On the Crowded Places Multi-Exits Emergency Evacuation Model and Algorithm

Li Dawei[1], Zhang Xiaoqi[2] and Wang Li[3]

**[1] Editorial Department, University of Science and Technology Liaoning
Anshan, Liaoning 114051, China**

**[2] School of Science, University of Science and Technology Liaoning
Anshan, Liaoning 114051, China**

**[3] School of Electronic and Information Engineering, University Department, University of Science and Technology Liaoning
Anshan, Liaoning 114051, China**

Abstract
Emergency evacuation in the crowed places was discussed, under the different analysis, description, and relevant research backgrounds. First, the evacuation shortest path optimization model was established. Then the optimization solution results obtained by using of software Lingo were analyzed and verified. Finally, the quantitative solution results were conversed to the version of variable, so that the results more suit with the actual situation. This research provided a basis for the practical application of the model to develop an emergency evacuation plan.
Keywords: *Crowed Place, Emergency Evacuation Model, Lingo, Variationized.*

1. Introduction

With the rapid economic development, the city buildings are increasingly dense, and people are more and more concentrated. Once crowded places sudden accident or disaster occurred, heavy casualties and property losses may be likely caused, even lead to confusion, and thousands of people must be evacuated [1]. For example, continued heavy rainfall triggered flood in some parts of England since September 23, 2012, hundreds of people were evacuated; 8:00 am in September 25, 2012, one residential building natural gas pipeline ruptured suddenly, brought about gas leak, 30 residents were emergency evacuated; in September 26, 2012, nearly 100 vessels had been evacuated after the commutation run 16 hours in the north line shiplock of the Yangtse Gorges; Business Daily news: in September 28, 2012, a emergency evacuation was run in New York’s Kennedy Airport because of a suspected bomb threat; Google interview strange title: design an evacuation plan for San Francisco.

How to evacuate safely and orderly in the shortest time, if the unexpected accident occurs? How the victims evacuate quickly? These are important issues not only related to the safety of life and social stability, but also the main research content and purpose of the emergency evacuation.

Crowded places, multi-exits emergency evacuation is one of the most important research content. Factors which affect the safe and rapid evacuation in crowded places not only include the position, the stadium design, the distribution and size of the exits[2] [3], but also depend critically on evacuees itself and the reasonable evacuation plan. Li investigated a fire safe evacuation model and algorithm, described in detail the relationship among the flow density, spacing, speed, and data in all kinds of circumstances, and safe evacuation in different environments were specific analyzed [4]. Based on the evacuation miracle in Sangzao middle school, Sichuan, China, Guo and Mao established three mathematical models to find the relationship among the evacuation time, speed, spacing and other variables, measured and empirical data were used to solve three models, infer the possibility of teachers and students which escaped within 1 minute and 36 seconds [5]. Combined the traditional cellular automata model with the network model, Zhu simulated people evacuation from the different room structures, focused the research on the influence of populated density and exit conditions on evacuation time [6]. Ma designed the evacuation paths integer programming model with capacity limit multi-exits, solved by combining backtracking algorithm and binary search algorithm [7]. Based on the audience seats area and evacuation paths distributed simulation scheme in crowed places, Zhang established a non-linear programming model, and solved by software Lingo [8] [9].

Against the crowded places multi-Exits emergency evacuation problem, this paper proposed a model from different opinions. Some analysis of the solution results were studied, such that the model was more close to the complex reality.

2. Model Assumptions, Analysis and Construction

2.1 Model Assumptions

i) Simplifying the different crowed places, drawing the schematic plan;
ii) Orderly evacuation, no rebound, no counter-current, evacuees have the same transfer velocity;
iii) Spacing and the thickness of each person's body are at an average level, and remain unchanged;
iv) The safe evacuations are completed if people were all out of the exits.

2.2 Model Analysis

It is not difficult to find by understanding of the actual situation, as well as various types of literatures, that crowded places were blocked in the emergency evacuation, especially in exit positions. The reason why the inevitable blocking is that in crowded places, such as large shopping malls, venue, cinema et al, the exit number i and width H_i are changeless, and people evacuation speed v is changed within a certain range, so the average speed is set to a fixed value in here. When emergency events happened, crowded people rush for the exits from all directions. Let S be the total number of crowded people in the places. Crowded people evacuate to exits mainly by two types: linear and L-shaped. Whether linear or L-shaped, the number of crowded people rush for the exits in a certain period of time will exceed exits outflow, because the width H_i of the i th exit is determined, so the blocking happen and the arch phenomenon is formed as the result. But the flow speed is constant in the exit sectional. This is only equivalent to divide crowd into some queues which pass through in a certain speed side by side. Let l_i be the closest distance from person's position to exit i, d_K be the minimum width evacuees occupied, and d_H be the sum of body thickness and spacing.

2.3 Model Construction

Let n_i be the number of crowd passed through exit i at the same time, so n_i is:

$$n_i = \frac{H_i}{d_K} \quad (1)$$

It is found that the queue length is all evacuees' body thickness plus spacing, as well as the number of queues. Single queue, double queue, and triangle queue were discussed and compared in literature [5]. Although triangle queue was better than two others, it is not possible in the case of an emergency. The queue length L_i is:

$$L_i = \left[\frac{S_i + n_i - 1}{n_i}\right] \cdot d_H \quad (2)$$

So the time passed exit i is:

$$t_i = \frac{l_i}{v} + \frac{L_i}{v} \quad (3)$$

Based on above assumptions and analysis, the evacuation model can be constructed as follow:

$$\begin{cases} T = \min\{\max t_i\} \\ \sum_{i=1}^{m} S_i = S \\ d_H, d_K > d_0 > 0 \end{cases} \quad (4)$$

where d_0 is a constant greater than zero, a threshold ensures that the evacuation pass orderly.

3. Model Solving

3.1 Solving Ideology

In order to ensure the safe evacuation of each person, the total time must be the shortest, which is equivalent to minimize $\max t_i$. On the other hand, the total number of crowded, exit width, and body thickness are constant. Generally, the walking speed is about $1.2\,m/s$ in an open space, and $1.0\,m/s$ in a relatively crowded place, while the spacing is about $1.0\,m$. The flow of the queue as shown in table 1:

Table 1: The flow of the queue under a variety of spacing

Classification	Spacing(m)	Queue flow
A	> 1.2	Slightly Restriction
B	1.1-1.2	Restriction
C	0.9-1.1	Restriction
D	0.6-0.9	Severely Restriction
E	0.6	Impossible
F	< 0.6	Impossible

Assumed that d_H is a constant. In general, people in the longer queue are allocated to the shorter queue, so that the evacuation time can be shortened. The shunt is stopped if the queue length is about equal, so the optimal evacuation time will be obtained. In addition, the number of people is an integer, and the times arrive at the exits are not equal perfectly, so the limitation thought is adopted:

$$T = \lim t_1 = \lim t_2 = \lim t_3 = \cdots$$

The above solving thought can get rid of some restrictions, such as the internal facilities, passageway in crowded places, et al. The exit flow will not interrupt, as long as the excessive herd behavior does not occur. The evacuations in meeting place, shopping mall, cinema and other crowded places can follow this model. Further, since seeking integer operation is used in the objective function, so that the number of people leading to each exit is not uniquely determined, but varies within a certain range. The optimal solution and the number of each exit can be obtained by using Lingo program.

4. Example Solving

In order to verify the actual effect of the proposed model, an example given in literature [7] was solved. The main data were as follow: a theater with about 3,000 seats, which were divided into six areas, and each of which had 300, 600, 300, 514, 800 and 514 seats, respectively. In four exits, exits 1 and 2 allowed four people, while exit 3 and 4 allowed three people pass through side by side without blocking.

Step 1: Directly compare the quantitative solution results.

For the same conditions and using the same software, the solutions obtained by proposed model in here are compared with other literatures.

With the same parameters: $d_H = 0.5m$, and $v = 1.0m/s$.

Using above data for the model, the follow solutions can be obtained by using software Lingo:

$t_1 = 108s$, $t_2 = 110s$, $t_3 = 110s$, and $t_4 = 110s$.

Therefore the optimal evacuation time is $T = 110s$, much more smaller than the result 122.3*s* solved in literature [7]. Furthermore, we have:

$S_1 = 853$, $S_2 = 871$, $S_3 = 652$, and $S_4 = 652$.

Step 2: Variationized the solution results.

It can be obviously seen that $t_1 < t_i,\ i = 2,3,4$, so each evacuation time do not reach the equal. So solutions are not the optimal because some people in exit 2, 3, and 4 may divert to exit 1. Continue to divert 3, 1, and 1 people in exit 2, 3, and 4, respectively, to exit 1, the optimal solution:

$S_1 = 858$, $S_2 = 868$, $S_3 = 651$, and $S_4 = 651$.

And

$t_1 = 108.5s$, $t_2 = t_3 = t_4 = 109.5s$.

Diversion can no longer conduct, so $T = 109.5s$.

Substituting t_i into the objective function, we have:

$S_1 \in [857,\ 860]$, $S_2 \in [865,\ 868]$, $S_3 \in [649,\ 651]$, and $S_4 \in [649,\ 651]$

Step 3: Variationized the condition data.

The sensitive data in example may be variationized, such that the variation between the various types of data can be found. In such a case, the model can be adapted to different environments, more reasonable and effective in the evacuation process.

But it can be seen from table 1 and literature [2] that the solutions obtained by literature [7] made an actual deviation because the spacing was set as $0.5\,m$. The flow of the queue can be reset for table 1, to determine the optimal matching of spacing and flow rate.

Table 2: The evacuation time under the different spacing and flow rate

Classification	Flow Rate(*m*/*s*)	Evacuation Time(*s*)
A	1.2	215.8
B	1.1	215.9
C	1.0	216.0
D	0.8	216.3
E	0.6	216.7

It can be seen from table 2 that the evacuation time is faster, if evacuees are near the exits, and withdraw with large flow rate. But in actual evacuation process, blocking inevitably occur if it is in the case of exercise. It is difficult to get the best effective if the spacing is not in a certain length. So spacing is set as $d_H = 1.0m$, and flow rate is set as $v = 1.0m/s$, while other conditions remain unchanged. Then solve the model, we can obtain:

$t_1 = t_2 = t_3 = t_4 = 218s$, so $T = 218s$.

Then, we have:

$S_1 \in [865,\ 868]$, $S_2 \in [865,\ 868]$, $S_3 \in [649,\ 652]$, and $S_4 \in [649,\ 652]$.

5. Conclusion

The rounding integer operation is used to get the queue length in formula (2), and the last row is also taken as one row, even if it is a shortage one. The locations where emergency events occur will also affect the number of evacuees in each exit. Here is just general modeling, emergency events occur in different location need to be further considered. Relative to the place, where the evacuees' distribution is looser, or evacuation route is more complex, the optimization of the evacuation route needs to be considered. Therefore, the model has a wide range of application, as long as pass through uninterrupted, all kinds of places can use. Of course, some of the details, such as the type of emergency incident, evacuees themselves, fall down, reflux can be joined as new constraints to be considered.

Acknowledgments

The research work was supported by Natural Science Foundation of Liaoning Province under Grant No. 20092177 and 20102097.

References

[1] C. E. Haque, “Perspectives of Natural Disasters in East and South Asia, and the Pacific Island States: Socio-Economic Correlates and Needs Assessment”, Natural Hazards, Vol. 29, No. 3, 2003, pp. 465-483.
[2] Zhao Daoliang, Yang Lizhong and Li Jian, “Exit Dynamics of Occupant Evacuation in an Emergency”, Physica A, Vol. 363, No. 2, 2006, pp. 501-511.
[3] Zhao Daoliang, Yang Lizhong, Li Jian, Zhu Yi and Zou Lan, “Relationship between Performance-based Design of Building Exits and State Transition of Pedestrian Flow during Occupant Evacuation”, Journal of Fire Protection Engineering, Vol. 16, No. 4, 2006, pp. 269-281.
[4] Li Yinqing, Building Fire Performance Design, Beijing: Chemical Industry Press, 2005.
[5] Guo Peijun and Mao Haizhou, “Study on Evacuation Model”. Mathematics in Practice and Theory, Vol. 41, No. 9, 2011, pp. 1-9.
[6] Zhu Yi. “CA Evacuation in Different Rooms of the Structure Simulation and Genetic Algorithm Evacuation Model”, M.S. thesis, Department of Safety Science Engineering, China Science and Technology University, Hefei, China, 2007.
[7] Ma Haobo, Ji Jianhua and He Bing, “Optimization of Large Scale Emergency Evacuation with Multiple Paths and Exits”, Journal of Systems Management, Vol. 20, No. 2, 2011, pp. 238-243.
[8] Zhang Yanfang, Yuan Jing, Wang Fuchang, Zhao Yibin and Zhao Yongan, “The mathematical model and the Optimal Solution of Emergency Evacuation Problem in Densely Populated Places”, Mathematics in Practice and Theory, Vol. 39, No. 24, 2009, pp. 48-52.
[9] Zhang Yanfang, Kang Yonggang, Zhang Lijuan, Yuan Jing and Zhao Yongan, “The Velocity Model of Emergency Evacuation Problem in Densely Populated Places”, Mathematics in Practice and Theory, Vol. 40, No. 1, 2010, pp. 122-126.

Li Dawei Born in 1962, professor, University of Science and Technology Liaoning, received his Bachelor of Science degree in 1984, and Ph.D. in 1998. Taught in Liaohe Petroleum Schools, 1984-1988, after that taught in University of Science and Technology Liaoning as an assistant, lecturer, associate professor, and professor, sequentially. More than 50 academic papers published up to now. Current research interests include emergency system modeling theory and methodology, scheduling theory and methods, and intelligent optimization algorithm, et al. A member of the Operations Research Society of China.

Zhang Xiaoqi Born in 1984, Postgraduate, University of Science and Technology Liaoning, received his Bachelor of Science degree in 2006, and Master of Science degree in 2013. His research interests include emergency system modeling theory and methodology, and intelligent optimization algorithm, et al.

Wang Li Born in 1963, professor, University of Science and Technology Liaoning, received her Bachelor of Science degree in 1984, and Ph.D. in 1998. Taught in Anshan Normal College, 1984-2002, after that taught in University of Science and Technology Liaoning as an associate professor, and professor, sequentially. More than 40 academic papers published up to now. Current research interests include large system modeling theory and methodology, scheduling theory and methods, and intelligent optimization algorithm, et al.