An intelligent floor field cellular automation model for pedestrian dynamics

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Abstract

A stochastic cellular automation (CA) model for pedestrian dynamics is presented. Our goal is to simulate different types of pedestrian movement, from regular to panic. But here we emphasize regular situations which imply that pedestrians analyze environment and choose their route more carefully. And transition probabilities have to depict such effect. The potentials of floor fields [5] and environment analysis [4] are combined in the model obtained. Model parameters adaptivity and modelling of people patience are included in the model. These things make simulation of pedestrians movement more realistic. Some simulation results are presented and comparison with basic model (FF-model [5]) is made.

INTRODUCTION

Modelling of pedestrian dynamics is actual problem at present days. Different approaches from the social force model ([2] and references therein) based on differential equations to stochastic CA models ([5, 4, 6] and references therein) are developed. They reproduce many collective properties including lane formation, oscillations of the direction at bottlenecks, the so-called "faster-is-slower" effect. These are an important and remarkable basis for pedestrian modelling. But there are still things to be done in order to reproduce individual pedestrian behavior more realistic and carefully.

The model presented takes its inspiration from stochastic f loor field (FF) CA model [5]. Here a static field is a map that pedestrian may use to orient in the space. Dynamic field is used to model herding behavior in panic situations.

It's known that regular situations imply that pedestrians analyze environment and choose their route more carefully (see [2] and reference therein). Pedestrians keep a certain distance from other people and obstacles. The more hurried a pedestrian is and more tight crowd is this distance is smaller. We adopted a mathematical formalization of these points from [4].

Pedestrians minimize efforts to reach their destinations: feel strong aversion to taking detours or moving opposite to their desired direction. However, people normally choose the fastest rout but not the shortest. This means that opportunity to wait (to stay at present place) has to be realized in the model. (Models [4, 5] (and other CA models) imply that people can stay at present place if there is no space to move only.) We realize this point (people patience) in the algorithm.

As well as it's necessary to take into account that some effects are more reside for certain regions. For instance, clogging situations are more pronounced in the nearest to an exit areas. This means that spatial adaptivity of correspondent model parameters to be introduced in the model. All these changes and additions extend basis FF model towards emotional aspect and improve and make flexible decision making process. By this reason model obtained was named as *Intelligent FF model*.

INTELLIGENT FLOOR FIELD MODEL
Space structure

As usual for CA models the space (plane) is sampled into cells $40cm \times 40cm$ (it's an average space occupied by a pedestrian in a dense crowd [3]) which can either be empty or occupied by one pedestrian (particle) only.

The von Neumann neighborhood is used. It implies that each particle can move to one of four its next-neighbor cells (i, j) or to stay at the present cell at each discrete time step $t \rightarrow t + 1$, e.i., $v_{max} = 1$. (Empirically the average velocity of a pedestrian is about $1.3m/s$. So real time corresponding to one time step in the model is about $0.3s$.) Such movement is in accordance with certain transition probabilities that are explained below.

Floor fields

Static (S) and dynamic (D) floor fields are introduced and discussed in [1, 3, 5]. For each cell (i, j) values of S_{ij} and D_{ij} are given.

Static floor field S describes the shortest distance to an exit (or other destination point that depends on a task). It doesn't evolve with time and isn't changed by the presence of the particles. The value of S_{ij} is set inversely proportional to the distance from the cell (i, j) to the exit. One can consider S as a map that pedestrian can use to move to the target point, e.g., exit.

Dynamic floor field D is a virtual trace left by the pedestrians similar to the pheromone in chemotaxis. It is used to model a " long-ranged" attractive interactions between the pedestrians, e.g., herding behavior that is observed in panic situations. Dynamic floor field is time dependent. In each time

step each D_{ij} decays with probability δ and diffuses with probability $\alpha \in [0,1]$ to one of its four neighboring cells. Decay and diffusion lead to broadening, dilution, and finally vanishing of the trace. At $t = 0$ for all cells $D_{ij} = 0$. $D_{ij} \to D_{ij} + 1$ just after particle left cell (i,j).

Field S and D works in such a way that transition probability increases in the direction of higher fields S and D, i.e. motion in such direction is more feasible.

Environment analysis

To make next step pedestrian observes surroundings. Let $r > 0$ be maximum distance (in cells) at which pedestrian can see around, by

$$f_{ij} = \begin{cases} 1, & \text{cell } (i,j) \text{ is occupied by a pedestrian;} \\ 0, & \text{cell } (i,j) \text{ is empty;} \end{cases}$$

denote the occupation number.

If desired direction (cell) is occupied to minimize efforts to reach destination or to realize the fasters rout pedestrian has to a have an opportunity to stay at present cell or move to one of the rest unoccupied nearest cells.

Keeping apart from other people and obstacles can be simulated by decreasing probability for such direction (let α be a name of the direction). For present position of some pedestrian let cell (i,j) be a next-neighbor in the direction α. For cell (i,j) we will calculate a term [4]

$$A_{ij} = \Big(1 - \frac{1}{r}\Big(\sum_{m=i(l=j)}^{i\pm r_{ij}^\star (j\pm r_{ij}^\star)} f_{ml} + r - r_{ij}^\star\Big)\Big),$$

where $r_{ij}^\star$ — distance to a nearest obstacle (wall, column, etc., but not pedestrian) in the direction α starting from cell (i,j) $(r_{ij}^\star \le r)$; $\sum_{m=i(l=j)}^{i\pm r_{ij}^\star(j\pm r_{ij}^\star)} f_{ml}$ — number of pedestrians that are in the direction α starting from cell (i,j) up to the nearest obstacle (sum is over lines (m) or over columns (l) depending on direction α), all cells behind obstacle are considered as occupied.

Update rules

Update rules for CA are the following:

1. For each pedestrian the transition probability p_{ij} to move to cell (i,j) one of four next-neighbors is

$$p_{ij} = Norm^{-1}\Big[\Big(1 - \frac{1}{r}\Big(\sum_{m=i(l=j)}^{i\pm r_{ij}^\star(j\pm r_{ij}^\star)} f_{ml} + r - r_{ij}^\star\Big)\Big)$$
$$\exp(k_S S_{ij})\exp(k_D D_{ij})\exp(k_I)\Big], \quad (1)$$

where k_S, k_D — sensitivity parameters; $\exp(k_I)$ — inertia effect: $k_I > 0$ for the direction of pedestrian's motion in

the previous time step and $k_I = 0$ for other cells; normalization

$$Norm = \sum_{(i,j)} A_{ij} e^{k_S S_{ij}} e^{k_D D_{ij}} e^{k_I},$$

where the sum is over all possible target cells.

2. If $Norm = 0$ then pedestrian stays at the present cell, otherwise pedestrian chooses randomly a target cell $(i,j)^*$ based on the transition probabilities determined by (1).

3. If $Norm \ne 0$ and $(1 - f_{ij}^*) = 0$ (i.e., cell $(i,j)^*$ is occupied) then pedestrian chooses randomly a target cell once again. Now target cell is chosen among the following candidates: rest next-neighbors available for moving (i.e., $(1 - f_{ij}) \ne 0$) and the present cell. For the available next-neighbor cell (i,j) new transition probability is $\frac{p_{i,j}}{\sum_{(i,j)} p_{i,j}}$ and pedestrian can stay at present cell with probability $\frac{p_{i,j}^*}{\sum_{(i,j)} p_{i,j}}$ (where sum is over all available candidates at now). Obviously, if there is no available next-neighbors then particle stays at present cell.

In contrast to [4, 5] this step gives an opportunity for pedestrians not to move and wait when preferable direction will free.

4. Whenever two or more pedestrians have the same target cell, the movement of all involved pedestrians is denied with probability $\tilde{\mu}_{ij}$, i.e. all pedestrians remain at their old places [5]. With probability $1 - \tilde{\mu}_{ij}$ one of the candidates moves to the desired cell. Pedestrian that is allowed to move has the largest probability among all candidates (in this case probability is a measure of pedestrians physical strength). The other probabilistic method [1, 4, 5] can be used here as well.

5. Pedestrians that are allowed to move perform their motion to the target cell. D at the origin cell (i,j) of each moving particle is increased by one $D_{ij} \to D_{ij} + 1$ and therefor can take any non-negative integer value.

These rules are applied to all particles at the same time, i.e., parallel update is used.

Model parameters

There are several parameters in the model obtained. Their values and physical meaning are presented below.

- $r > 0$ — maximal distance at which pedestrian can feel the surroundings. People avoid to walk close to obstacles and other people. $A_{ij} = 0$ if there is no free space to move, $A_{ij} = 1$ if direction is free, $0 < A_{ij} < 1$ for any other intermediate situation.

- $k_S \geq 0$ — sensitivity parameter that can be interpreted as the knowledge of the shortest way to the destination point, or as a wish to move in a certain direction. $k_S = 0$ means that pedestrian don't use information from the field S. The higher k_S is movement of the pedestrians is more directed.

- $k_D \geq 0$ — sensitivity parameter that can be interpreted as a rate of herding behavior. It is known that people try to follow others particulary in panic situations [2]. $k_D = 0$ means that pedestrian chooses a way of their own ignoring ways of others. The higher k_D is the herding behavior of the pedestrians is more pronounced.

- $k_I \geq 0$ — parameter that determines the strength of inertia which suppresses quick changes of the direction.

- $0 \leq \tilde{\mu}_{ij} \leq 1$:

$$\tilde{\mu}_{ij} = \begin{cases} \frac{S_{ij}}{\max\limits_{i,j} S_{ij}} \mu, & \text{if } k_S \neq 0, \\ \mu, & \text{otherwise,} \end{cases}$$

where $\mu \in [0,1]$ — friction parameter that controls the resolution of conflicts in clogging situations. $\tilde{\mu}_{ij}$ works as some kind of local pressure between the pedestrians. The higher $\tilde{\mu}_{ij}$ is pedestrians are more handicapped by others trying to reach the same target cell. Such situations are natural and well pronounced for nearest to exit (destination point) space. For other areas it's not typical but it's possible. So to realize it and make simulation of individuals realistic the coefficient $\frac{S_{ij}}{\max\limits_{i,j} S_{ij}}$ is introduced (in contrast with original FF model [5]).

- $\delta, \alpha \in [0,1]$ — these constants control diffusion and decay of the dynamic floor field [5]. "It reflects the randomness of people's movement and the visible range of a person, respectively. If the room is full of smoke, then δ takes large value due to the reduced visibility. Through diffusion and decay the trace is broadened, diluted and vanishes after some time."

DISCUSSION OF THE MODEL

Model obtained is simple. For one time step there are $O(n)$ calculations if n pedestrians are involved. It gives advantage over continuous social-force model [2] where each time step $O(n^2)$ interaction terms have to be evaluated. The discreteness of the model is advantage as well. It allows for a very efficient implementation for large-scale computer simulations.

It's shown [5, 1, 3] that original FF model reproduces variety of collective effects: clogging at large densities, lane formation in counterflow, oscillation in counterflow at bottlenecks, patterns at intersection, trail formation, "faster-is-slower" and "freezing-by-hearting" (in panic). All these effects are simulated by varying of the model parameters. Model obtained saves this opportunities. Modifications and improvements made here mainly concern the quality of pedestrians behavior reproducing. They allow more realistically (carefully) simulate analysis that people accomplish while they choose a direction for moving. Idea of parameters adaptivity makes model more flexible and closer to real life.

At first let us consider components that determine probability p_{ij}. In contrast to FF model [5] one can distinguish two different types of terms in (1).

Term A_{ij} characterizes the physical possibility to move, $A_{ij} \in [0,1]$. It takes maximal value if movement conditions in the direction are favorable. And $A_{ij} = 0$ if there is no free space to move. Term A_{ij} proportionally decreases with the advent and approaching of some obstacles (people, wall, etc.) in the direction.

Other terms $e^{k_S S_{ij}}$, $e^{k_D D_{ij}}$, e^{k_I} vary form 1 to ∞ (in general case) and characterize style of people behavior. Minimal value of parameter ($k_S = 0$, $k_D = 0$ or $k_I = 0$) means that correspondent feature of behavior isn't realized and term doesn't affect the probability. If all three terms are minimal then pedestrians walk free. And in this case only term A_{ij} determines the transition probability for each next-neighbor cell (i, j) in accordance with people features: keeping apart from other people and obstacles, patience.

In FF model [1, 3, 5] pedestrians stay at present cell if there is no space to move only. Here we give pedestrians the opportunity to wait when preferable direction will free even if other directions are available for moving at this time. Such behavior is reside to low and middle densities. To realize it transition probabilities (1) don't include a checking if cell (i, j) occupied or not. In this case transition probabilities (1) can be considered as a rate of wish to go to the certain directions. Possibility not to leave present cell is realized in step 3.

The idea of spatial adapted parameters is introduced here. It's clear that conditions can't be equal for all people involved. Position of pedestrian in the space may determine some features of the behavior. Thus clogging situations are natural and well pronounced for nearest to exit (destination point) space. For other areas it's not typical but it's possible. To realize it the coefficient $\frac{S_{ij}}{\max\limits_{i,j} S_{ij}}$ for clogging parameter μ is introduced.

SIMULATION RESULTS

In order to test our model a regular evacuation process was simulated. This means that $k_D = 0$ in examples presented. And we set $k_I = 0$, $\mu = 0$.

One pedestrian case

There was simulated evacuation of one person (n=1) from a room $6.8m \times 6.8m$ (17 cells $\times$ 17 cells) with one exit ($0.8m$)

in the middle of a wall. Recall that the space is sampled into cells of size $40cm \times 40cm$ which can either be empty or occupied by one pedestrian only. Static field S was calculated in accordance with [3]. Stating position is a cell in a corner near wall opposite to the exit. Pedestrian moves towards the exit with $v = v_{max} = 1$. For such sampled space minimal value of time steps that require to leave the room starting from initial position is $T_{min} = 26$.

Different combinations of parameters k_S and r were considered. Total evacuation time and trajectories were investigated. Following table contains results over 500 experiments.

Table 1. Modes T_{mo} of total evacuation time distributions in one pedestrian case.

k_S	r	T_{mo}	k_S	r	T_{mo}	k_S	r	T_{mo}
1	1	45	2	1	29	4	1	26
1	8	40	2	8	29	4	8	26
1	17	35	2	17	27	4	17	26

Figures 1 show total evacuation time distributions for some couples of the parameters from table 1 over 500 realizations.

a) $k_S = 1$, $r = 1$.   b) $k_S = 1$, $r = 17$.

c) $k_S = 2$, $r = 1$.   d) $k_S = 2$, $r = 17$.

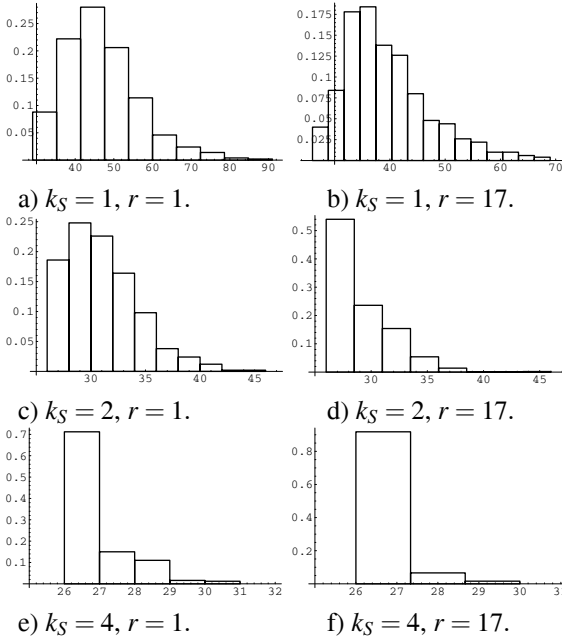e) $k_S = 4$, $r = 1$.   f) $k_S = 4$, $r = 17$.

Figure 1. Total evacuation time distribution for different k_S and r over 500 experiments.

Figures 2 present tracks of pedestrian ways over 500 realizations for some couples of the parameters from table 1.

Different moving conditions are reproduced by these combinations. They vary from $r = 1$, $k_S = 1$ to $r = 17$, $k_S = 4$. The former case can be interpreted as pedestrian moves in a very low visibility (or by touch) but he approximately knows
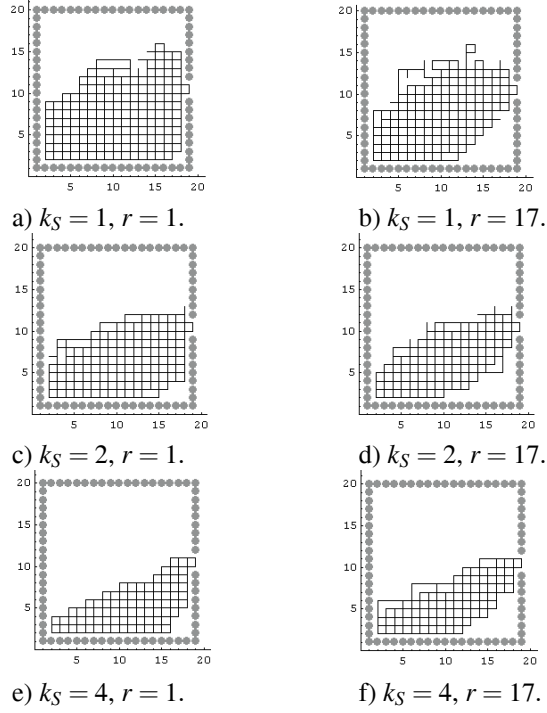

a) $k_S = 1$, $r = 1$.   b) $k_S = 1$, $r = 17$.

c) $k_S = 2$, $r = 1$.   d) $k_S = 2$, $r = 17$.

e) $k_S = 4$, $r = 1$.   f) $k_S = 4$, $r = 17$.

Figure 2. Tracks of one pedestrian for different k_S and r over 500 experiments.

the direction to destination point. In other words one can say that pedestrian doesn't see, knows, and wants not so much to go to destination point (exit). Last one ($r = 17$, $k_S = 4$) describes situation when pedestrian sees, knows, and wants to go to destination point very much.
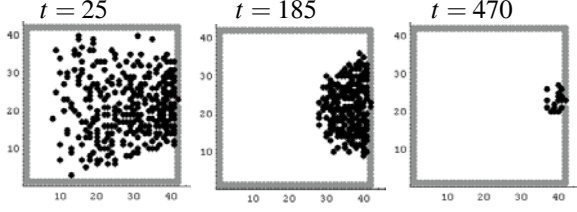
Note that if $r = 1$ model presented corresponds to FF-model [1, 3] with the same other parameters. And it's clear that the pedestrian patience that was introduced in the model doesn't pronounced in one pedestrian case.

One can see that for small $k_S = 1$ mode T_{mo} is very dependent on parameter r. The bigger parameter k_S is an influence of r to T_{mo} is less pronounced. But the bigger parameter r is more natural way pedestrian chooses — tracks are more close to a line connecting starting point and exit (non the less random component takes place). Under $r > 1$ a proximity of wall decreases the probability (1) to move in this direction. Thereby tracks are forced to tend to natural one. Thus parameter r fulfils its role to simulate environment analysis here.
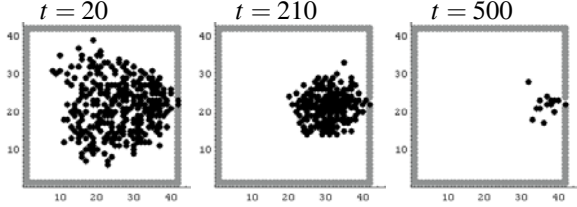
Many pedestrians cases
Influence of k_S and r

For this collective experiment the space was a room $16m \times 16m$ (40 cells $\times$ 40 cells) with one exit ($0.8m$). Initial number of people is $N = 300$ (density $\rho \approx 0.19$). Initial positions are random and people start to move towards the exit with
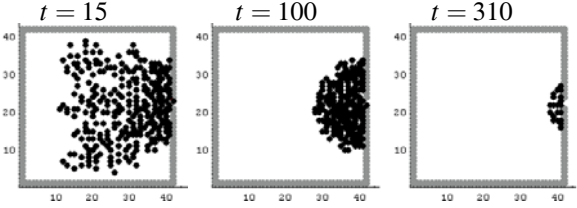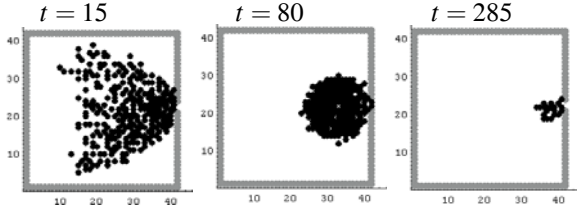
a) $k_S = 1, r = 1, T_{total} = 509$

b) $k_S = 1, r = 40, T_{total} = 603$

Figure 3. Evacuation stages for 300 people for $k_S = 1$ and different r.

a) $k_S = 3, r = 1, T_{total} = 336$

b) $k_S = 3, r = 40, T_{total} = 317$

Figure 4. Evacuation stages for 300 people for $k_S = 3$ and different r.

$v = v_{max} = 1$. Exit is in the middle of east wall. Figures 3, 4 present typical stages of evacuation process for different k_S and r.

One can see that evacuation dynamics in case a) differs from case b) in both figures 3, 4. The reason of it is different parameters r. If $r > 1$ people avoid to approach to walls. And while crowd density allows pedestrians try to follow more natural way to the exit. The bigger r is shape of crowd in front of exit is more diverse from the case of $r = 1$. (Note if $r = 1$ we have FF-model with the same other parameters.)

One can notice that the closer to the exit pedestrians are circle shaped crowd in front of the exit is more unrealistic.

The problem comes from computational aspect of coefficient A_{ij}. It's a positive that in the model obtained people avoid to approach to walls. But this effect has to be less pronounced with approaching to wall (walls as in a subsection example below) surrounding exit. Thus parameter r has to be spatial adaptive.

Next table demonstrates numerical description of cases presented. Let f_α be frequency to choose direction $\alpha = \{N, E, S, W, C\}$ over all experiment for each couple of parameters. Here N, E, S, W, C are north, east, sought, west, center (stay at present place) correspondingly, M — total number of movements including stayings at current position over all experiment.

Table 2. Direction frequencies.

k_S, r	f_N	f_S	f_W	f_E	f_C	M
1) 1, 1	0.23	0.23	0.17	0.27	0.08	77961
2) 1, 40	0.16	0.16	0.10	0.20	0.38	77976
3) 3, 1	0.21	0.2	0.13	0.31	0.15	49313
4) 3, 40	0.06	0.06	0.01	0.18	0.69	47133

Comparing cases 1) and 2), 3) and 4) correspondingly one can notice that greater r leads to significant redistribution of f low. In the case of $r = 1$ low f_C says that people move as much as possible (because people can stay at current position if all nearest cells are occupied only). If $r = 40$ the opportunity to wait is realized — in cases 2) and 4) f_C has the greatest value. f_W has the smallest value (this direction is opposite to the exit), f_N, f_S are approximately equal because exit is in the middle of the wall. Thus in cases 2) and 4) model reproduces more natural decision-making process.

At the same time let us remark that increasing k_S makes evacuation process more directed and reduces total evacuation time (see cases 1) and 3), 2) and 4) correspondingly).

Influence of exit position

For this collective experiment the space was a room $6.8m \times 11.2m$ (17 cells $\times$ 28 cells) with one exit ($0.8m$). Initial $N = 150$ (density $\rho \approx 0.31$). Initial positions are random and people start to move towards the exit with $v = v_{max} = 1$. Spaces are presented in the figures 5a, 5b.

Two combinations of parameters k_S and r were considered. And total evacuation time was investigated. Table 3 contains results over 100 experiments. Initial positions of people were the same for all experiments.

One can notice once again that in the case a) parameter r doesn't influence on total evacuation time under such k_S. But in other case increase of r leads to significant delay of evacuation. The reason of it is "computational" repulsion from the walls. And as a result pedestrians don't use corner between wall and exit, exit is not fully used, total evacuation time in-
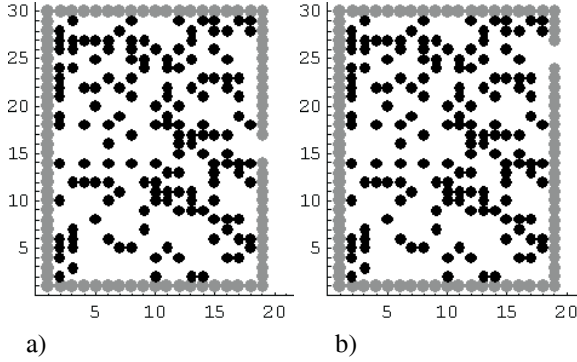
Figure 5. Initial people position and exits position.

Table 3. Modes T_{mo} of total evacuation time distributions with middle exit (a) and corner exit (b).

	k_S	r	T_{mo}		k_S	r	T_{mo}
a)	3	2	158	b)	3	2	174
	3	20	160		3	20	226

creases. So this is one more example that shows necessity in at least parameter r adaptivity.

CONCLUSION AND FURTHER PLANS

In the paper the intelligent FF cellular automation model is presented. Modifications made are to improve realism of the individual pedestrian movement simulation. The following features of people behavior are introduced: keeping apart from other people (and obstacle), patience. Idea of spatial adaptation of model parameters is pronounced and one method is presented (parameter $\tilde{\mu}_{ij}$). Model obtained saved opportunities to reproduce variety of collective effects of pedestrian movement from free walk to escape panic and took more flexibility.

The simulation made showed real improvements in decision-making process in comparison with basic FF model and pointed out some problems. The following points seem to be very important for realistic pedestrian simulation and are under future investigations.

Jam

In a case of emergency appearing of clogging situation in front of exit often leads to appearing fallen or injured people (or jam). The physical interactions in such crowd add up and cause dangerous pressures up to $4,450 Nm^{-1}$ [2] which "can bend steel barriers or push down brick walls". Fallen or injured people act as "obstacles", and escape is further slowed. Continuous model can reproduce pushing and physical interactions among pedestrians. CA model doesn't allow to do it. Parameter $\tilde{\mu}_{ij}$ works in the model as some kind of local pres-

sure between the pedestrians (the higher $\tilde{\mu}_{ij}$ is pedestrians are more handicapped by others trying to reach the same target cell). But by means of $\tilde{\mu}_{ij}$ fallen or injured people are not simulated. Our further intention is to produce method to evaluate common pressure to each pedestrian in CA model, and if pressure is over some barrier to indicate correspondent cell as new obstacle.

Parameters adaptation

There are at least two reasons for parameters to be adaptive. One of them is learning that is reside to people. Therefor at least parameters k_S and k_D need to be time adaptive and spatial dependent as well. Parameter r needs to be spatial adaptive because of negative computational effects. So methods to adapt model parameters are under further investigation.

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