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Simulation of competitive egress behavior: comparison with aircraft evacuation data

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Abstract

We report new results obtained using cellular automata for pedestrian dynamics with friction. Monte-Carlo simulations of evacuation processes are compared with experimental results on competitive behavior in emergency egress from an aircraft. In the model, the recently introduced concept of a friction parameter μ is used to distinguish between competitive and cooperative movement. However, an additional influence in competition is increased walking speed. Empirical results show that a critical door width w_c separates two regimes: for $w < w_c$, competition increases egress times, whereas for $w > w_c$ it leads to a decrease. This result is reproduced in the simulation only if both influences, walking speed and friction, are taken into account.

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1. Introduction

Pedestrian dynamics has received growing interest over the last decades [1–3]. Several models have been proposed, either based on a continuous representation of space or on a grid, to describe the observed phenomena and predict egress times, etc.

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[4–8]. Cellular automata, which belong to the grid-based models, are successfully applied in road traffic simulations and well understood theoretically [2,3,9]. Furthermore, they are—by construction—well suited for large-scale simulations. Nevertheless, they are based on assumptions which obviously deviate from reality with respect to the degrees of freedom pedestrians have. Therefore, these assumptions have to be justified. One way to do this is to show that the model sufficiently reproduces and predicts measurable quantities. One step in this direction is presented in this paper.

Evacuations and panics have been studied in Ref. [10] by computer simulations of the social-force model. In contrast to our approach (see Section 2), pedestrians interact via repulsive forces in this continuum model. Empirical results in the field of pedestrian dynamics in egress situations can be found in Refs. [11–13].

Experimental studies [14] show that the egress times from an aircraft depend sensitively on the door width as well as on the motivation of the evacuees. The latter is described by the labels *competitive* and *non-competitive*. For a narrow door, *non-competitive* behavior is superior. However, for a wider door, the opposite holds. The experimental setting and results will be described and compared to simulation results in Section 3. But first, we will briefly review the fundamental characteristics of the model in the next section.

2. Review of model characteristics

2.1. Basic principles

The model used here is a cellular automaton (CA) where space is discretized into cells of size 40 cm × 40 cm which can either be empty or occupied by one pedestrian (*hard core exclusion*). Each pedestrian can move to one of its unoccupied next-neighbor cells (i,j) at each discrete timestep $t \to t+1$ according to certain transition probabilities p_{ij}. These probabilities are given by the interaction with a so-called *floor field* [6,15,16]. A movement is only possible to one of the four nearest-neighbour cells.

For the case of the evacuation processes considered here, the (static) floor field S describes the shortest distance to an exit door measured in steps, i.e., number of lattice sites that have to be transgressed to reach the exit. The field strength S_{ij} is thus inversely proportional to the distance from the door measured using a Manhattan metric, i.e., S_{ij} increases in the direction of the door.

Other phenomena, like lane formation or herding, that are based on a long-range interactions between pedestrians can be taken into account by a dynamically varying floor field D [6,15,16]. However, for the simulations presented here, such aspects can be neglected and only the static floor field S is used.

Also the matrix of preference, introduced in Ref. [6] to simplify the description of an inhomogeneous system (e.g., pedestrians with different desired walking directions) is not necessary for the present case. It is assumed that all evacuees want to move towards the exit. All information about its location and the desired speed is obtained via the (static) floor field and the coupling to it.

2.2. Update rules

The update rules of the model including the interaction with the floor field can be summarized as follows [6,15]:

(1) For each pedestrian, the transition probabilities p_{ij} for a move to an unoccupied neighbor cell (i,j) (including the origin cell, corresponding to no motion) are determined:

$$p_{ij} = N\xi_{ij}(1 - n_{ij})\exp(k_s S_{ij}) \tag{1}$$

with the occupation number[1] $n_{ij} = 0, 1$, the obstacle number

$$\xi_{ij} = \begin{cases} 0 & \text{for forbidden cells, e.g., walls} , \\ 1 & \text{else} \end{cases}$$

a sensitivity parameter $k_s \in [0, \infty)$, and the normalization

$$N = \left[\sum_{(i,j)} \xi_{ij}(1 - n_{ij})\exp(k_s S_{ij})\right]^{-1} .$$

(2) Each pedestrian chooses a target cell based on the transition probabilities p_{ij} determined by (1).

(3) Conflicts arising by two or more pedestrians attempting to move to the same target cell are resolved by a probabilistic method. The pedestrians which are allowed to move execute their step. The explicit procedure of conflict resolution will be described below. Here also the friction parameter will be introduced.

The above rules are applied to all pedestrians at the same time (parallel update). This introduces a time-scale of about 0.3 s/timestep [6]. The velocity of $v_{\max} = 1$ corresponds to an empirical maximum velocity of 1.3 m/s.

2.3. Conflict resolution and friction

Due to the use of parallel dynamics it is possible that two or more particles choose the same destination cell in Step 3 of the update procedure. Such situations are called conflicts. To describe the dynamics of such situations in a quantitative way, we have extended the basic model described above by the *friction parameter* $\mu \in [0, 1]$. As shown in Refs. [16,17], the introduction of this parameter allows to describe clogging and stucking effects between the pedestrians in a proper way. In a conflict the movement of *all* involved particles is denied with probability μ, i.e., all pedestrians remain at their site (see Fig. 1). Therefore, one of the individuals is allowed to move to the desired cell with probability $1 - \mu$. The pedestrian which actually moves is then chosen randomly with equal probability. As we will see, this local effect can have a strong influence on macroscopic quantities like flow and evacuation time.

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[1] Note that the occupation number of the origin cell is also set to 0.

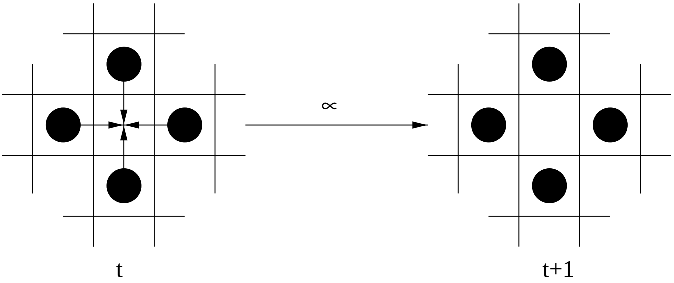

Fig. 1. Refused movement due to the friction parameter μ.

2.4. Influences of k_s and μ

In Refs. [15,17] results of simulations of the evacuation of a large room with one single door have been presented. Here we want to focus on the effects of a variation of the two parameters k_s and μ. In Ref. [15] it has been argued that the coupling strength k_s can be interpreted as the degree of information about the environment of the pedestrians. In an evacuation situation for $k_s \to 0$ the pedestrians do not sense the field S. Therefore, they do not have any guidance through the surroundings and perform a pure random walk which leads to maximal evacuation times. On the other hand, for $k_s \to \infty$ they have full information about the shortest distance to the door and the evacuation time converges towards a minimal value. The movement of the particles becomes deterministic. We want to emphasize that k_S cannot only be interpreted as a measure of information about the environment, but also as *motivation level*. Even if one has complete knowledge about the location of an exit one might just stroll there in cases where there is no need to hurry. The latter interpretation of k_S is more appropriate for the situation studied in this paper.

Using the simple example of motion along a corridor we want to exemplify the influence of the parameter k_S. The motion of pedestrians in $+x$-direction can be described by a static floor field $S_{ij} = i$, i.e., the field increases linearly in the direction of motion and is constant orthogonal to it. The effective walking speed of a single pedestrian is then approximately given by the probability $P(v_x > 0)$ that the motion occurs in positive x-direction, or explicitly,

$$v_{\mathrm{eff}} = P(v_x > 0) = \frac{\mathrm{e}^{k_s}}{3 + \mathrm{e}^{k_s} + \mathrm{e}^{-k_s}} \,. \tag{2}$$

For $k_s \to \infty$ one has $v_{\mathrm{eff}} \to 1$, i.e., a deterministic motion. On the other hand, for $k_s = 0$ one finds $v_{\mathrm{eff}} = 0.2$, corresponding to an isotropic random walk.

The friction parameter μ shows its influence only in interactions between particles, namely in conflict situations. An increased μ-value leads to a mutual hindrance of the pedestrians, e.g., due to rude combating for the unoccupied target sites near the exit. So a strong coupling to S together with a high μ value describes a competitive situation, where an ordered outflow is inhibited due to local conflicts and misbehavior near bottlenecks or doors, resulting in high egress times. Such situations are well

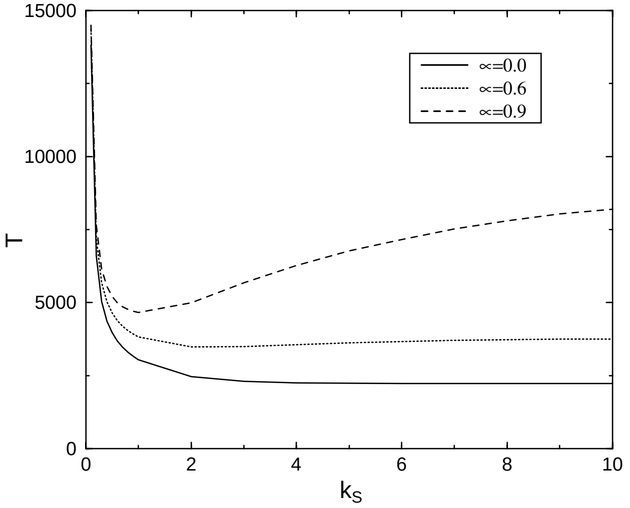

Fig. 2. Evacuation time as function of the sensitivity parameter k_s for different μ values. The initial density is $\rho = 0.3$.

known from emergency evacuations due to fire or other reasons in sports arenas or on passenger vessels.

Note that the parameters k_S and μ have opposite effects: increasing k_S increases the effective velocity, whereas increasing μ decreases it. This competition can be seen from Fig. 2, where the influence of an the coupling strength to S for fixed μ values is shown. For $k_s \to 0$ conflicts between the particles are not very important for the dynamics, especially the evacuation time. Due to the random walk nature of the motion, close to the exit only a few conflicts occur. For $\mu \to 1$ the number of unsolved conflicts increases with k_s. This results in stucking and clogging phenomena and increases evacuation times. For $\mu = 0.9$ (Fig. 2) one therefore finds a *minimal* evacuation time for an intermediate coupling ($k_s \approx 1$).

In the following section, we present simulation results concerning the dependency of the egress time of a room on k_s and μ. As we will see one can distinguish competitive and non-competitive behavior of the pedestrians by varying k_s and μ.

3. Modeling of competitive and cooperative behavior via friction

3.1. Experimental results

One very interesting experimental result [14] shows that the motivation level has a significant influence on the egress time from a narrow body aircraft. The experiment was carried out with groups of 50–70 persons, where in one case (competitive) a bonus was paid for the first 30 persons; in the non-competitive case, no bonus was paid. The time of the 30th person reaching the exit was measured ($t_{\text{comp.}}$ and $t_{\text{non-comp.}}$, resp.) for

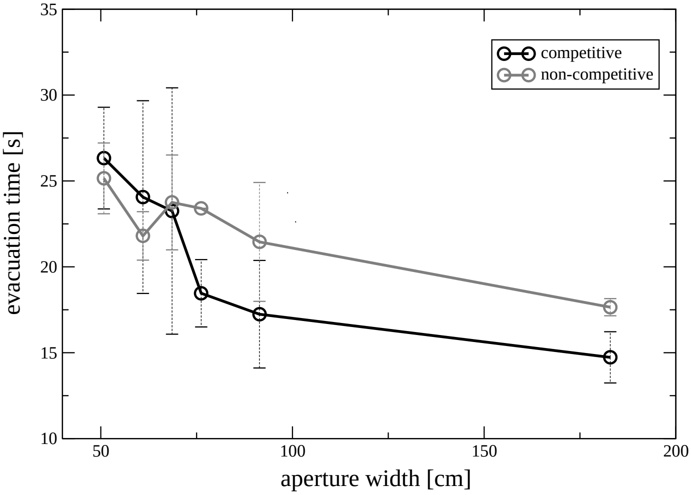

Fig. 3. The evacuation time for an aircraft increases with decreasing aperture width, as has been shown in experiments [14]. For non-competitive situations, this decrease is rather smooth. However, if there is competition, at a certain aperture width ($w_c \approx 70$ cm) the increase in the egress time is quite drastic and the performance is worse than in the case of cooperation. The error bars indicate the standard deviation for the mean value of several measurements.

variable exit widths w. The main result is

$$t_{\text{comp.}} > t_{\text{non-comp.}} \quad \text{if } w < w_c \,, \tag{3}$$

$$t_{\text{comp.}} < t_{\text{non-comp.}} \quad \text{if } w > w_c \,, \tag{4}$$

where w_c was determined experimentally to be about 70 cm (see Fig. 3). This shows that competition is beneficial if the exit width exceeds a certain minimal value. For small exit widths, however, competition is harmful. The question arises, how the motivation level can be represented in a CA model.

Within the framework of the model described above, competition is described as a increased assertiveness (large k_s) and at the same time strong hindrance in conflict situations, i.e., large μ. Cooperation is then represented by small k_s and vanishing μ. This allows to quantitatively distinguish competition from cooperation and compare the experimental results to simulations.

3.2. Comparison between simulation and experimental results

In the following, we try to reproduce the experimental results qualitatively using a simplified scenerio. Instead of a real airplane we simulate an evacuation from a room without additional internal structure. The size of the room is 63 × 63 cells with an exit located at the center of one wall. The distinction between competitive and non-competitive behavior is made by setting $k_s = 10$ and $\mu = 0.6$ for the first, and $k_s = 1.0$ and $\mu = 0$ for the latter. Competition therefore means high assertiveness as

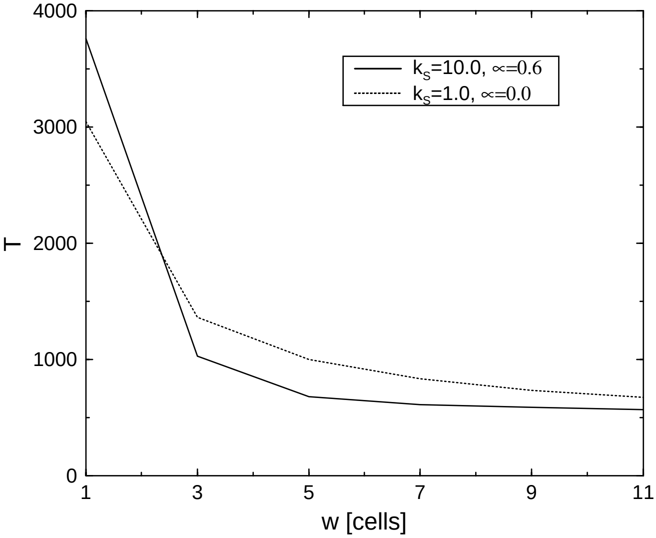

Fig. 4. Average egress times for variable door width w. For the competitive case (full line) $k_s = 10$ and $\mu = 0.6$ has been chosen, and for non-competitive behavior (dotted line) $k_s = 1.0$ and $\mu = 0$.

well as the possibility of having only losers and no winner in conflicting situations. Fig. 4 shows typical average evacuation times for the non-competitive and the competitive regime with an initial particle density of $\rho = 0.03$ (116 particles). The door width is variable and ranges from 1 to 11 lattice sites. Clearly the simulations are able to reproduce the observed crossing of the two curves at a small door width qualitatively.

As can be seen from the two curves in Fig. 4 for $\mu = 0$, increasing k_s alone always decreases t_{egress}. The effect is therefore only obtained by increasing both, k_s and μ.

In summary, we have two influences that determine the egress of persons and the overall evacuation time in our scenario: On one hand, the walking speed (controlled by the parameter k_s) and, on the other hand, the friction (controlled by μ). These parameters depend in a different way on the door width: the influence of the friction dominates for very narrow doors which leads the crossing shown in Fig. 4.

It should be emphasized that conflicts close to the exit are most important (see Fig. 5) since they have a *direct* influence on the evacuation time. Therefore, in case of competitive behavior and narrow doors it is important to find other means in order to reduce the number of conflicts occurring at the exits.

4. Conclusion

We have employed the concept of friction to model competitive egress behavior in 2D CA simulations. The parameter μ determines the probability of having a winner in a conflict. Large values of μ allow to represent the disadvantageous aspects of competition, e.g., increasing the overall loss. On the other hand, increased assertiveness

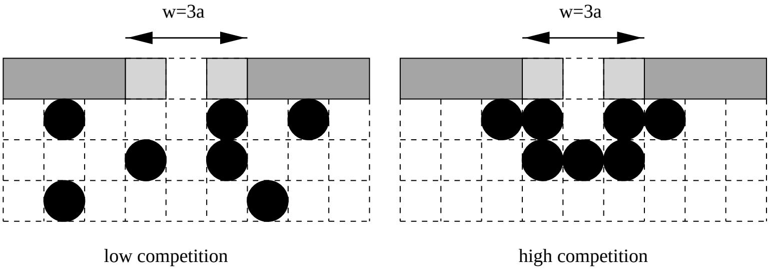

Fig. 5. This figure illustrates how high competition (right) can lead to a slower egress than low competition (left) for small door width. If the door width is increased to $3a$ then higher competition performs better, since the high assertiveness leads to a more direct movement towards the exit and outweighs the loss due to friction.

leads to higher walking speeds in the competitive case. These two aspects compete and there relative importance for the egress time is determined by the width of the exit. The astonishing result—which was first obtained experimentally and is reproduced here by simulations—is the existence of a critical exit width w_c. Competitive behavior that leads to lower egress times for $w > w_c$ produces higher egress times than the non-competitive behavior for $w < w_c$. Furthermore, without friction (i.e., $\mu = 0$) this distinct aspect of egress situations cannot be obtained in the framework of the CA model. Therefore, the model presented is minimal in the sense that all its characteristics are necessary for reproducing phenomena observed in reality.

The phenomenon is based on a cooperative effect. For low densities, there are few conflicts and friction does not impede the motion of a single pedestrian. However, if pedestrians interact with each other conflict solution (covered by μ) is of major importance. This could be interpreted in a game theoretical way if the average number of winners which is given by $1 - \mu$ is equated with the payoff. Further research along those lines could provide interesting insights into the common aspects of pedestrian dynamics and social behaviour theories.

Furthermore, it would be interesting to search for a similar effect in granular materials. Although several experimental and theoretical studies of granular flow through an aperture of discharge from a hopper exist, see e.g., Refs. [18–20], it is generally assumed that the grains are much smaller than the aperture. We expect that for a width of the same order of the grain size a similar effect as described here can be observed.

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