Effects of evacuation assistant's leading behavior on the evacuation efficiency: Information transmission approach*

Wang Xiao-Lu(王晓璐)[a], Guo Wei(郭 玮)[a], and Zheng Xiao-Ping(郑小平)[b]†

[a] College of Information Science & Technology, Beijing University of Chemical Technology, Beijing 100029, China
[b] Department of Automation, Tsinghua University, Beijing 100084, China

(Received 23 December 2014; revised manuscript received 11 April 2015; published online 29 May 2015)

Evacuation assistants are expected to spread the escape route information and lead evacuees toward the exit as quickly as possible. Their leading behavior influences the evacuees' movement directly, which is confirmed to be a decisive factor of the evacuation efficiency. The transmission process of escape information and its function on the evacuees' movement are accurately presented by the proposed extended dynamic communication field model. For evacuation assistants and evacuees, their sensitivity parameter of static floor field (SFF), k_S^L, and k_S^e, are fully discussed. The simulation results indicate that the appropriate k_S^L is associated with the maximum k_S^e of evacuees. The optimal combinations of k_S^L and k_S^e were found to reach the highest evacuation efficiency. There also exists an optimal value for evacuation assistants' information transmission radius.

Keywords: information transmission, leading behavior, evacuation efficiency, cellular automata

PACS: 05.65.+b, 05.50.+q **DOI:** 10.1088/1674-1056/24/7/070504

1. Introduction

During emergency evacuation, well-trained evacuation assistants (EAs) generally have global information and greater experience, and their duty is to help evacuees escape as quickly as possible. Generally, EAs can be divided into two types in terms of functions: guider and leader. The former guides evacuees by transmitting route information with respect to the exits, and the latter leads evacuees by transferring the route information concerning his own position. When the escape routes are too complex to be understood by evacuees, EAs that act as the leader can gather evacuees and lead them toward the exit together.[1] To improve their leading efficiency, EAs have to continually shout out command signals such as "follow me", and transmit their own position information such that evacuees can find and follow them. Then it is necessary for EAs to adjust their leading speed according to the crowd's collective motions. However, EAs' personal abilities such as physical agility and event handling capability are limited. The leading efficiency is greatly influenced by the leading speed and mobilization ability of EAs, crowd's following speed, etc. Therefore, it is essential and significant to explore the factors that influence an EA's leading behavior from the perspective of information transmission.

The escape speed of the crowd directly affects the evacuation time. Based on the information transmission, the current studies mainly focus on EAs' guiding and leading speed and related factors that influence the evacuation efficiency. Both the biology studies[2,3] and human evacuation experiments[4,5] have demonstrated that the information plays an important role in the route selection process of individuals. Through their experiments, Faria *et al.*[6] concluded that the individuals with information were able to lead the group effectively and accurately to the target and that the group position of informed individuals was indeed correlated with group performance. By modeling and simulation, Aubé and Shield[7] analyzed the effectiveness of EAs' placement on crowd control. Mixing in different leader types, placing some in the immediate proximity of the crowd and others scattered around the environment, provides desirable results, and leaders that operate at approximately half the speed of other agents lead to the most efficient evacuations. Pelechano *et al.*[8] presented a "multi-agent communication for evacuation simulation", where an EA who has the complete route knowledge aimed to communicate with others during the evacuation. Yuan *et al.*[9] simulated the phenomenon of "flow with the stream" based on the cellular automaton (CA) model and showed that the route information was indirectly shared through individuals' tendency to follow behavior that improved the evacuation efficiency. Henein and White[10] introduced the role of force and developed the CA model to be more realistic in the aspect of describing the information communication process among individuals. Wang *et al.*[11] proposed the communication field (CF) model to de-

*Project supported by the National Basic Research Program of China (Grant No. 2011CB706900), the National Natural Science Foundation of China (Grant Nos. 71225007 and 71203006), the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (Grant No. 2012BAK13B06), the Humanities and Social Sciences Project of the Ministry of Education of China (Grant Nos. 10YJA630221 and 12YJCZH023), and the Beijing Philosophy and Social Sciences Planning Project of the Twelfth Five-Year Plan, China (Grant Nos. 12JGC090 and 12JGC098).

†Corresponding author. E-mail: asean@mail.tsinghua.edu.cn

© 2015 Chinese Physical Society and IOP Publishing Ltd

scribe the transmission and effect of escape information spread by EAs, showing how evacuees gradually increase the knowledge of unknown exit and escape routes after receiving the escape information. The result indicated that locating EAs near exits reduces the time delay for pre-evacuation. Hou *et al.*[12] studied the effects of the number and positions of the trained EAs in multi-exits rooms based on the SF model. The results indicated that there should be as many EAs as the number of exits, and the initial positions and responsible areas of EAs should be focused on. More and more works focus on the importance of information transmission, which is the way that EAs influence the evacuation process. However, the relationship of relative movement speed between EAs and evacuees has not attracted sufficient attention so far.

CA is a typical discrete model that is widely used in simulating pedestrian movement.[13–17] Three methods are commonly used for describing an agent's speed. The first one takes advantage of the sensitivity parameter k_S of the static floor field in the floor field model, which could control the effective walking speed.[18–22] It is based on the transition probability that an agent moves from the current position to a neighboring cell per time step. For high computational efficiency of the floor field model, it is the most common application in various scenario simulations.[23,24] The second one uses a fine division of a discrete cell.[25–27] However, the calculation consumption is a great issue that must be considered. Furthermore, only the final state of an agent's movement and conflicts in the desired new positions are considered, while the intermediate positions are ignored. The third way is to divide the time scale into multiple sub-time steps; agents of different speeds asynchronously update the position in each corresponding sub-time step.[28] Through this way, the simulation time also increases due to the successive treatment of the sub-time steps, which is not suitable for large crowd evacuation simulation. In essence, the three methods all approximate the agent's speed. In the present work, the first description method is adopted.

For the leading efficiency of EAs, an extended dynamic communication field (DCF) model is presented to describe the transmission process of an EA's dynamic position information as well as the information function on evacuees that gather around and follow the EA. The effect of the EA's leading behavior on evacuation efficiency was examined and analyzed.

2. Model

Because CA models can be used to describe the transmission and effect of information from the microscopic perspective, the CF model (based on CA) is used to describe the efficiency of an EA.[1] For the previous model, information disseminated by an EA is considered to be the shortest path from an evacuee's current position to the exit (represented by a static floor field that remains constant over time). However, when EAs show the leading behavior, their dynamic position information must be spread to the evacuees following them. Because an EA's position and leading routes change every moment during the leading process, an extended dynamic communication field (DCF) model is incorporated.

2.1. Representation of information

The route information field $S^{L(i)}$, which is time-dependent, is introduced to describe the shortest route, with the position of EA $L(i)$ as the destination. The value of $S^{L(i)}$ for position (x,y) at time t, expressed as $S^{L(i)}(x,y,t)$, is determined by the nearest distance from any position in a scene to the EA's position (a,b) and is calculated by the Euclidean measure given by

$$S^{L(i)}(x,y,t) = \max_{(x,y)}\left(s^{L(i)}(x,y,t)\right) - s^{L(i)}(x,y,t),$$
$$s^{L(i)}(x,y,t) = \sqrt{(a(t)-x)^2+(b(t)-y)^2}. \quad (1)$$

The route information of the building exit $E(i)$ is expressed as $S^{E(i)}$ (static floor field) to describe the shortest route, with the building exit's position as the destination. The complete route information for the scene S is given by

$$S = \left\{S^{E(1)},\ldots,S^{E(n)},S^{L(1)},\ldots,S^{L(m)}\right\}. \quad (2)$$

Corresponding to the scene shown in Fig. 1(a) (with an EA located in the compartment), figure 1(b) describes the value of the static floor field $S^{E(i)}$ and figure 1(c) describes the value of the route information field $S^{L(i)}$. From Fig. 1(c), one can see that the EA's position appears similar to an exit inside the scene, which also attracts the evacuees just as a building exit would.

In previous literatures, the value of k_S, as the coupling to SFF, refers to escape motivation[10,18,21] or the knowledge of escape routes.[29] Here, for individuals the sensitivity parameter k_{S^i} reflects the degree of uncertainty concerning the route information $S^i \in S$. For $k_{S^i} \to 0$, the individual is entirely ignorant of S^i, and thus would perform a pure random walk. In contrast, a larger k_{S^i} means that the individual knows more about S^i, and for $k_{S^i} \to \infty$ he is capable of knowing the whole escape routes and can make deterministic choices according to the shortest routes. This means that a larger k_{S^i} implies a larger average velocity of freely moving pedestrians. During the evacuation, evacuees would continually receive the information transmitted by EAs, thus causing their k_{S^i} to change dynamically. In contrast, the k_{S^i} of EAs would remain the same in an evacuation. For distinction, we use $k^{\mathrm{e}}_{S^i}$ to express an evacuee's k_{S^i} and use $k^{\mathrm{L}}_{S^i}$ to express an EA's k_{S^i}. Note that for all EAs, $k^{\mathrm{L}}_{S^{L(i)}}$ was ignored because an EA would not be led by other EAs.

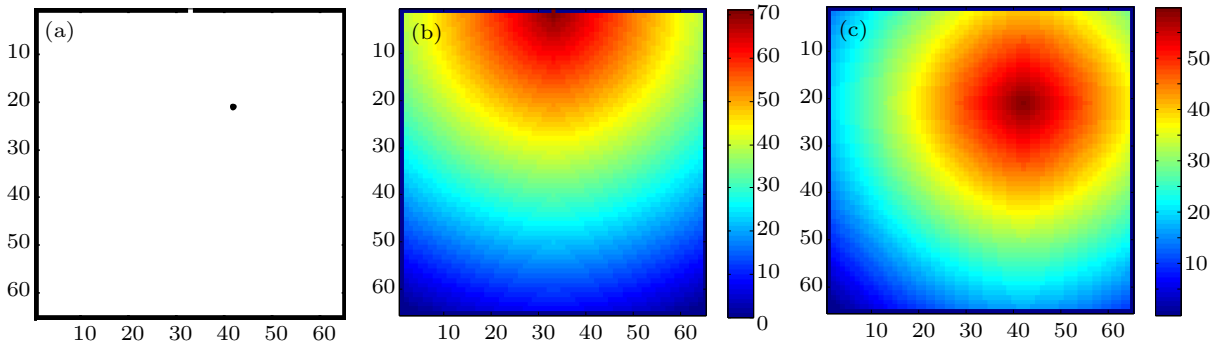


Fig. 1. (color online) Route information field value: (a) the scene; (b) with the exit as the destination; (c) with the EA's position as the destination.

2.2. Transmission and effect of information

2.2.1. The transmission of information

Analogous to the sound propagation process, some information particles are dropped by an EA at each time step, with his position as the center and within a radius of $R^{L(j)}$ m which is a key factor of an EA's mobilization ability. At the next time step, these information particles vanish. $N_{S^i}^{L(j)}$ is used to represent the number of particles that were dropped by EA $L(j)$ and express information S^i. Additionally, a release intensity H is introduced, which corresponds to the environmental noise levels. A small value of H, of which the unit is square meter to ensure that $N_{S^i}^{L(j)}$ is dimensionless, indicates a high level of noise. Thus, $N_{S^i}^{L(j)}$ in each grid within the radius $R^{L(j)}$ is determined by H and the distance $r^{L(j)}$ between the grid and the position of $L(j)$, which is indicated by

$$N_{S^i}^{L(j)} = \begin{cases} H/(r^{L(j)})^2, & r^{L(j)} \le R^{L(j)}, \\ 0, & r^{L(j)} > R^{L(j)}. \end{cases} \tag{3}$$

Figure 2 shows the information particles' instant picture. Figure 2(a) shows the transmission range at a fixed position, and figure 2(b) shows the transmission range during the dynamic process of an EA moving from the lower right corner to the exit. In addition, the transmission of information incorporates an EA's leading behavior, and the above processes constitute the complex transmission mode of information.

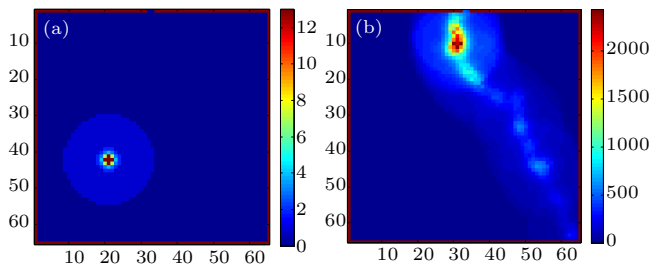


Fig. 2. (color online) Information particles' instant pictures: (a) the transmission range at a fixed position; (b) the transmission range during the dynamic process of an EA moving from the lower right corner to the exit.

2.2.2. Effect of information

As long as the current location contains information particles, evacuees at that location will receive the information. The evacuees who have received information particles will comprehend relevant escape routes S according to the specific route information, and the change rate of $k_{S^i}^{\mathrm{e}}$ is determined by $N_{S^i}^{L(j)}$. Thus, an EA can achieve leading behavior by spreading route information, with his position as the destination. At time t, the effect of $N_{S^i}^{L(j)}$ on $k_{S^i}^{\mathrm{e}}$ is assumed to be an S-type function,

$$k_{S^i}^{\mathrm{e}}(t) = \frac{k_{S^i\max}^{\mathrm{e}} + \left(2k_{S^i}^{\mathrm{e}}(t-1) - k_{S^i\max}^{\mathrm{e}}\right)\exp\left(-\sum\limits_{j=1,\ldots,m} N_{S^i}^{L(j)}\right)}{1+\exp\left(-\sum\limits_{j=1,\ldots,m} N_{S^i}^{L(j)}\right)}, \quad i \in \{E(1),\ldots,E(n),L(1),\ldots,L(m)\}, \tag{4}$$

which is monotonically increasing. Here $k_{S^i\max}^{\mathrm{e}}$ is the ceiling of $k_{S^i}^{\mathrm{e}}$.

At each time step, evacuees will choose the most advantageous escape route according to their comprehension. By using the DCF model, the transition probability P that evacuees or EAs will move from their cell (x_0, y_0) to a neighboring cell (x, y) is expressed by

$$u = \begin{cases} \underset{i\in\{E(1),\ldots,E(n),L(1),\ldots,L(m)\}}{\arg\max} \left(k_{S^i}^{\mathrm{e}} S^i(x_0,y_0)\right), & \text{for evacuees,} \\ \underset{i\in\{E(1),\ldots,E(n)\}}{\arg\max} \left(k_{S^i}^{\mathrm{L}} S^i(x_0,y_0)\right), & \text{for EAs,} \end{cases} \tag{5}$$

$$P(x,y) \propto \exp\left(k_{S^{\mathrm{u}}} S^{\mathrm{u}}(x,y) + k_{\mathrm{D}} D(x,y)\right), \tag{6}$$

where D refers to the dynamic floor field (DFF) and $k_{\mathrm{D}} \in [0,\infty)$ represents its parameter, indicating the degree of herding behavior among evacuees or EAs. Each single boson of the DFF decays with probability $\delta \in [0,1]$ and diffuses with probability $\alpha \in [0,1]$.

3. Simulation and analysis

The proposed DCF model is applied to a single-exit compartment discretized into 65×65 CA cells, with two cells representing the exit. Each cell is 0.4 m $\times$ 0.4 m and can be occupied by a pedestrian or an obstacle. In the following simulations, 400 evacuees and 1 EA are assumed. When $t = 0$, we set $k^{\mathrm{e}}_{S^{\mathrm{E}}}(0) = 0.5$ and $k^{\mathrm{e}}_{S^{\mathrm{L}}}(0) = 0$.

The update rules are described as follows.

Step 1 The room and the positions of the exits, the EA and evacuees are initialized. The value of S^{E} is calculated, and the initial value of DFF is 0.

Step 2 The value of S^{L} is calculated. The EA drops information particles. The values of the evacuees' DFF are updated. If an evacuee has received information particles, the value of his $k^{\mathrm{e}}_{S^{\mathrm{E}}}$ is changed according to Eq. (4).

Step 3 Transition probability is calculated separately for the EA and evacuees. According to the results, target cells are chosen. More than one evacuee should choose the same target cell at the same time, then one evacuee is randomly assigned to the cell, while the rest remain in their original positions.

Step 4 Evacuees who change positions generate DFF. Information particles dropped by the EA disappear.

Step 5 Upon passing through the exit and leaving the compartment, evacuees are removed from the system. The simulation ends when all evacuees have left the compartment; otherwise, Step 2 is repeated.

3.1. EA's leading effect on evacuation efficiency

For evacuees, the value of $k^{\mathrm{e}}_{S\max}$ varies within the range of $[0.5, 2]$, with an interval of 0.1. The initial position of the EA is assigned in line 64, column 33. For an EA, it is set that $R^{\mathrm{L}} = 4$ m and $k^{\mathrm{L}}_{\mathrm{S}} \in [0.3, 2]$ with an interval of 0.05. For each $k^{\mathrm{L}}_{\mathrm{S}}$, 16 simulations with different $k^{\mathrm{e}}_{S\max}$ within the range of $[0.5, 2]$ are performed 50 times. The average total evacuation times are recorded and the standard deviations were acceptable. Thus, the evacuation times for every group comprising the EA's $k^{\mathrm{L}}_{\mathrm{S}}$ and the evacuees' $k^{\mathrm{e}}_{S\max}$ are shown in Fig. 3(a). The average numbers of evacuees that the EA successfully lead during each simulation are shown in Fig. 3(b).

From Fig. 3(a), one can observe that the evacuation time could be less than 1100 time steps (which is relatively low in the current simulation scenario) in certain combinations of $k^{\mathrm{L}}_{\mathrm{S}}$ and $k^{\mathrm{e}}_{S\max}$. According to Fig. 3(b), these combinations also match a large number of evacuees led by the EA, which is approximately 300 evacuees. When considering $k^{\mathrm{e}}_{S\max} \leq 0.8$ or $k^{\mathrm{L}}_{\mathrm{S}} \leq 0.4$, the evacuation time is always longer than 1100 time steps. For each $k^{\mathrm{e}}_{S\max}$, when $k^{\mathrm{L}}_{\mathrm{S}}$ increases, the evacuation times first decrease and then increase, which indicates that there are optimal combinations of $k^{\mathrm{L}}_{\mathrm{S}}$ and $k^{\mathrm{e}}_{S\max}$ for achieving the shortest evacuation time.

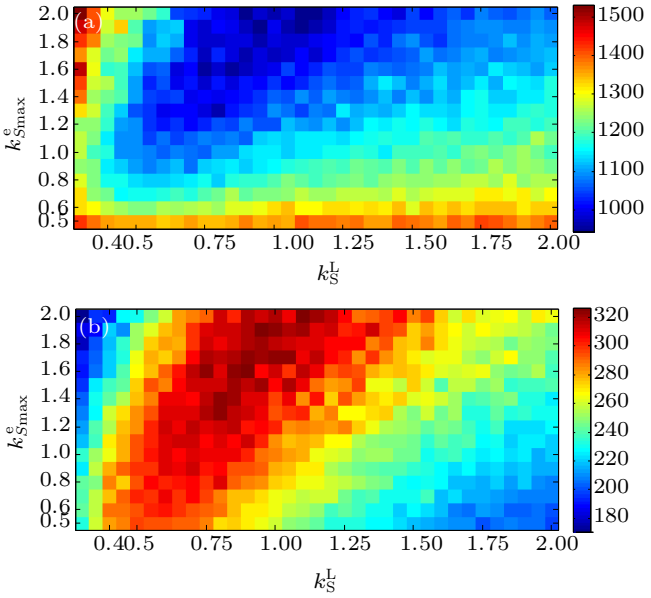


Fig. 3. (color online) For every group comprising the EA's $k^{\mathrm{L}}_{\mathrm{S}}$ and evacuees' $k^{\mathrm{e}}_{S\max}$: (a) evacuation time; (b) the number of evacuees led by the EA.

To analyze the evacuation processes with different $k^{\mathrm{L}}_{\mathrm{S}}$ and $k^{\mathrm{e}}_{S\max}$ combinations, three evacuation processes were chosen: $k^{\mathrm{e}}_{S\max} = 1.5$, $k^{\mathrm{L}}_{\mathrm{S}} = 0.3$, 0.8, 2, and the curves of the number of escaped evacuees are shown in Fig. 4. The three colored dots indicate the different exit times of the EA. For $k^{\mathrm{L}}_{\mathrm{S}} = 0.3$, the curve contains two obvious turning points. One is located at approximately the 700$^{\mathrm{th}}$ time step, and the curve exhibits a plateau until the 1000$^{\mathrm{th}}$ time step. The other one is located at approximately the 1200$^{\mathrm{th}}$ time step, and the plateau lasts for a longer time until the 1800$^{\mathrm{th}}$ time step. The EA leaves at approximately the 1900$^{\mathrm{th}}$ time step, which is near the end of the evacuation, and the total evacuation time is the longest. For $k^{\mathrm{L}}_{\mathrm{S}} = 0.8$, the curve goes up sharply after the 200$^{\mathrm{th}}$ time step and keeps moving upward until the end. The EA leaves in the middle of the process and the evacuation time is the shortest among the three simulations. For $k^{\mathrm{L}}_{\mathrm{S}} = 2$, the curve first shows a rapid growth stage, which goes up even earlier than that of $k^{\mathrm{L}}_{\mathrm{S}} = 0.8$, and soon enters the slowly rising stage (after the

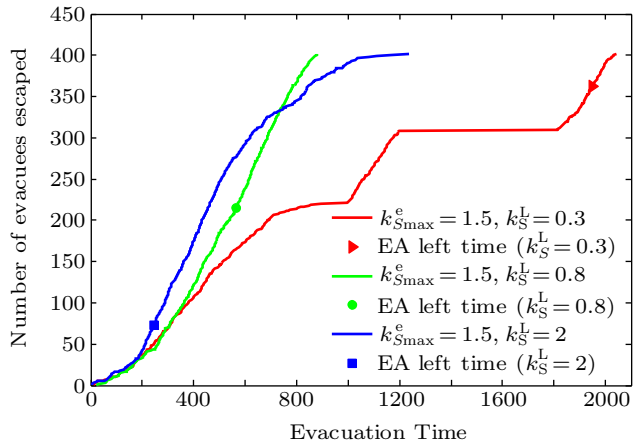


Fig. 4. (color online) The number of evacuees that escape during three evacuation processes: $k^{\mathrm{e}}_{S\max} = 1.5$, and $k^{\mathrm{L}}_{\mathrm{S}} = 0.3, 0.8, 2$.

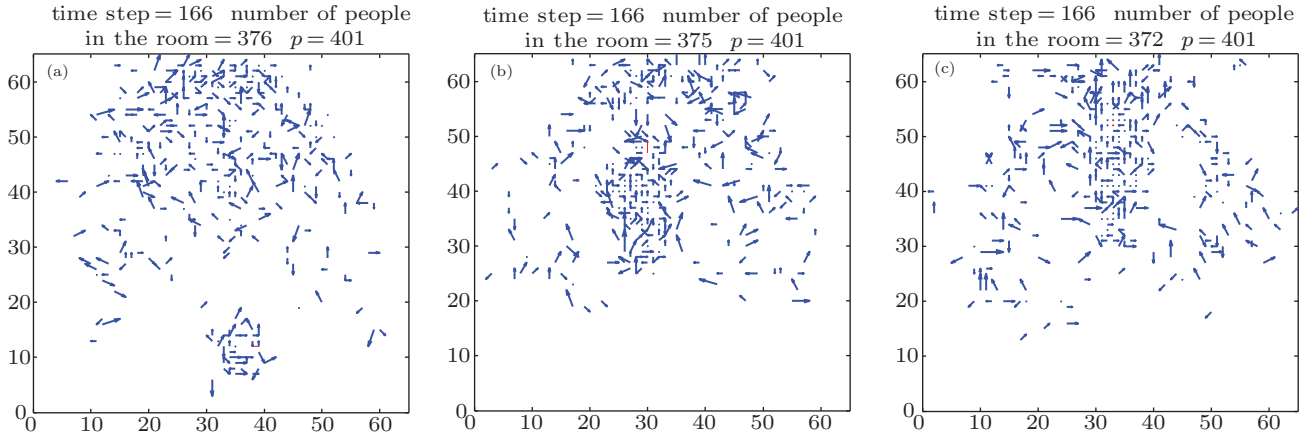


Fig. 5. (color online) Screenshots of typical evacuation processes at the same 166th time step, corresponding to the three curves: (a) $k_S^L = 0.3, k_{S\max}^e = 1.5$; (b) $k_S^L = 0.8, k_{S\max}^e = 1.5$; (c) $k_S^L = 2, k_{S\max}^e = 1.5$.

600$^{\text{th}}$ time step). The EA leaves in the early stage of the process and the evacuation time is between the first two simulations.

For further analysis on the evacuation curves, the screenshots of a few typical evacuation moments corresponding to the above three curves are shown, respectively. The velocities of evacuees are represented by blue arrow lines; the velocity of the EA is represented by a red arrow line. The velocities of the EA and evacuees are calculated by their average velocity within 5 time steps.

The screenshots of the evacuation processes at the same 166th time step, corresponding to the three curves, are shown in Figs. 5(a)–5(c). For $k_S^L = 0.3$ (Fig. 5(a)), the EA leads only a small amount of evacuees and obviously falls behind. He hinders his followers instead of helping them. Although the evacuees expect to move faster, they have to follow the EA, who moves slowly. It is extremely difficult for the crowd to move forward and they are delayed for quite a long time. When the front evacuees have successfully escaped, the exit flow interrupts; thus, the process curve shows turning points. According to Fig. 5(b), for $k_S^L = 0.8$, the EA has not only gathered almost half of the evacuees, but also keeps the leading position in front of the crowd. An obvious ribbon-like flow is formed. In Fig. 5(c), for $k_S^L = 2$, the EA moves even faster and arrives at the exit ready to leave, which corresponds to the rapid growth stage of the curve. The crowd is obviously moving faster than the surrounding evacuees, who are still distributed around discretely and randomly. These evacuees spend a longer time before leaving due to not being notified and led, which explains the slowly rising tail of the curve.

Corresponding to Fig. 3(a), the contour plot for an evacuation time less than 1050 time steps is shown in Fig. 6. Two tangent lines, l_1 and l_2, are obtained with an intersect point at $(0.5, 1)$, and their slopes are calculated, respectively, as $k_{l_1} = (2-1)/(0.75-0.5) = 4$ and $k_{l_2} = (2-1)/(1.5-0.5) = 1$. All the optimal combinations of k_S^L and $k_{S\max}^e$ for achieving the shortest evacuation time in less than 1050 time steps are sandwiched between the two tangents. Therefore, it is confirmed that EA moving faster is not better. The highest evacuation efficiency cannot be achieved when the EA's k_S^L is either too large or too small. The efficiency of the EA's k_S^L is associated with the evacuee's $k_{S\max}^e$, which needs to fall in the optimal range $k_S^L \in \left[0.25k_{S\max}^e + 0.25,\ k_{S\max}^e - 0.5\right]$. An EA with an overly small k_S^L would hinder the movement of the evacuees following him; however, with an overly large k_S^L, there is not enough time for quite a number of evacuees to be notified and led, which would prolong the evacuation time.

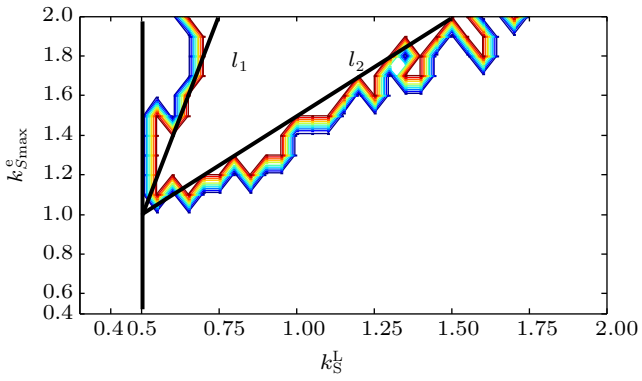


Fig. 6. (color online) Contour plot of the evacuation time, which is less than 1050 time steps.

3.2. Effect of the EA's information transmission radius on evacuation efficiency

Assume that the evacuees are randomly distributed in the compartment with $k_{S\max}^e = 2$. It is given that $\eta = k_S^L/k_{S\max}^e$. According to the above obtained optimal range for k_S^L, $k_S^L \in \left[0.25k_{S\,\max}^e + 0.25,\ k_{S\,\max}^e - 0.5\right]$, η is set to be $\eta = 0.3, 0.4, \ldots, 1$ to make sure that k_S^L would fall in the range; accordingly, $k_S^L = 0.6, 0.8, \ldots, 2$. The EA's information transmission radius is set as $R^L = 0.2, 0.4, \ldots, 6$ m. For each value of R^L, 8 simulations with different values of η are carried out 50 times. The average total evacuation times are recorded and are shown in Fig. 7, and the standard deviations are acceptable.

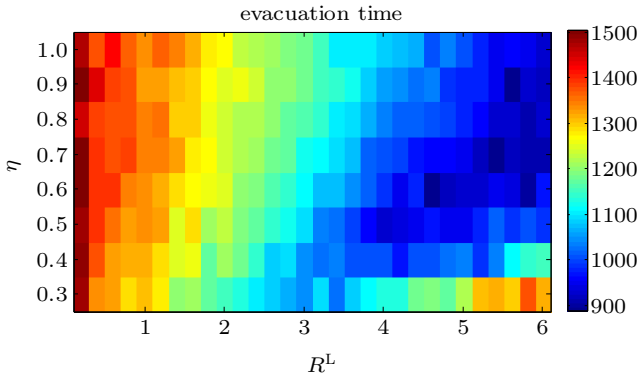


Fig. 7. (color online) Evacuation times for R^L and η.

Table 1. Estimated values of each variable.

Regression coefficient	Regression coefficient estimates	95% confidence interval
β_0	1365.1156	[1336.7989, 1393.4324]
β_1	−88.4944	[−92.5267, −84.4621]
β_2	75.3032	[40.4021, 110.2043]
$R^2 = 0.9013$,	$F = 945.0801$,	$p < 0.0001$, $s^2 = 2632.4979$

From Fig. 7, one can see that the evacuation time could be less than 1000 time steps for certain R^L and η combinations. When $\eta \geq 0.4$, the evacuation time decreases along with R^L growing large. Regression analysis is carried out on the evacuation time with R^L and η. After removing the data group with $\eta = 0.3$, the evacuation times of $\eta \geq 0.4$ are presented as the three-dimensional diagram in Fig. 8. It is found that there is a linear relationship between evacuation time and η and R^L. A regression equation is assumed as $\hat{T} = \hat{\beta}_0 + \hat{\beta}_1 R^L + \hat{\beta}_2 \eta$. The estimated values of each variable are obtained and shown in Table 1.

The regression plane and the data points in the three-dimensional diagram are shown in Fig. 9. Most of the data points are located in or close to the regression plane. When $R^L > 5$ m and $\eta < 0.6$, the deviation of data points with the regression plane is large, which is presented as the upward tilt in the lower right corner of the evacuation time surface in Fig. 8. Taking the sequence number of the observed value as the horizontal coordinate and the residual error as the vertical coordinate, as shown in Fig. 10, the variation range of each observed value's residual error and the confidence interval are presented. The exceptional data points are marked in red. Most of the exceptional data points distribute at the end of the axis.

Looking into the regression parameters in Table 1, the coefficient of determination is $R^2 = 0.9013$, which indicates that the regression plane could fit well with the relationship between the data. $F = 945.0801 > F_{1-0.05}(2, 207) = 3.00$ and significance level $p < 0.0001 < 0.05$, which explains that there is a significant linear relationship between the independent variable and dependent variable and that the change of the independent variables can really reflect the linear change of the dependent variable. For the regression coefficients β_0 and β_1, the 95% confidence interval is narrow, which shows a high credibility of the estimated value. For the regression coefficient β_2, the confidence interval is relatively wide, which shows less credibility of the estimated value; a reason for that is the influence of the exceptional data points. By administering the t-test on the regression coefficients, the result is $H = 1$. Thus, the original hypothesis is rejected and it is believed that both of the regression coefficients β_0 and β_1 are significantly different from 0. This means that the two independent variables all show significant linear relationships with their respective dependent variables and should be kept in the regression equation. Thus, the relationship between evacuation time, R^L, and η can be approximately expressed as

$$T = 1365.1156 - 88.4944 R^L + 75.3032 \eta. \quad (7)$$

From Eq. (7) it is known that the evacuation time is shorter when R^L is larger and longer when η is larger. The evacuation time should remain constant when the ratio of the increment of R^L and the increment of η is approximately 75/88. However, the exceptional data points converge on $\eta = 0.4$, which indicates that the data group of $\eta = 0.4$ has a weak linear relationship with the evacuation time.

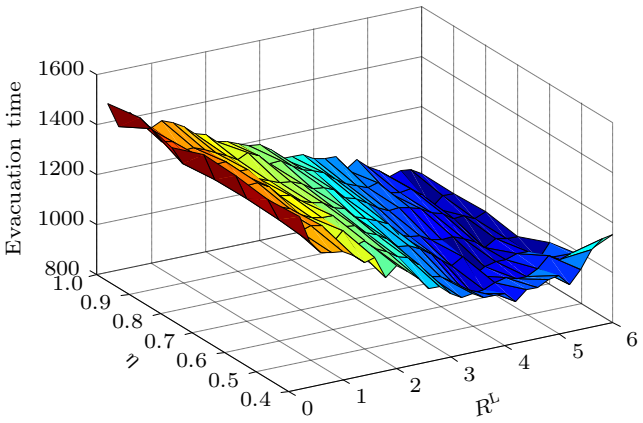


Fig. 8. (color online) Three-dimensional diagram of evacuation times (except the data for $\eta = 0.3$).

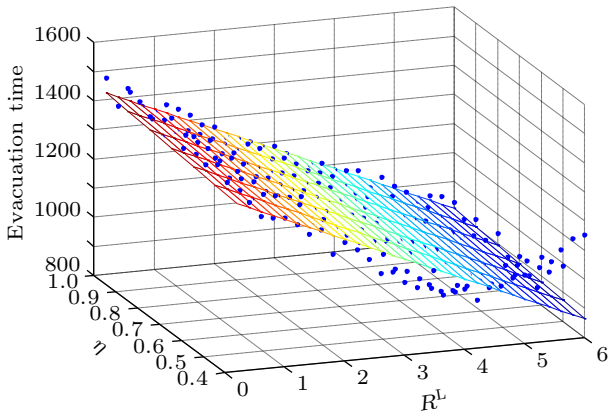


Fig. 9. (color online) Three-dimensional diagram of the regression plane and the evacuation time data points.

Compare the evacuation time with $\eta = 0.3$ and $\eta = 0.4$, as shown in Fig. 11. When $\eta = 0.3$, the non linear relationship is quite clear between R^{L} and evacuation time. The optimal value of R^{L} is 3.4 m when the evacuation time is at its lowest, which is at the 1024$^{\mathrm{th}}$ time step. When $\eta = 0.4$, the evacuation time first decreases when R^{L} increases and then rises when $R^{\mathrm{L}} > 5$ m. The optimal value of R^{L} is 4.2 m when the evacuation time is at its lowest, which is at the 966$^{\mathrm{th}}$ time step. Therefore, it is confirmed that, as η reduces from 0.4 to 0.3, the relationship between R^{L} and the evacuation time changes from linear to nonlinear; the reason for the change can be attributed to the disturbance factors in the system. When $\eta \leq 0.3$, the EA's $k_{\mathrm{S}}^{\mathrm{L}}$ is smaller than 0.6, which is close to the evacuees' initial $k_{\mathrm{S}}^{\mathrm{e}}$ or may be even smaller than the average $k_{\mathrm{S}}^{\mathrm{e}}$ of the surrounding evacuees; the EA could easily be trapped by the surrounding evacuees. When R^{L} increases, more evacuees will receive information and move close to the EA, which could aggravate the congestion. The total evacuation time is eventually long. Therefore, when $k_{\mathrm{S}}^{\mathrm{L}}$ is larger than $k_{S\max}^{\mathrm{e}}$ (in their optimal combinations), increasing the transmission radius can improve the evacuation efficiency. Conversely, the EA could be disturbed by his followers, and the relationship between the transmission radius and evacuation time turns out to be nonlinear; thus, there exists an optimal value for the EA's information transmission radius.

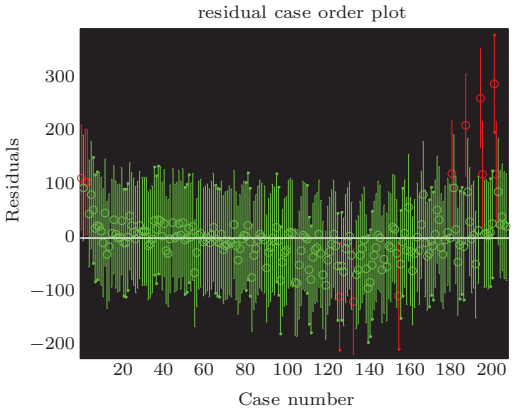


Fig. 10. (color online) Sequential residual figure.

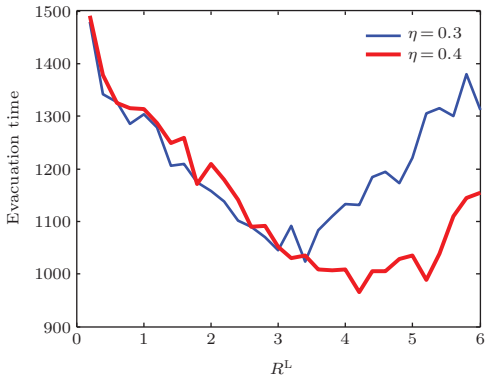


Fig. 11. (color online) Evacuation time of two data groups: $\eta = 0.3$ and $\eta = 0.4$.

3.3. Effect of the EA's initial position and $k_{\mathrm{S}}^{\mathrm{L}}$ on evacuation efficiency

The effect of the EA's $k_{\mathrm{S}}^{\mathrm{L}}$ on evacuation efficiency could also be influenced by the EA's initial positions. The analysis of the EA's initial positions when evacuees were randomly distributed in the same compartment has been mentioned in our previous work.[1] Concerning this further research, 400 evacuees were assumed to initially locate in the square zone of 20×20 cells in the middle of the same compartment. Any other given cell in the compartment is assigned as the initial position of the EA for 20 time simulations. To reduce the statistical error, the average total evacuation time is recorded. It is assumed that the evacuees have an initial $k_{\mathrm{S}}^{\mathrm{e}}$ of 0.5 towards the building exit, with the $k_{S\max}^{\mathrm{e}}$ reaching 1 after receiving route information. For EAs, $k_{\mathrm{S}}^{\mathrm{L}} = 1.5, 1, 0.5$. Additionally, $R^{\mathrm{L}} = 4$ m.

The evacuation times of all the initial positions for the three simulation groups are shown in Fig. 12(a). The evacuation time is short when the EA's initial positions are in the back of the evacuee crowd and the EA can go through the crowd when he leads them to the exit (for the blue color zone). However, during the process when the EA leads them to the exit, if he only passes by the crowd from the right or left edge, then the evacuation times are longer. Even for the initial positions in front of the crowd, the evacuation times are also longer, which are shown as the green color zone. Furthermore, in the rear of the evacuee crowd, evacuation times for $k_{\mathrm{S}}^{\mathrm{L}} = 1.5$ and $k_{\mathrm{S}}^{\mathrm{L}} = 1$, which are larger than or equal to the $k_{S\max}^{\mathrm{e}}$ value of the evacuees, are less than those for $k_{\mathrm{S}}^{\mathrm{L}} = 0.5$, which is smaller than the $k_{S\max}^{\mathrm{e}}$ value of the evacuees. Figure 12(b) shows the number of evacuees led by the EA at different initial positions, and figure 12(c) describes the evacuation time as it corresponds to the different number of evacuees led by the EA. It can be observed that evacuation time is inversely proportional to the number of evacuees that an EA can lead. Therefore, for the concentration distribution crowd, the EA should start at the rear of the crowd and head toward the exit, which can help in leading more evacuees and improving the evacuation efficiency.

The present work aims at the model's theoretical analysis. When focusing on the EA's leading behavior and his special role during an evacuation, it is necessary to study the process by which the EAs transmit position information and the action behaviors of evacuees when they receive the information. The settings of the related parameters in the model have ensured their proper implementation above. Furthermore, the simulation results demonstrate the importance of the EA's leading behavior during evacuation and show that the extended DCF model is effective as an information mechanism. Through hu-

man evacuation experiments, the quantitative validation of the theoretical model could be done to help apply the model accurately. However, any human experiment conducted within a simulated emergency evacuation process needs to take into consideration the experimental risk, ethical issues, and intensive organization required, which is beyond the scope of the theoretical analysis in this paper and will be performed in our future work.

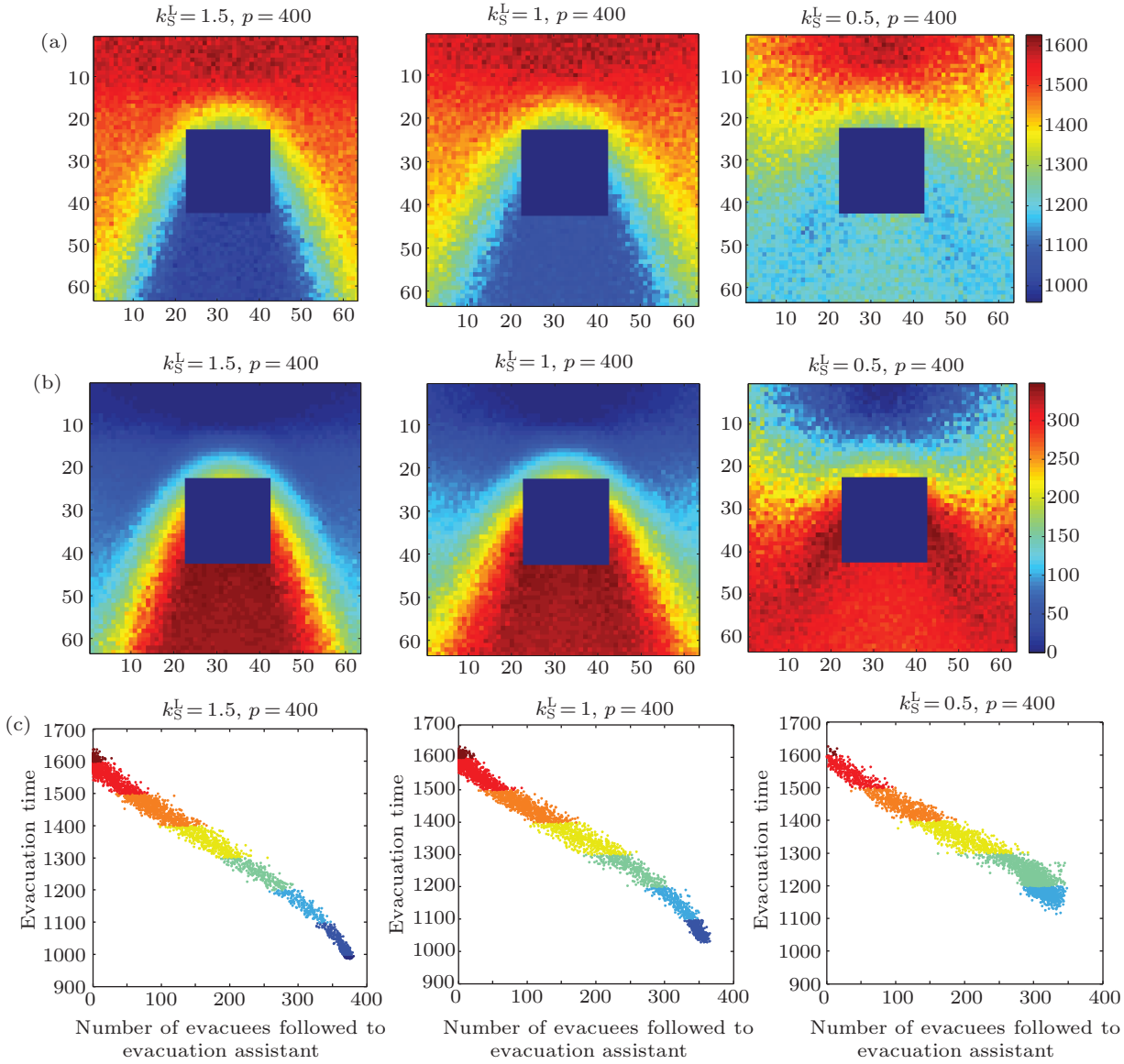


Fig. 12. (color online) Simulation results when the evacuees' initial position are fixed: (a) evacuation time of each initial position at three k_S^L value of the EA; (b) the number of evacuees led by the EA at each initial position; (c) evacuation times corresponding to the different number of evacuees led by the EA.

4. Conclusions

An extended DCF model is proposed in the present research. The transmission and function process of the escape information when an EA is moving and leading evacuees to the exit is presented. Through a large number of simulations, the relationship between the sensitivity parameters for EA's k_S^L and the evacuee's $k_{S\max}^e$, and their effect on evacuation efficiency were focused on. The simulation results demonstrated the importance of the EA's leading behavior during evacuation and showed that the extended DCF model is effective as an information mechanism. The following conclusions were made.

i) The optimal combinations of k_S^L and k_S^e were found to reach the highest evacuation efficiency. An EA with an overly small k_S^L could hinder the movement of the evacuees following him; however, with an overly large k_S^L, there is not enough time for quite a number of the evacuees to be notified and led, which could prolong the evacuation time.

ii) There exists an optimal value for an EA's information transmission radius. When an EA's k_S^L is larger than evacuees' $k_{S\max}^e$, the information transmission radius has a linear relationship with the evacuation time, and increasing the trans-

mission radius can improve the evacuation efficiency. On the contrary, an EA could be disturbed by his followers, and the relationship between the transmission radius and evacuation time turns out to be nonlinear.

iii) For the concentration distribution crowd, an EA should start at the rear of the crowd and head toward the exit, which can help in leading more evacuees and improving the evacuation efficiency.

However, in reality, individuals rely on information not only from leaders but also from their neighbours and would group together into family or friendship units. The efficiency of leaders will be influenced by such kind of social behaviors and responsibilities. In addition, the key parameters and the model have to be further verified and validated through human experiments considering leader's behavior. All of these above should be improved in the further work.

References

[1] Wang X L, Guo W, Cheng Y and Zheng X P 2015 *Safety Sci.* **74** 150
[2] Couzin I D, Krause J, Franks N R and Levin S A 2005 *Nature* **433** 513
[3] Sumpter D, Buhl J, Biro D and Couzin I 2008 *Theor. Biosci.* **127** 177
[4] Fang T Y, Li J, Zhu K J, Liu S B and Yang L Z 2009 *Int. J. Mod. Phys. C* **20** 1583
[5] Zhu K J, Liu S B, Rao P and Yang L Z 2012 *Int. J. Mod. Phys. C* **23** 1250049
[6] Faria J, Dyer J R G, Tosh C R and Krause J 2010 *Anim. Behav.* **79** 895
[7] Aubé F and Shield R 2004 6*th International Conference on Cellular Automata for Research and Industry*, October 25–27, 2004 Amsterdam, Holland, p. 601
[8] Pelechano N and Badler N I 2006 *IEEE Comput. Graph.* **26** 80
[9] Yuan W F and Tan K H 2009 *Curr. Appl. Phys.* **9** 1014
[10] Henein C M and White T 2010 *Physica A* **389** 4636
[11] Wang X L, Zheng X P and Cheng Y 2012 *Physica A* **391** 2245
[12] Hou L, Liu J G, Pan X and Wang B H 2014 *Physica A* **400** 93
[13] Wang H N, Chen D, Pan W, Xue Y and He H D 2014 *Chin. Phys. B* **23** 080505
[14] Yue H, Zhang B Y, Shao C F and Xing Y 2014 *Chin. Phys. B* **23** 050512
[15] Lu L, Ren G, Wang W and Wang Y 2014 *Chin. Phys. B* **23** 088901
[16] Zhu N, Jia B, Shao C F and Yue H 2012 *Chin. Phys. B* **21** 050501
[17] Xu Y, Huang H J and Yong G 2012 *Chin. Phys. Lett.* **29** 080502
[18] Kirchner A, Klupfel H, Nishinari K, Schadschneider A and Schreckenberg M 2003 *Physica A* **324** 689
[19] Kirchner A, Klupfel H, Nishinari K, Schadschneider A and Schreckenberg M 2004 *J. Stat. Mech.* P10011
[20] Schadschneider A, Kirchner A and Nishinari K 2003 *Appl. Bionics. Biomech.* **1** 11
[21] Peng Y C and Chou C I 2011 *Comput. Phys. Commun.* **182** 205
[22] Wang X L, Guo W, Cheng Y and Zheng X P 2015 *Safety Sci.* **74** 150
[23] Varas A, Cornejo M D, Mainemer D, Toledo B, Rogan J, Muñoz V and Valdivia J A 2007 *Physica A* **382** 631
[24] Alizadeh R 2011 *Safety Sci.* **49** 315
[25] Leng B, Wang J Y, Zhao W Y and Xiong Z 2014 *Physica A* **402** 119
[26] Guo R Y 2014 *Physica A* **400** 1
[27] Chen M, Han D F and Zhang H P 2011 *J. Mar. Sci. Appl.* **10** 340
[28] Yuan W F and Tan K H 2007 *Physica A* **379** 250
[29] Kirchner A and Schadschneider A 2002 *Physica A* **312** 260