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Investigation of Human Behavior in Emergent Evacuation from an Underground Retail Store

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Abstract

Pedestrian evacuation from underground building in emergency situations could be influenced by the structure of buildings, characteristics of pedestrian movement and seriousness of emergency events. To understand the evacuation process of pedestrian in emergency, evacuation drills on an underground retail store and a questionnaire survey are conducted. The characteristics of human evacuation behaviour are discussed and the evacuation time and specific flow in each evacuation scenario are analyzed. The phenomenon of unbalance exit-selection is revealed, and more guidance devices are needed in the underground retail store. The results also indicate that obstacles nearby the emergency exits should be removed and the clustering places for evacuees should be far away from the emergency exits. It is concluded that the results could provide assessment of the accuracy of existing egress models, and ensure that building owners and managers have a sound basis for evacuation planning.

Keywords: emergency evacuation, human behavior, fire compartment, exit selection, evacuation drill

1. Introduction

Human behaviors in fire have attracted researchers from all over the world to carry out research, especially ever since the "911" disaster. For the reason that more complexity of human behaviors in fires, the means of data collection, such as questionnaire survey, interviews with survivors of fire, evacuation drills and unannounced evacuations involving members of the public [1], have been used to explore human behaviors.

The evacuation process might be influenced by many factors, especially the human behaviors, such as recognition, response and motion characteristics of evacuees [2, 3]. Referring to the evacuation from retail stores, the complex building structures and evacuation routes should be taken into consideration. Shields et al. [4, 5] and Samochine et al. [6] had conducted unannounced evacuation drills in retail stores to obtain the original data of evacuation process and capture the characteristics of human behavior. In their studies, the participants had no prior knowledge of the evacuations, and the evacuation processes were recorded by digital cameras. Moreover, an announced evacuation drill from retail store [7] was also conducted in China. These researches mainly focus on the pre-movement time, exit choice during the evacuation process, as well as the influences of staff behaviors on evacuation process and so on. However, there are usually many fire

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compartments in the retail stores, and they will be closed in emergency situations except the fire doors between the fire compartments. The influences of taking fire doors of adjacent fire compartments as emergency exits on evacuation process have not been clearly identified, and more researches with respect to this issue are needed.

To explore the effect of useable fire doors of adjacent fire compartments and individual characteristics on the efficiency of retail store evacuation, in this paper, the evacuation drills in different scenarios from an underground retail store and a questionnaire survey are conducted to investigate the evacuation process. The evacuation processes are recorded by digital cameras placed beside the exits and the surveillance cameras in the retail store. In this way, the evacuation time, the ratio of exit selecting, as well as the influences of useable of fire doors of adjacent fire compartments and pedestrian distributions on evacuation efficiency can be obtained and discussed.

The rest of this paper is organized as follows. In section 2, evacuation drills in an underground retail store and a questionnaire survey are presented. The results and discussion are given in section 3 follows by a brief summary of the findings in the last section.

2. Evacuation drill

2.1. Design and implementation of the evacuation drill

The evacuation drill was conducted in a retail store, which had two floors above the ground floor and one floor under the ground floor. The retail store occupied 6000m^2 with 1100 staffs. The underground floor of the retail store was divided into four fire compartments, and the building area of fire compartments are shown in Fig 1. There were totally 14 emergency exits, in which 5 exits lead to fire-protection passageway (2, 3, 4, 5, 13), 3 exits lead to staircases (1, 6, 14), and 5 exits lead to the adjacent fire compartment (7, 8, 9, 10, 11).

For the efficiency and simplicity of the evacuation drill, we chose the fire compartment four as the original location, on which the participants were distributed. The participants were staffs who do not work in underground floor and the evacuation drill were conducted from 7 to 8 a.m. The participants in fire compartment four could reach fire-protection passageway by exits 3, 4, reach fire compartment two by exit 7, and reach fire compartment three by exit 8. Four different scenarios were set in the evacuation drill, and the detailed information could be found in Table 1. The homogeneous distribution can be defined that the participants were distributed uniformly in fire compartment four, and the inhomogeneous distribution means that the participants were distributed in the one side of fire compartment four, which is far away from the fire-protection passageway. Besides, eight digital cameras were placed on exits 1, 2, 3, 4, 5, 6, 7, 8 to record the evacuation processes.

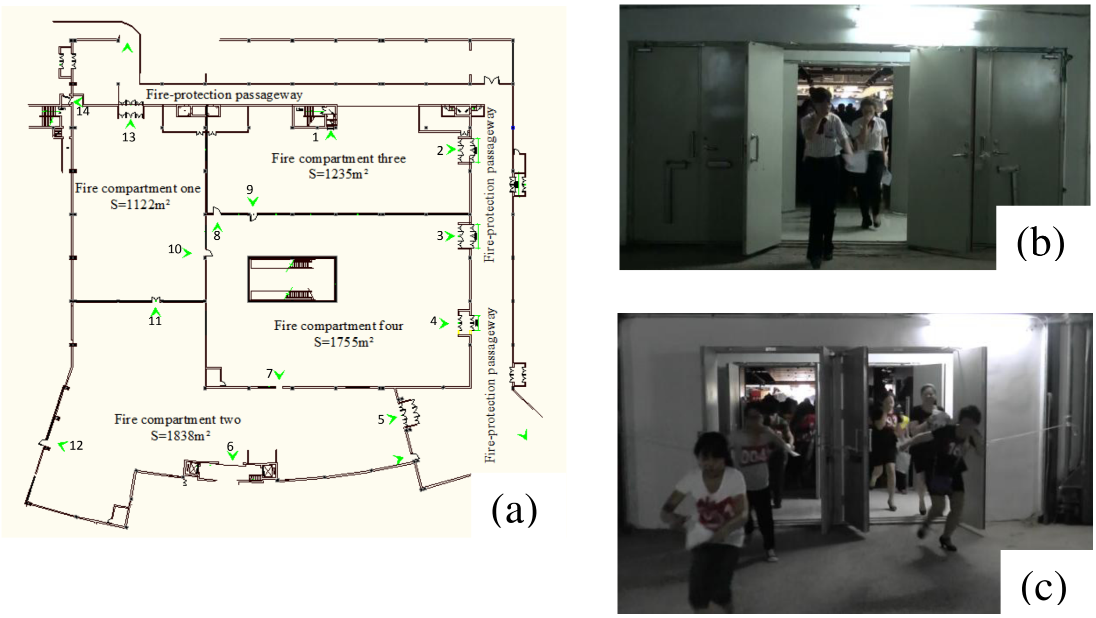

Fig. 1. Schematic of the underground floor of the retail store(a); Snapshots of the evacuation processes from cameras on (b)exit 3 and (c)exit 4.

The participants were told the destinations of evacuation drill, including exits 1, 2, 3, 4, 5, 6, and they could choose one of them as their evacuation destination. In every evacuation scenario, participants were distributed in fire compartment four and the participants began to evacuate if the fire alarm was activated. Until everyone reached the destinations, the evacuation scenario of the evacuation drill was terminated.

2.2. Questionnaire survey

In order to have a deep understanding of the characteristics of pedestrian behaviors in evacuation process, a questionnaire about evacuation was designed. The questionnaires were filled out by the participants when they finished the evacuation drill.

Table 1. Information of the four different scenarios in the evacuation drill.

Scenarios	Number of participants	Participants distribution	Fire door of adjacent fire compartments	Exits
1	312	Inhomogeneous	Useable	3, 4, 7, 8
2	299	Homogeneous	Useable	3, 4, 7, 8
3	279	Inhomogeneous	Unusable	3, 4
4	232	Homogeneous	Unusable	3, 4

3. Results and discussion

3.1. Characteristics of evacuation behavior

In the process of evacuation drill, participants were told the final destinations without the specific exits in the underground floor; therefore, they could choose any of the exits to reach the destinations. For the analysis of the pedestrian's behaviors of exit-selection, we collected the number of participants who walk through the exits 3, 4, 7, and 8, respectively. The ratios of exit-selection in different Evacuation scenarios are shown in Table 2. The width of exits 3, 4, 7, 8 in the evacuation process could be found in Table 3.

Table 2. Ratio of exit-selection in different evacuation scenarios.

Scenarios	Exit 3	Exit 4	Exit 7	Exit 8
1	18.58%	41.99%	16.35%	23.08%
2	8.70%	36.79%	24.74%	29.77%
3	31.90%	68.10%	—	—
4	29.74%	70.26%	—	—

Participants could walk through exits 3, 4, 7, 8 to finish the evacuation in scenario one and two, and only walk through 3, 4 to finish the evacuation in scenario three and four. It can be clearly seen from Table 2 that comparing with other exits the number of participants who walk through exit 4 is the largest in scenario one (41.99%) and scenario two (36.79%). The reasons account for the results could be summarized that the width of exit 4 is the largest and the exit 4 locates at nearly the middle of the boundary of fire compartment adjacent to the fire-protection passageway. Therefore, participants in fire compartment four could see the exit 4 clearly and then majority of participants chose exit 4 in the evacuation process. It should be noted that when the fire door of adjacent fire compartments are useable, that is in scenario one and two, 39.43% (scenario one) and 54.51% (scenario two) participants chose the fire door of adjacent fire compartment. The results reflect the fact that the useable of fire door of adjacent fire compartment reduces the possibility of congestion in emergency exits, increases the evacuation routes for occupants in the underground retail store. Moreover, it can be seen from the results of scenario 3 and scenario 4 that the numbers of evacuees walking through exit 4 are more than twice of the numbers of evacuees walking through exit 3. The results demonstrate that phenomenon of the unbalance exit selection happened in the evacuation process, and more appropriate guidance devices are needed in the retail store to assist occupants to evacuate through the proper exits.

Then, the speeds of participants in the passage of retail store are calculated and the probability and cumulative probability of participants' speeds are presented in Fig. 2. We can see that the 69% of participants' speeds belong to the range from 3.6m/s to 4.3m/s. Moreover, it also can be seen from Fig. 2 that the range of participants' speeds in the evacuation process is from 2.8m/s to 4.8m/s, which is obvious larger than the mean free walking speed 1.51m/s [8]. One reason accounting for the higher speeds might be that the participants had experienced evacuation drills and/or safety trainings and knew that they should evacuate the building at their fast speeds. Another explanation for the higher speeds is that the speeds obtained are mainly movement speeds of participants on passage, in which participants could move without congestion.

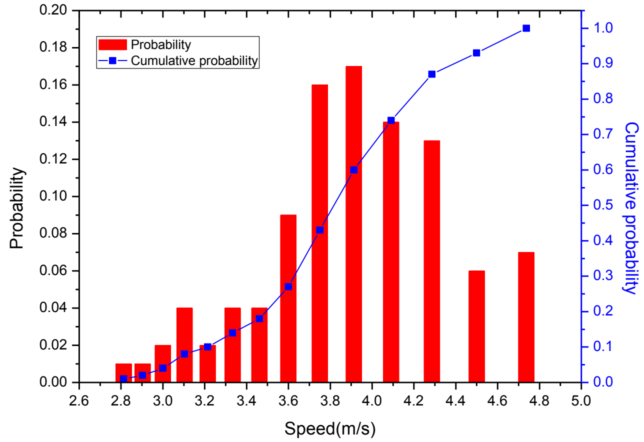

Fig. 2. Probability and cumulative probability of pedestrian movement speeds in evacuation drills.

For the understanding of the characteristics of evacuation, we explored the behaviors of pedestrian by analyzing the results of questionnaires. Finally, we collected 190 valid questionnaires, even though we sent out 300 questionnaires, because that the time was limited for the participants who were eager to conduct their morning work to complete the whole questionnaire. From the results of questionnaire, we found that 97% of the participants were the staffs of the retail store, average 30 years of age. Besides, 95% of the participants have attended fire evacuation drill and safety training.

It is found that when participants hear the fire alarm, 40.53% of participants chose running toward to exits, followed by 25.95% and 25.41% of participants chose calling the police immediately and informing others, respectively. The results reflect the fact that the staffs who have attended fire evacuation drill and safety training could evacuate properly and could also inform the customers or others to evacuate immediately, which is beneficial to the safety evacuation of the retail store in emergency situations. Moreover, we found that 63.24% of participants might choose the nearest exit, and only 13.51% of participants might choose the most familiar exit in the emergency situations. It should be noted that most participants in our questionnaire survey were familiar with the building, so the results may be different for people who are not familiar with the building, just as Sekizawa [9] stated that people are likely to choose the route they usually use rather than a closer route, which was obtained from a survey of occupants who experienced the apartments fire in Hiroshima City. As for the behaviors of people seeing someone running with panic, 70.05% chose the option of enquiring situations, which demonstrates that someone's panic emotion could barely influence the staffs' emotion and they prefer checking the serious of the situation before taking actions. If congestion happened in front of the participants, 47.57% of them might wait patiently, and 31.35% of them might detour to avoid the congestion, which shows that most participants are more likely to avoid being caught in the congestion situations. However, the results may be different if the participants are not familiar with building and/or if they are in a real emergency situation. More research and investigation are needed in future to capture the detailed characteristics of pedestrian evacuation in emergency situations.

3.2. Evacuation time and specific flow

The process of evacuation can be divided into three phases, including the cue validation phase, decision-making phase and movement phase [10]. The time that the occupants spend on the cue validation phase and decision-making phase can be defined as pre-movement time [11], and the time that the occupants spend on the movement phase can be defined as movement time [12]. The pre-movement time and movement time constitute the total evacuation time. However, in our evacuation drills, the participants were told evacuating immediately when they heard the fire alarm, so the pre-movement time can be ignored and the movement time can be regarded as evacuation time. Emergency door capacity, which may be influenced by the door width, population composition and stress level [13], is a fundamental parameter to assess the evacuation safety of buildings, stadiums, subway stations or some other places with a high density of people. In this section, we will analyze the evacuation drills from the aspects of the evacuation time and exits capacity. Table 3 presents the cumulative evacuees and evacuation time in different exits of each evacuation scenario.

Table 3. Cumulative evacuees and evacuation time of each exit in different evacuation scenarios

Evacuation scenarios	Exits	Width of exits(m)	Cumulative evacuees	Evacuation time(s)
Scenario one	3	1.7	58	18.86
	4	3.0	131	29.44
	7	1.4	51	18.72
	8	1.6	72	17.48
Scenario two	3	1.7	26	25.68
	4	3.0	110	25.84
	7	1.4	74	20.51
	8	1.6	89	15
Scenario three	3	1.7	89	26.64
	4	3.0	190	32.8
Scenario four	3	1.7	69	21.56
	4	3.0	163	29

First, we take into account the scenario one and scenario three, which have the same inhomogeneous pedestrian distribution. It can be seen from Table 3 that when the fire doors of adjacent fire compartment are useable, the evacuation times of exits 3, 4, 7 and 8 are 18.86s, 29.44s, 18.72s and 17.48s respectively. Therefore, the total evacuation time in this scenario is 29.44s. When the fire doors of adjacent fire compartment are unusable, the evacuation times of exits 3, 4 are 26.64s, 32.8s respectively. Therefore, the total evacuation time in this scenario is 32.8s. Meanwhile, the cumulative evacuees in scenario one and scenario three are 312, and 279 respectively, as shown in Table 1. We might draw the conclusion that the evacuation time will be reduced when the fire doors of adjacent fire compartment are useable, even though there were more participants in evacuation process. However, it should be noted that the total width of exits in scenario one and scenario three is different, so we should introduce a new parameter exit capacity to assess the evacuation efficiency of different scenarios.

$$C=(\sum_{i=1}^{m} n_i)\Big/[(\sum_{i=1}^{m} w_i)\times \max\{t_1,t_2,t_3,t_4\}] \qquad (i=1,2,3,4) \tag{1}$$

$$C=(\sum_{i=1}^{m} n_i)\Big/[(\sum_{i=1}^{m} w_i)\times \max\{t_1,t_2\}] \qquad (i=1,2) \tag{2}$$

The exits capacity of scenario one and two can be calculated by Equation (1), while the exits capacity of scenario three and four can be calculated by Equation (2). Where, i=1,2,3,4 represent the exits 3, 4, 7 and 8 respectively, C denotes the exits capacity; n denotes the evacuees from one exit in each scenario; w represents the width of one exit and t represents the evacuation time from one exit. The total evacuees and width of exits can be found in Table 1 and Table 3, so we could obtain the results that the exit capacity of scenario one is 1.38person/ms and the exit capacity of scenario three is 1.89person/ms, as shown in Fig. 3. The results show that the exit capacity decreases with the fire door of adjacent fire compartments useable. One reason accounting for the decrease of exit capacity might be that more participants chose exit 4, which induced the increase of evacuation time through exit 4. Therefore, the obvious unbalance of exit usage occurred in the evacuation process. Except for this reason, another possible explanation for the decrease of exit capacity might be due to the limited number of participants. Because of the limited number of participants, participants could evacuate through exits 3 and 4 without congestion in scenario three, then, in this situation, the usable of exits 7 and 8 in scenario one could not enhance the evacuation efficiency sharply. Based on the analysis above, we could infer that the usable of fire door of adjacent fire compartments could increase the evacuation efficiency when the pedestrian density in the fire compartment increases to some extent. Moreover, from Fig. 3, it is also found that the exit capacity of scenario two (1.50persons/ms) is less than the exit capacity of scenario four (1.70 persons/ms), which is similar to the results between the scenario one and scenario three.

Then, the influence of pedestrian distribution on evacuation process is discussed. From Fig. 3, it is found that in the condition of the fire doors of adjacent fire compartment useable, the total evacuation times for scenario one and scenario two are 29.44s and 25.84s respectively, and the exits capacities for scenario one and scenario two are 1.38 person/ms and 1.50 person/ms respectively. Meanwhile, in the condition of the fire doors of adjacent fire compartment unusable, the total evacuation times for scenario three and scenario four are 32.8s and 29s respectively, and the exits capacities for scenario three and scenario four are 1.81 person/ms and 1.70 person/ms respectively. It should be noticed that the number of participants in scenario two is less than scenario one, and the number of participants in scenario four is less than scenario three. Therefore, the decreases of evacuation time in scenario two and in scenario four can be attributed to the decreases of the number of participants. Moreover, we can see that the differences of exit capacity caused by different pedestrian distribution are not significant. The reason accounting for this phenomenon might be that the participants began evacuation immediately with higher velocities when they heard the fire alarm. Therefore, the distance difference of participants can be ignored in the evacuation process.

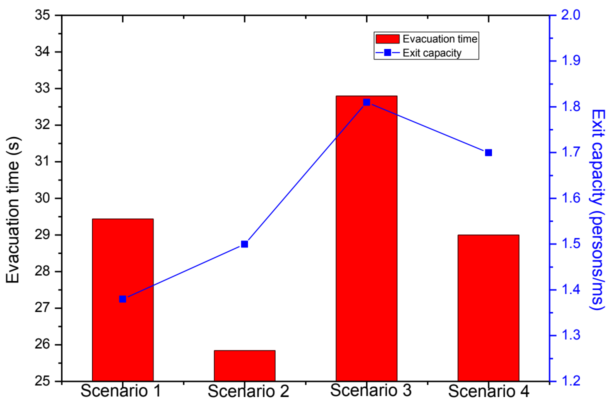

Fig. 3. Illustration of the total evacuation time and exit capacity in different evacuation scenarios.

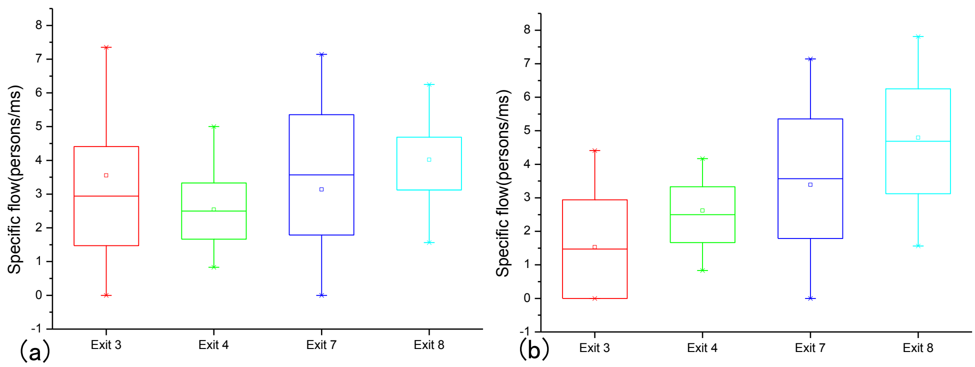

Fig. 4. Plots of specific flow of pedestrians walking through different exits in evacuation scenario one (a) and evacuation scenario two (b).

Besides, for the analysis of the evacuation efficiency of exits 3, 4 and exits 7, 8, we presented the specific flow of these exits in scenario one and scenario two, as shown in Fig. 4. The numbers of evacuees through each exit are recorded manually every 0.4s, then the specific flow of each exit can be obtained. We can see that the mean specific flows on exit 7 and exit 8 have relatively higher values, which represents that the fast and efficient flows occurred in exit 7 and exit 8. One possible explanation might be that participants will evacuate to the final destinations after they pass the exit 7 and exit 8, and no potential obstacles obstruct the movement of participants. In the contrary, participants might stay when they pass the exit 3 and exit 4, because that the fire-protection passageway adjacent to the exit 3 and exit 4 is their final destinations, and the standing participants might obstructs the movement of participants behind. The results reflect the fact that obstacles nearby the emergency exits should be removed and the clustering places for evacuees should be far away from the emergency exits.

4. Conclusions

Aiming at understanding the characteristics of pedestrian movement in emergent situations, evacuation drills from an underground retail store were conducted followed by a questionnaire survey. The parameter of exit capacity was introduced to assess the evacuation efficiency in different evacuation scenarios. Based on the results, the pedestrian evacuation behavior, evacuation time and specific flow in different evacuation scenarios were analyzed and discussed. The main conclusions can be summarized as follows:

- The useable fire door of adjacent fire compartment reduces the possibility of congestion in emergency exits, increases the evacuation routes for occupants in the underground retail store. Meanwhile, the usable fire door of adjacent fire compartments could also increase the evacuation efficiency when the pedestrian density in the fire compartment increases to some extent.
- The phenomenon of unbalance exit selection happened in the process of evacuation drill, and more appropriate guidance devices are needed in the retail store to assist occupants to select the exits properly.
- The staffs who have attended fire evacuation drill and safety training could evacuate properly and could also inform the customers or others to evacuate immediately, which is beneficial to the safety evacuation of the retail store in emergency situations.
- The differences of exit capacity caused by different pedestrian distributions are not significant because of the higher velocities of the participants.
- Obstacles nearby the emergency exits should be removed and the clustering places for evacuees should be far away from the emergency exits.

The data and results presented in the present paper are useful in providing fundamental parameters to the assessment of building safety and corresponding evacuation models and are also useful for building designers.

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References

[1] Gwynne, S., 2010. “Conventions in the collection and use of human performance data,” NIST GCR 10-928.
[2] Ma, J., Song, W. G., Tian, W., Lo, S. M., Liao, G. X., 2012. Experimental study on an ultra high-rise building evacuation in China, Safety Science 50, p. 1665.
[3] Proulx, G., 2007. “High-rise office egress: The human factors,” Architectural Engineering Institute of the American Society of Civil Engineers Symposium on High-rise Building Egress, New York City, May 15, 2007.
[4] Shields, J., Boyce, K, 2000. A study of evacuation from large retail stores, Fire Safety Journal 35, p. 25.
[5] Shields, J., Boyce, K, Silcock, G. W. H., 2000.Towards the characterization of large retail stores, Fire and Materials 23, p. 325.
[6] Samochine, D, Boyce, K., Shields, J., 2005. “Investigation into staff behaviour in unannounced evacuations of retail stores - Implications for training and fire safety engineering,” Fire Safety Science - Proceedings of the 8th International Symposium, International Association for Fire Safety Science, pp. 519-530.
[7] Cheng, X. D., Zhang H. P., Xie Q. Y., Zhou, Y., Zhang H. J., Zhang C. J., 2008. Study of announced evacuation drill from a retail store, Building and Environment 44, p. 864
[8] Ma, J., Song, W. G., Fang, Z. M., Lo, S. M., Liao, G. X., 2010. Experimental study on microscopic moving characteristics of pedestrians in built corridor based on digital image processing, Building and Environment 45, p. 2160.
[9] Sekizawa, A., Ebihara, M., Notake, H., Kubota, K., Nakano, M., Ohmiya, Y., and Kaneko, H., 1999. Occupants’ behavior in response to the high-rise apartments fire in Hiroshima City, Fire and Materials 23, p. 297.
[10] Kobes, M., Post, J., Helsloot, I., Vries, B., 2008. “Fire risk of high-rise buildings based on human behavior in fires,” In: Conference Proceedings FSHB 2008. First International Conference on Fire Safety of High-rise Buildings, Bucharest, Romania, May 07-09.
[11] Gwynne, S., Galea, E., Parke, J., Hickson, J., 2003. The collection and analysis of pre-evacuation times derived from evacuation trails and their application to evacuation modeling, Fire Technology 39, p. 173.
[12] Proulx, G., 1995. Evacuation time and movement in apartment buildings, Fire Safety Journal 24, p.229.
[13] Daamen, W., Hoogendoorn, SP., 2010. Emergency door capacity: influence of door width, population composition and stress level, Fire Technology 48, p. 55.