ISSN 1 746-7233, England, UK
World Journal of Modelling and Simulation
Vol. 15 (2019) No. 1, pp. 25-32

Modelling and Simulation of Evacuation Dynamics in Fire by Cellular Automata Model*

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(*Received December 02 2017, Accepted July 21 2018*)

Abstract. Since a fire is one of the most serious disasters, we need to reduce the potential of damages such as injury and burn, which can be caused by high heat flux from the burning area with strong luminous flames, gas explosions, and carbon monoxide contained in smoke. In order to mitigate these damages, it is important to consider the appropriate room design with exits in the building for setting a safe evacuation route, coupled with fire protection equipment such as fire extinguishers, sprinklers and alarms. Additionally, an appropriate fire evacuation drills in periodic is important. In this study, a numerical simulation of evacuation dynamics in fire was demonstrated. First, the spread rate of burning area in fire was evaluated by FDS (Fire Dynamics Simulator), which is a large-eddy simulation (LES) based CFD code of fire dynamics. Next, the room evacuation in fire was simulated by using predicted spread rate by FDS. We considered two more cases without fire for discussion of evacuation dynamics. We changed the number of evacuees in order to discuss the evacuation time and the evacuation route. Interesting findings are the scaling of the evacuation time based on evacuee's density.

Keywords: evacuation, simulation, fire, cellular automata

1 Introduction

Recently, various types of buildings have been constructed in the area markedly concentrated in urban cities. Since a fire is one of the most serious disasters, we need to reduce the potential of damages such as injury and burn, which is mainly caused by high heat fluxes from the burning area with strong luminous flames, accidental explosions, and toxic species in smoke[4]. The combustion of organic materials accompanied by high temperature and huge heat release rate produces a great amount of smoke and toxic gases[20]. The hot smoke of building fires is also a critical problem for fire protection. The safety of the occupants and firefighters in the contaminated area is severely affected by this fire-induced hot smoke[11]. Thus, it is important to predict the flame spread of flammable materials in the fire precisely.

On the other hand, for risk analysis in building fire, we need to consider many factors such as fire-fighting assessment. One is indoor emergency response which could play an important role in disaster management for many cities. It is reported that, in case of China with rapid urbanization, the indoor emergency response is critically necessary[9]. In order to mitigate the damages, it is important to consider the appropriate room design with exits in the building for setting a safe evacuation route, coupled with fire protection equipment such as fire extinguishers, sprinklers and alarms. Even in case of a forest fire, Nauslar et al. has examined extreme fire events which impacted Southern California fire in late 2017. For a case study, they have discussed further fire suppression, along with limited evacuation protocols[7]. As for a new trial, a mobile interface for emergency cases is garnering attention, because it is a real-time, dynamic and user specific evacuation tool for finding a personal route for evacuation[1]. To couple such a system with the effective placement of fire prevention

* Authors want to thank Dr. Sinnosuke NISHIKI for supporting FDS code.
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Published by World Academic Press, World Academic Union

equipment, it is necessary to understand the fire phenomenon and simulate the fire evacuation plan in advance. Moreover, a time-aware routing map could be useful for the indoor evacuation[21].

In our recent study [16], we have simulated a tunnel fire to discuss the evacuation time. The effects of the wind velocity and the number of evacuees in the tunnel have been revealed. Resultantly, it could be crucial to predict an evacuation situation in which a fire breaks by performing a numerical simulation and evaluating the evacuation safety. These give us useful information on the design of the exit route for evacuation. Additionally, an appropriate fire evacuation drill in periodic is needed. For this purpose, we must predict evacuees' behaviors in case of fire, and it is very useful to propose an evacuation model for buildings in emergency situations[10]. However, a demonstration experiment assuming an actual fire is difficult to perform; therefore, the simulation of fire evacuation is highly demanded.

To model the evacuation situation and simulate the evacuation dynamics in fire, several researches have been conducted. Lizhong et al. examined the human behavior and proposed the evacuation model using cellular automata[19]. Here, we try to model the evacuation process in case of the compartment fire. Since the evacuation dynamics are described by collective evacuees' behaviors, there are some difficulties to conduct the evacuation simulation by solving coupled differential equations[3]. As one of the alternative approaches for evacuation dynamics, the so-called Cellular Automata (CA) model has been proposed, where the time and space are all discrete. In the classical CA model originally for pedestrian dynamics[2, 8], the von Neumann neighbourhood was adopted. The evacuee is moved to the nearest cell at next time step, but its movement is limited only four-direction: forward, backward, left, and right. Recently, we have proposed a new model, which is called the real coded Cellular Automata (RCA)[12–14]. It is possible to treat evacuee's movement in any direction and any velocity. So far, several results have been presented, showing the lane formation in the street as well as the bottleneck in the room evacuation. It is confirmed that RCA can be a good tool for the simulation of the evacuation dynamics.

The present study demonstrates the evacuation dynamics in room fire, using RCA model. Needless to say, the phenomena in actual fires are very complex, because the process in fire includes many aspects including fluid dynamics, heat and mass transport, and chemical reaction. In former studies, the flame spread rate was examined for describing the fire properties[15, 17, 22]. From the novel researches, it is well known that there are many key factors essential for the fire safety management. Although, in terms of the scale modelling, it could be possible to conduct smaller-scale experiments for description of full-scale fire[5], but still, there are many difficulties for considering the large-scale fire with real size. Then, for the prediction of room fire, we use a validated CFD code in fire engineering, FDS (Fire Dynamics Simulator[6, 18]). The code has been developed by the National Institute of Standards and Technology (NIST), and it is based on a large-eddy simulation (LES) code for low-speed flows in fire. Firstly, the burning area of the room fire can be well predicted for evacuation simulation. Secondly, the evacuation dynamics in fire is simulated by using predicted spread rate of burning area. We consider two other cases without fire. One is that we set the obstacle in the room, in order to examine the effect of fire spread which affects the evacuation dynamics. We change the number of evacuees to discuss the evacuation time and the evacuation route.

As already explained, the background and the objective have been described. The rest of the paper is organized as follows. In the next section, the numerical method is drawn. The brief introduction of the RCA model and its numerical approach are given. In Section 3, the numerical results related with the room evacuation in fire are presented to show the potential of the RCA simulation. In Section 4, conclusions and issues for further research are summarized.

2 Numerical method

2.1 Real-coded cellular automata (RCA)

The movement of each evacuee is determined automatically by the floor field, which is the distance from the exit (see Fig. 3)[8, 12]. Based on the floor field, all evacuees in the room could reach the exit along the shortest route. Different from the classical CA model[2, 3, 8], the evacuee's speed can be set freely. However, on the way to the exit, there may be the burning area in the room. In this case, evacuees need to avoid the burning area.

This process is explained in Fig. 1. Two specified areas are given. One is the evasive area I, where the evacuee goes around the burning area on the inflammable floor. The other is the evasive area II. When an evacuee enters this region, the evacuee is kept away from the burning area. Specifically, the evacuee is forced to move outward in the direction on which the burning area expands. The width of each evasive area is L. In this study, L is set to be 1.6 m, but it could be a parameter to keep the evacuee's safety[12]. After the evacuee is out of these evasive areas, he keeps moving toward the exit based on the floor field.

2.2 Calculation domain and conditions

In this paper, we considered three cases for the room evacuation, corresponding to cases A, B, and C. First two cases are those without fire. Only in case C, we consider the fire. We explain each calculation domain in Fig. 2. The evacuation simulation is conducted in 2D of (x, y). The room (floor) size is 16 m $\times$ 16 m, and the width of the exit on the right is 2.4 m. There is an origin at the centre of the room, and the exit is located at y = 8 m. In case A, all evacuees can move freely, because there are no obstacles in the room. In case B, we set one square obstacle at the centre of the room, which is the simplification of burning area. The obstacle size is 6 m$\times$6 m. In case C, there is a fire. As explained later, the burning area expands from the centre of the room. The part of the floor is made of inflammable polyurethane, which has circular shape whose diameter is 8 m shown by a dotted circle. Only the floor of polyurethane is burned.

The mapping of the floor field in cases A and B are shown in Fig. 3. On each grid, the floor field of ϕ is given, which describes each evacuee's motion toward the exit. The advantage is that the evacuee's direction to the exit is automatically determined by the floor field. The unit vector of the evacuee's velocity is given by

$$\begin{cases} -e_x = \cos\theta = \partial r/\partial x = \varDelta\phi/\varDelta_x \\ -e_y = \sin\theta = \partial r/\partial y = \varDelta\phi/\varDelta_y \end{cases} \tag{1}$$

In the simulation, the time step of $\varDelta_t$ is 0.3 s, and the spatial grid of $\varDelta_x$ or $\varDelta_y(= \varDelta)$ is 0.4 m[8, 18]. In this evacuation simulation, this spatial mesh size exactly matches the typical shoulder width. Hence, each mesh can be occupied by one evacuee. The same mesh size is used in the fire simulation of FDS. In the present simulation, the number of the evacuees in the room, N, was varied, but the evacuee's moving speed was set to be the constant of 1.6 m/s. The simulation was performed five times by changing the initial locations of evacuees, and the average of the evacuation time was calculated and discussed.

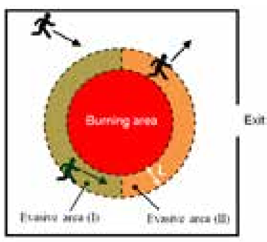

Fig. 1: Evacuee's movement to the exit in case of fire

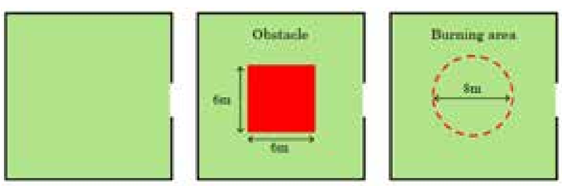

Fig. 2: Calculation domain; three cases A to C are considered

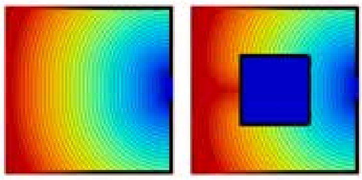

Fig. 3: Floor field in case A (left) and case B (right)

3 Results and discussion

3.1 FDS simulation of room fire

As already mentioned, the FDS code was used to evaluate the flame spread rate of burning area. The detail of the calculation method is not described here, but it is based on Large Eddy Simulation (LES), where the combustion field is determined by the governing equations with filtered discrete equations.

Fig. 4 shows the numerical domain of the room fire. It is a 3D simulation, and the room height is set to be 3 m in this case. The total size is 16 m × 20 m × 3 m, because the corridor is placed next to the room. At the centre of the room, the heat source is placed for initiating the fire spread. As already explained, the exit width is 2.4 m, and the grid size is 0.4 m. These values are the same as those of the evacuation simulation, but the time step is different. In FDS code, the time step is automatically chosen for numerical stability.

First, the combustion field calculated by FDS code is briefly explained. Fig. 5 shows the profiles of temperature and heat release rate. The time after the ignition is counted. These are obtained at t = 14.1 s. In Fig. 5(a), two temperature profiles are shown. One is the profile in the $y - z$ plane at x = 0 m. The other is the profile at z = 0 m, together with the mesh location on the floor. Due to the dynamics of the fire plume, the temperature field is largely fluctuating. In 5(b), the profile of the heat release rate corresponds to the region where the heat release rate is over 50 kW/m^3. It shows that the fire plume reaches the ceiling. On the floor, the sharp temperature rise is observed, which is due to the burning of polyurethane. Also, we confirmed that the complex flow pattern is observed, strongly coupled with the burning area of large heat release rate. As the time goes on, the burning area expands.

To simulate the evacuation dynamics in room fire, the information of time-dependent burning area was needed. The burning area was determined by the region where the temperature at z = 0.4 m is over 200 °C. In Fig. 6, the temperature distributions evaluated by FDS code are shown. These are profiles at t = 12, 13.2, and 14.1 s. As shown in these figures, the burning area expands from the centre, and the expansion was in almost a concentric configuration. Then, in the evacuation simulation, the circular fire spread is assumed.

Fig. 7 shows the temporal change in the radius (R) of the burning area, corresponding to the locations where the temperature reaches 200 °C. Based on the region where the temperature exceeds 200°C, the averaged radius of the burning area was specified. It is found that the burning area begins to expand approximately 8 s after initiating the calculation, and the expansion velocity was almost constant, corresponding to the slope in Fig. 7. The flame spread rate of burning area was 0.8 m/s. Then, we used this value in the evacuation simulation in the room fire.

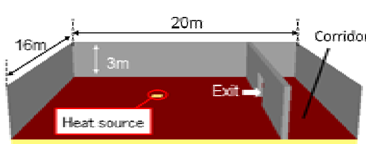

Fig. 4: Numerical domain by FDS is shown, with location of a heat source for ignition

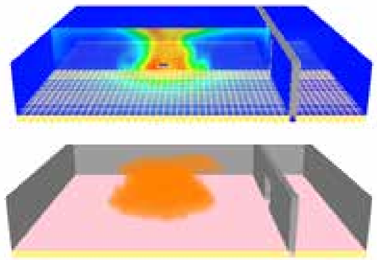

Fig. 5: Combustion field calculated by FDS at t = 14.1 s. Upper figure shows the temperature profile and lower figure shows the profile of the heat release rate

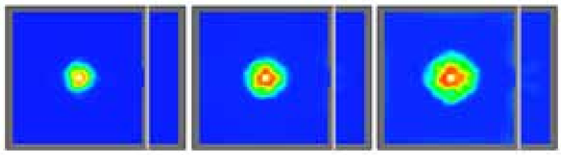

Fig. 6: Profiles of temperature at z = 0.4m; t = 12 s (left), t = 13.2 s (middle), and t = 14.1 s (right)

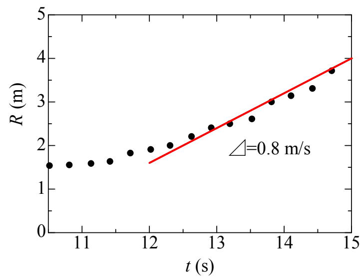

Fig. 7: Radial position of burning area is shown with the slope of spread rate of burning area

3.2 Evacuation simulation

Figs. 8 and 9 show the time evolution of evacuees' location in cases A and B. In these figures, the dot and arrow express the location and the movement direction, respectively. For both cases A and B, initial number of evacuees in the room (N) is 100. In case A, all evacuees can move to the exit directly. It is found that, depending on the number of N, the bottleneck of evacuee's crowded area appears at the exit[2, 12–14]. On the other hand, in case B, most of evacuees in the room bypass the obstacle and take the longer route. Therefore, two bottlenecks are observed on the corner of the obstacle and at the exit.

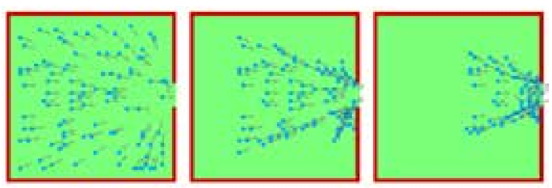

Fig. 8: Evacuation in case A of N = 100; t = 0 s (left), t = 2 s, (middle), t = 7 s (right)

Next, we change the number of evacuees in the room. Expectedly, as N is larger, more evacuees are crowded at the exit, because there is a limitation that the evacuee can go through the exit. Fig. 10 shows the evacuation time (T_E) by changing the number of evacuees in cases A and B. The evacuation time (T_E) is the total time when all evacuee passes through the exit. It should be noted that the evacuation time (T_E) could be

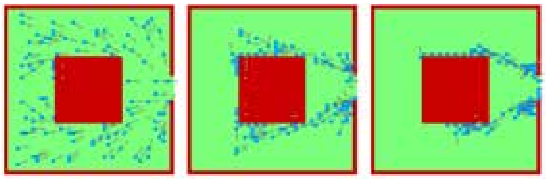

Fig. 9: Evacuation in case B of N = 100; t = 0 s (left), t = 2 s, (middle), t = 7 s (right)

slightly changed by the given initial evacuees location. Thus, as already mentioned, the averaged evacuation time was obtained by changing initial locations of evacuees for five simulations.

In case A, as N is larger, more people gather at the exit. Then, the evacuation time becomes longer, as N increases. In case B, the similar tendency is observed if N is smaller than 80. However, when N is over 80, the evacuation time suddenly increases, because the congestion appears on both on the corner of the obstacle and at the exit, which is shown in Fig. 9. It corresponds to the well-known bottleneck in the evacuation dynamics[12–14]. The evacuation time (T_E) in case B is always longer than that in case A. This is caused by the longer evacuation distance when the obstacle is placed in the room. Additionally, as already mentioned, more congestion is observed on the corner of the obstacle.

Finally, the evacuation dynamics in fire is discussed. Fig. 11 shows the fire evacuation in case C at N = 100. These are results at t = 0, 2, and 7 s after initiating the calculation. As shown in this figure, there are two types of evacuees; i.e., some directly move toward the exit and others are bypassed to avoid the burning area. Moreover, after t = 6.0 s, the bottleneck at the exit is observed.

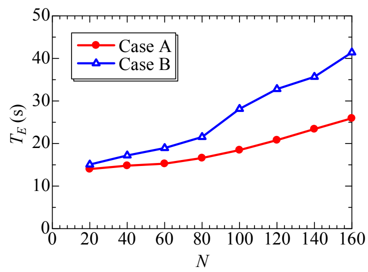

Fig. 10: Variation of evacuation time with the number of evacuees in room

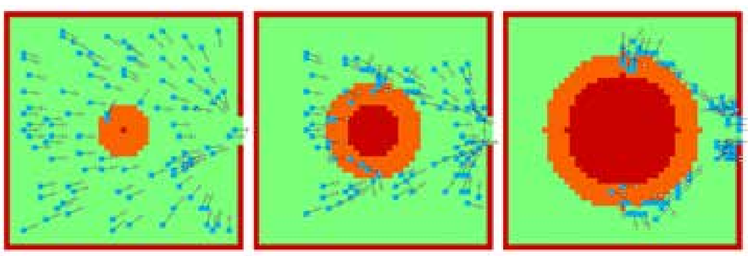

Fig. 11: Evacuation in case C of N = 100; t = 0 s (left), t = 2 s, (middle), t = 7 s (right)

Next, we investigated the evacuation time in case C by changing N. Results are shown in Fig. 12, together with the results of cases A and B. In case C, as N is larger, more people must evacuate from the room. They need to avoid the burning area, and the evacuation route is longer. This situation is quite similar to that of case B. However, as seen in Fig. 11, less congestion between evacuees is observed. This may be because the burning area is always expanding, and the distance between evacuees is gradually increased, resulting in the smooth evacuation dynamics. Needless to say, as seen in Fig. 12, the evacuation time is longer than that of case A, but is shorter than that of case B if N is larger than 60.

For further discussion, we examined the evacuation time based on the evacuee's density, S, which corresponds to the number of evacuees divided by the evacuee's space where evacuee can move freely in the room. For example, as for case B, S is the evacuee's number divided by the room size subtracted by the obstacle area. In case C, it is the value of N divided by non-inflammable area. Results are shown in Fig. 13. Interestingly, if S is larger than 0.4 1/m^2, the evacuation time of cases A and C is almost the same, but the evacuation time of case B at fixed S is much longer. Therefore, the evacuation time in fire can be estimated by the evacuee's density. We conclude that it could be an important parameter to model the congestion for the evacuation in the room fire.

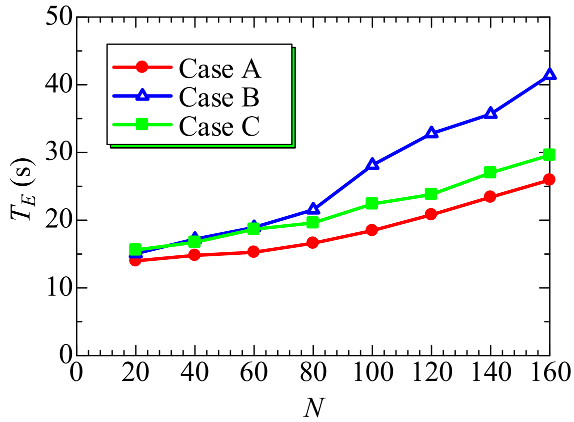

Fig. 12: Variation of evacuation time with the number of evacuees in room

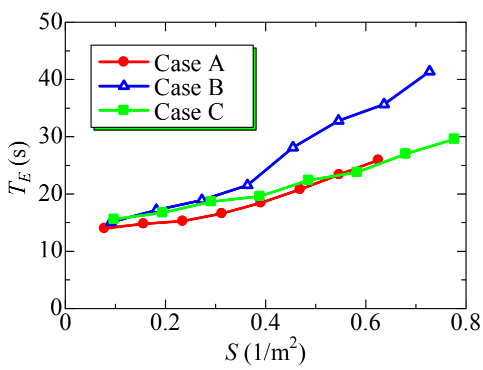

Fig. 13: Variation of evacuation time with the evacuee's density in room

4 Conclusion

In the present study, the evacuation simulation in the room fire was conducted using the real coded Cellular Automata (RCA). The flame spread rate of the burning area was predicted by the Fire Dynamics Simulator (FDS). To examine the evacuation dynamics in fire, we considered three cases: no fire in case A, one obstacle at the centre in case B, fire in case C. Following results were obtained.

1. In the situation of fire in which a part of floor was made of inflammable polyurethane, the combustion field was numerically reproduced. Based on the high temperature region with large heat release rate, the burning area was simply widened with the fire plume. Initially, the burning area was slowly enlarged right after the ignition, but the spread rate of burning area was almost constant after t = 8 s, showing the flame spread rate of 0.8 m/s.

2. In case A, all evacuees can move toward to the exit directly. Depending on the number of evacuees, the bottleneck of evacuee's crowded area appears at the exit. On the other hand, in case B, most of evacuees in the room bypass the obstacle and take the longer route. Therefore, two bottlenecks are observed on the corner of the obstacle and at the exit. In case C with fire, some evacuees who can move toward the exit directly are not affected by the burning area. However, others must keep away from the burning area and take the longer route.

3. The evacuation time becomes longer as the number of evacuees in the room increases. Expectedly, the evacuation time in cases B and C is longer than that in case A. Especially, the evacuation time in case B is the longest because of more bottlenecks.

4. To predict the evacuation time in advance, a useful parameter was proposed. It is the evacuee's density, corresponding to the number of evacuees divided by the evacuee's space where evacuee can move freely in the room. Resultantly, in cases A and C, the evacuation time is the same value at the condition when the evacuee's density is the same. In terms of the evacuee's density, it is possible to evaluate the congestion for the evacuation in the room fire. Thus, it could be an important parameter in advanced safety management.

References

[1] U. Atila, Y. Ortakci, et al. Smartescape: A mobile smart individual fire evacuation system based on 3d spatial model. *International Journal of Geo-Information*, 2018, **7**(6): 223.

[2] C. Burstedde, K. Klauck,et al. Simulation of pedestrian dynamics using a two-dimensional cellular automaton. *Physica A Statistical Mechanics & Its Applications*, 2001, **295**(3): 507–525.

[3] D. Helbing, I. Farkas, T. Vicsek. Simulating dynamical features of escape panic. *Nature*, 2000, **407**(6803): 487–490.

[4] T. Hirano. Combustion science for safety. *Proceedings of the Combustion Institute*, 2002, **29**(1): 167–180.

[5] T. Hirano, K. Saito. Fire spread phenomena: The role of observation in experiment. *Progress in Energy & Combustion Science*, 1994, **20**(6): 461–485.

[6] H. Huang, C. Su, et al. Enhancement of fire safety of an existing green building due to natural ventilation. *Energies*, 2016, **9**(3): 192.

[7] N. Nauslar, J. Abatzoglou, P. Marsh. The 2017 north bay and southern california fires: A case study. 2018.

[8] K. Nishinari, A. Kirchner, et al. Extended floor field ca model for evacuation dynamics. *Ieice Transactions on Information & Systems D*, 2003, **87**(3): 726–732.

[9] L. Niu, Y. Li, Y. Zhou. A dynamic indoor field model for emergency evacuation simulation. *ISPRS International Journal of Geo-Information*, 2017, **6**(4): 104.

[10] L. O. S. M., Z. Fang. A spatial-grid evacuation model for buildings. *Journal of Fire Sciences*, 2000, **18**(5): 376–394.

[11] Z. Xing, J. Mao, et al. Scaled experimental study on maximum smoke temperature along corridors subject to room fires. *Sustainability*, 2015, **7**(8): 11190–11212.

[12] K. Yamamoto. *Evacuation Simulation in Floor Field by Real-Coded Cellular Automata*. DBLP, 2008.

[13] K. Yamamoto, S. Kokubo, K. Nishinari. *New Approach for Pedestrian Dynamics by Real-Coded Cellular Automata (RCA)*. Springer Berlin Heidelberg, 2006.

[14] K. Yamamoto, S. Kokubo, K. Nishinari. Simulation for pedestrian dynamics by real-coded cellular automata (rca). *Physica A Statistical Mechanics & Its Applications*, 2012, **379**(2): 654–660.

[15] K. Yamamoto, Y. Ogata, H. Yamashita. Flame structure and flame spread rate over a solid fuel in partially premixed atmospheres. *Proceedings of the Combustion Institute*, 2011, **33**(2): 2441–2448.

[16] K. Yamamoto, Y. Sawaguchi, S. Nishiki. Simulation of tunnel fire for evacuation safety assessment. 2018, **4**(2): 12.

[17] K. Yamamoto, S. Seo, K. Mori. Thermal structure of flame spread in partially premixed atmospheres and effects of fuel lewis number. *Proceedings of the Combustion Institute*, 2014, **35**(3): 2589–2596.

[18] K. Yamamoto, Y. Takeuchi, S. Nishiki. Effects of a sprinkler on evacuation dynamics in fire. *Computation*, 2015, **3**(2): 274–284.

[19] L. Yang, W. Fang, W. Fan. Modeling occupant evacuation using cellular automata - effect of human behavior and building characteristics on evacuation. *Acoustics Speech & Signal Processing Newsletter IEEE*, 2003, **21**(3): 227–240.

[20] T. Zhang, X. Zhou, L. Yang. Experimental study of fire hazards of thermal-insulation material in diesel locomotive: Aluminum-polyurethane. *Materials*, 2016, **9**(3): 168.

[21] H. Zhao, S. Winter. A time-aware routing map for indoor evacuation. *Sensors*, 2016, **16**(1): 112.

[22] K. Zhao, X. Zhou et al. Width effects on downward flame spread over poly(methyl methacrylate) sheets. *Journal of Fire Sciences*, 2015, **33**(1): 69–84.