the parameters, for the number of people is the largest on this floor, having the greatest impact on evacuation. Since the number of people to be evacuated is related to the stairs and the passages connected to the stairs, the stairs and the passages in each floor were numbered from 1 to 12, and the passages were marked from a to o. Shoulder width taken from males (18-60 years old) is 469mm, and females (18-55 years old) 438mm, so the average value is 453.5mm, considering the range of activities, the estimated human sizes $453.5\text{mm} \pm 453.5\text{mm}$ were adopted in calculating the maximum capacity of the stairs and various passages, as is shown in Tab.2:

| Number | Stairs 1-12 | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o |
|--------|-------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| c      | 117         | 40| 39| 56| 60| 39| 60| 39| 95| 137| 111| 44| 83| 98| 137| 60|

**Tab. 2 Maximum capacity of the stairs and passages on the 5th floor**

Assuming that the arrival rates of people in the staircase are 1 person/s, 2 persons/s, 3 persons/s, 4 persons/s, 5 persons/s, 6 persons/s, the following values can be worked out: congestion probability of each passage, output rate, expected service time, and expected queue length. In this paper, the congestion probability and personnel output rate were calculated. Fruin density-speed formula was used to fit the personnel speed [1]. The calculation results are shown in Tab.3 and Tab.4:

| Arrival rate (person/s) | 1   | 2   | 3   | 4   | 5   | 6   |
|-------------------------|-----|-----|-----|-----|-----|-----|
| stairs                  | 0.125 | 0.53 | 0.861 | 0.857 | 0.855 | 0.852 |
| a                       | 0.21 | 0.41 | 0.51 | 0.39 | 0.45 | 0.06 |
| b                       | 0.43 | 0.98 | 2.46 | 0.64 | 0.6  | 0.6  |
| c                       | 0.535 | 1.02 | 2.985 | 0.92 | 0.115 | 0.108 |
| d                       | 0.01 | 0.02 | 0.42 | 0.12 | 0.1  | 0.12 |
| e                       | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 |
| f                       | 0.19 | 0.26 | 0.42 | 0.12 | 0.1  | 0.12 |
| g                       | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 |
| h                       | 0.69 | 0.77 | 1.17 | 0.78 | 0.75 | 0.78 |
| i                       | 0.5  | 0.79 | 3   | 0.544 | 0.535 | 0.534 |
| j                       | 1.03 | 1.98 | 3   | 2.52 | 0.3  | 0.3  |
| k                       | 1.38 | 1.94 | 2.994 | 1.84 | 1.35 | 1.5  |
| l                       | 0.53 | 0.68 | 2.34 | 0.32 | 0.3  | 0.3  |
| m                       | 0.5  | 0.79 | 3   | 0.544 | 0.535 | 0.534 |
| n                       | 0.5  | 0.79 | 3   | 0.544 | 0.535 | 0.534 |

**Tab. 3 Occupant flow rate**

| Arrival rate (person/s) | 1   | 2   | 3   | 4   | 5   | 6   |
|-------------------------|-----|-----|-----|-----|-----|-----|
| stairs                  | 0   | 0.001 | 0.713 | 0.785 | 0.829 | 0.858 |
It can be seen from the calculation results that with the increase of the arrival rate $\theta$, the congestion probability of stairs and passageways $P_c$ gradually increases, and its output rate increases first and then decreases with the arrival rate of people. The output reaches maximum when the arrival rate of stairs and some reaches 3 people/s. The uneven distribution between the evacuation flow and the number of evacuation stairs will cause serious congestion in individual staircases and a serious reduction in personnel output rate.

4. Pathfinder-based simulation and optimization

4.1. Simulation-related parameter settings
The random distribution of personnel was adopted. The setting ratio of the personnel forms and the speed of personnel movement [4] conform to the standards of the People's Republic of China [2-3]. The setting parameters are shown in Tab.5.

| Shoulder width (cm) | Young men | Young women | Senior men | Senior women | Male Child | Female Child |
|---------------------|-----------|-------------|------------|--------------|------------|--------------|
| 431                 | 394       | 431         | 386        | 373          | 376        |
| 40                  | 40        | 5           | 5          | 5            | 5          |
| 1.2-1.5             | 0.8-1.1   | 0.6-1.1     | 0.5-0.8    | 0.7-1        | 0.6-0.9    |

Tab. 5 The setting parameters of evacuees

4.2. Current status simulation and optimized scheme simulation
Because this simulation experiment involved complex escape routes and large numbers of people without taking into account the elevators and escalators, the evacuation took longer time. The effect pictures of the simulation are shown in Fig.1. There is a subway exit on the first underground floor, so some people can withdraw form it. Some people on the first underground floor (Floor 0.00) and all those on the 6 floors above ground-1st floor (Floor 0.00), 2nd floors (Floor 6.00), 3rd floor (Floor 12.00), 4th floor (Floor 18.00), 5th floor (Floor 24.00), 6th floor (Floor 30.00) - must reach the exit on the 1st floor through the evacuation stairs.
It can be seen from the simulation that it takes 864.3 seconds to complete the evacuation of 4141 people in the mall. The result is higher than the real value. The number of people in rooms, passages and staircases varies with time. The output rates are shown in Fig. 2 and 3.

Fig. 1 Hierarchical evacuation display

Fig. 2 Diagram of the number of occupants varying time before the optimisation

Fig. 3 Flow rates for selected doors
Fig. 3 Diagram of the flow rate at the selected exits before the optimisation

Fig. 2 shows that the passages and stairs are the first places where the flow of people increases with time and then gradually decreases to 0, and that the flow of people in the rooms gradually decreases with time to 0. From Fig. 3, it can be seen that between the beginning of the evacuation to 0 and 100s, the maximum output rate is 4.52 persons/s. Within 100s-500s, the personnel output rate is lowered to 2.89 persons/s, and then within 500s-864.3s, the flow rate becomes stable.

For economic reasons, an improvement plan was proposed on the basis of not changing the original building structure as much as possible. The improvement could be achieved mainly by adding evacuation passages and guiding people. The specific plan is as follows:

(1) Adding passages
In the center of the fifth floor, there is a food court able to cater up to 370 people. From the simulation, it can be seen that during the evacuation, the people here tend to withdraw from the exits at the two ends, and then look for the nearest evacuation stairs. Fig. 4 shows the improvement scheme: add a door with a width of 3 meters at ①, and add a passage leading to passage n at ②. Because there are fire compartments on other floors, adding passages will damage the building structure, so adding additional passages on the other floors is beyond consideration.

(2) Adding guidance personnel
The purpose of increasing the guidance personnel is to facilitate evacuation. Usually, the evacuation doors are closed and the stairs are located relatively backward, rendering evacuees difficult to find them. With the help of guidance personnel, the evacuees can be channeled fairly evenly to the passages, avoiding following others aimlessly, which may otherwise cause congestions and chaos. The workers of the shops can serve as the guides for the nearby areas, for they can reach them timely. On the basis of simulation, the guidance areas are located near the stairs that are not so often used by customers.

4.3. Simulation results and analysis of improved evacuation scheme
According to the above improvement plan, the simulation model built earlier was modified. As for the scheme of adding passages and doors to the improvement scheme (1), direct operation was performed by adding door buttons in the original model with drawing tools; As to the improvement scheme (2), improvement was made by stipulating withdrawal routes for people in specific rooms. The improved evacuation results are displayed hierarchically in Fig. 4:
The operation of the improved program showed that the time taken by the entire evacuation was 697.5s. Fig. 6 is the graph of the variation of the number of people in each room.

Fig. 5 Hierarchical diagram of improved evacuation scheme

Fig. 6 The variation of number of occupants rooms with time before improvement
Fig. 7 Variations of the flow rate at selected doors after the optimisation

It can be seen from the figure that within 50s when the evacuation started, the number of people in rooms fell sharply since the evacuees had run rapidly to the evacuation doors. The curves because even and in the end reached 0, for it took longer time for the evacuees farther away from the doors to get there. The number of people in each passage increased sharply first, and then gradually decreased to 0. The personnel output rate of each evacuation door is shown in Fig. 7.

Similar to the output rate before the improvement, the output rate of each evacuation door after improvement rises first and then falls until reaching 0. The difference lies in the fact that the peak value of the output rate after improvement becomes greater than that before the improvement, and occurrence of the peak value is delayed, partially explaining the shortened evacuation time.

From Fig. 7, it can be seen that before and after optimization, when the simulation goes on for 3.5s, the density and moving speed of people undergo no great changes, but greater changes occur when simulation goes on for 50.4s.

From the evacuation simulation, it can be seen that when the evacuation goes on for 50.4s, the density is still 3occs/m² at certain exits on the 1st underground floor, and the moving speed is 0.24m/s at the exist with great evacuee density. Most of the stairs are in working condition. On the first floor, the maximum density of personnel reaches 2.7occs/s, with a moving speed of 0.45m/s and all stairs are in working condition. On the 2nd floor, the personnel density is 3occs/ m², and the moving speed of the personnel is 0.24m/s, with all stairs in working condition. On the third floor, the density reaches 3occs/ m² at two places, with a moving speed of 0.12m/s, and all stairs in working condition. On the 4th floor, the density of places density is 3occs/ m², with a moving speed of 0.12m/s, and all stairs in working condition. On the 5th floor, the personnel density at 5 places reaches 3occs/ m² at 50.4s, with a moving speed of 0.12m/s, and all stairs in working condition. On the 6th floor, the density at places reaches 3occs/ m², with a moving speed of 0.12m/s, and all stairs in working condition.

From the above analysis of the situation on each floor, the improvement plan rationalizes the ratio between the number of evacuees and the number of exits, enabling each exit to be in working condition as much as possible. Although due to the sizes of some stairs, serious congestions do occur at some exits, the evacuation guides channel the flow timely to other exits, as a result, the number of people held up in the congestion is lowered, in turn lowering the time spent on evacuation, and ultimately shortening the evacuation time to 697.5s.

5. Conclusion
(1) Before improvement, due to the fact that some staircases are idle and some are over used in case of emergency, the time required for evacuation is 861.8s. After the improvement, the total evacuation time is shortened to 697.5s, with the total evacuation time reduced by 19%
(2) After adding more passages and putting evacuation guides to use, some people no longer blindly follow others, and the efficiency of stairs is raised. After the improvement, the number of evacuation stairs from the first underground floor to the fifth floor has increased, and each floor has 15 staircases. There are 7 staircases on the 6th floor. The number of negative 1st floor stairs is increased from 8 to 10. Evacuees leave the building through the exits on the first floor, using no stairs. The number stairs on the second floor is increased from 9 to 11, from 7 to 10 on the third floor, from 8 to 12 on the fourth floor, from 9 to 12 on the fifth floor, and from 5 to 7 on the sixth floor.
For the sake of economy, evacuation guides are introduced into the evacuation to achieve the optimal match between the evacuees and evacuation stairs and passages. The results of the simulations conducted show that the optimization scheme to shopping mall is feasible and efficient. Hopefully, the model in this research would benefit other researchers working on the evacuation of large buildings.

Acknowledgements
This work is supported by Shaanxi Provincial Key R&D Program Fund (Grant No.2019GY-024).
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