Cellular Automaton Approach to Pedestrian Dynamics - Applications

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Abstract. We present applications of a cellular automaton approach to pedestrian dynamics introduced in [1, 2]. It is shown that the model is able to reproduce collective effects and self-organization phenomena encountered in pedestrian traffic, e.g. lane formation in counterflow through a large corridor and oscillations at doors. Furthermore we present simple examples where the model is applied to the simulation of evacuation processes.

1 Introduction

In Part I [1] (see also [2]) we have introduced a two-dimensional cellular automaton model for the description of pedestrian dynamics. In the model the space is discretized into small cells which can either be empty or occupied by exactly one pedestrian. These can move to one of the neighbouring cells where the direction of motion is chosen with certain probabilities. These probabilities depend on the

1. occupation of the targets cells: Motion to a cell already occupied is forbidden.
2. matrix of preference: It encodes the direction of motion including the average velocity of the pedestrian.
3. value of the dynamic floor field: This corresponds to a virtual trace left by the other pedestrians.
4. value of the static floor field: This allows to specify preferred regions, e.g. to incorporate effects of the geometry of a building etc.

The introduction of the floor fields allows to translate the long-ranged interactions between pedestrians into local ones. Thus the model is extremely efficient in computer simulations and large crowds can be simulated much faster than real time. Despite this simplicity the cellular automaton allows to reproduce the collective effects and self-organization phenomena encountered in pedestrian traffic. Examples will be given in the following sections.
2 Self-Organization Phenomena

One of the major design principles of our model is to provide the simulated individuals with as little intelligence as possible. There have been approaches where the pedestrians examine their surroundings or look ahead a certain amount of grid cells in order to decide where and how far to move. It has also been proposed to select a target cell and repeatedly choose a different one if it is found occupied.

These approaches imply the need for more complicated algorithms which reduce the simulation speed. Furthermore, it inhibits the unambiguous definition of the update procedure used. We avoid this strategy and rely on the concept of self-organization to model pedestrian behaviour.

We argue that simple, local update rules for the pedestrians and optionally one or more floor fields are sufficient to yield a richness of complex phenomena. Obviously this route is superior concerning the computational efficiency and even allows for faster-than-real-time simulations of large crowds, e.g. in evacuation processes in public buildings.

2.1 Lane Formation

The most prominent collective phenomenon is the formation of lanes out of an unordered group of pedestrians. This corresponds to a spontaneous breaking of the symmetry of the particle number distribution in space. Our simulations show that an even as well as an odd number of lanes may be formed. The latter corresponds to a spontaneous breaking of the left-right symmetry of the system.

We present simulations of a rectangular corridor which is populated by two species of pedestrians moving in opposite directions (see Fig. 1). Parallel to the direction of motion we assume the existence of walls. Orthogonal to the direction of motion we investigated both periodic and open boundary conditions. The length of the corridor is set to 200 cells. Widths of 15 and 25 cells have been used.

With periodic boundary conditions, the density of pedestrians is fixed for each run. It is ensured that the overall number of pedestrians is evenly divided by the numbers for the different species: with two species, one is moving to the left and the other to the right. For open boundaries, we fix the rate at which pedestrians enter the system at the boundaries. The pedestrians leave the system as soon as they reach the opposite end of the corridor.

Fig. 1 shows the graphical frontend running a simulation of a small periodic system. The lanes can be spotted easily, both in the main window showing the cell contents and the small windows on the right showing the floor field intensity for the two species.

This model clearly provides the option for a complete jam. The jamming probability with periodic boundaries at constant density increases with the length of the system. An open system can be thought of as the limit of an

\[\text{1 For a more complete discussion of other modelling approaches, see [1] and references therein.}\]
Figure 1: Snapshot of a simulation with $\rho = 0.17$, $w = h = 50$. The left part shows the parameter control. The central window is the corridor and the light and dark squares are right- and left-moving pedestrians, respectively. The right part shows the floor fields for the two species.

Infinitely long periodic system, although density and entry rates do not correspond absolutely.

We performed several runs for different densities and insertion rates, respectively. The focus of our attention is the parameter range where the transition from a stable flow to a complete jam takes place.

To obtain information about the lanes we measured the pedestrian velocities at a cross section perpendicular to the direction of flow. Selected velocity profiles are shown in Figs. 2-4.

It is obvious that the lane formation in the periodic system works far better than in the open system. The floor field leads to an effective attraction of identical pedestrians while different pedestrian species separate. This results in the formation of a stable pattern in the periodic case.

In a certain density regime, these lanes are metastable. Spontaneous fluctuations can disrupt the flow in one lane causing the pedestrians to spread and interfere with other lanes. Eventually the system can run into a jam by this mechanism. The average time after which the system is blocked by a jam is an interesting observable which depends on the density of pedestrians. We observe large fluctuations of this quantity which require many samples to find statistically significant information.

To create Fig. 5 we sampled 700 initial conditions for each of two densities and let them evolve for at most 125,000 timesteps. The diagram shows how the
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Figure 2: Velocity profile of a periodic system with $\rho = 0.12$.

Figure 3: Velocity profile of an open system at $x = \frac{L}{2}$ with $\alpha = 0.04$.

Figure 4: Velocity profile of an open system at $x = \frac{L}{4}$ with $\alpha = 0.04$. 
percentage of systems with nonzero flow (i.e. jam-free systems) decreases with time. In this regime, the density has a big impact on this quantity.

2.2 Different geometries

Our model can easily be generalized for the use with different geometrical setups. The transition rules for the particles do not need to be altered, and the computational speed does not suffer.

In Fig. 6 a wall with two doors has been added to the system. It is oriented perpendicular to the direction of flow. With the appropriate choice of the doors’ width and the distance between them, they support the separation of the two particle species.

Another feature of pedestrian behaviour are oscillations of the direction of flow when two groups of opposite walking direction are facing each other at a
tight spot like a narrow door. If we simulate this setup using our model, we can observe oscillation on two time scales (provided that the parameters are suitably chosen): An exchange between a blocked situation and a flow in both directions is the main result. Inside the blocked period small groups of only one species can break through. This is illustrated in Fig. 7. These breaks can alternate between the two species and can therefore be interpreted as oscillations.

Figure 7: Oscillations of the direction of flow: A group of particles of the same species break through a blockade at a door.

To simulate a crossing, four species of particles are inserted into the system. Their directions of preference differ by 90 degrees. The system is surrounded by walls which have doors in the middle through which the system is closed periodically. Several flow patterns arise from these boundary conditions; the most common one is shown schematically in Fig. 8. In each of the two roads we observe the formation of lanes as discussed in this section, while the orientation
is different: In one the particles tend to walk on the right side, in the other on the left. The region of highest disorder lies in the center of the system where the two roads meet. It is marked with a shaded circle.

3 Evacuation Simulations

In the following we describe results of simulations of a typical situation, i.e. the evacuation of a large room (e.g. in the case of a fire). We try to show the relevance of our model for practical applications. It is able to cope with the complex geometrical structures of any given environment and is therefore of use for architectural planing and safety estimations of evacuation times of arbitrary buildings. First we study a large room without any internal structure (e.g. a ballroom) and just one door. As an example for a more complex surrounding we investigate in Sec. 3.2 the stylized geometry of a typical lecture hall. It will be shown that our model captures the main aspects of the dynamical behaviour of large crowds even in such a complex situation.

3.1 Evacuation of a Large Room

Fig. 9 shows a large room, e.g. a ballroom, with one door only. We have simulated the behaviour of more than 100 people, which are initially distributed randomly, leaving this room. It is assumed that they have no knowledge of the exact location of the exit. The only information they get is through the floor fields. The static floor field has been chosen such that its strength decreases radially from a maximum value at the door to zero at the corners opposite to the door. This is already sufficient to achieve a complete evacuation of the room. The measured evacuation times depend on the coupling parameters to the static and
dynamic floor fields and the parameters specifying the evolution of the dynamic floor field. Without any fine-tuning of these parameters it is already possible to find reasonable evacuation times.

Fig. 10 shows the situation in the room after several timesteps of the simulation. The left picture shows the people crowding in front of the door in the typical half-circle way. The right picture depicts the underlying dynamical field, i.e. the virtual trace left by the pedestrians. The main traces in the direction of the door are easily spotted.

Figure 10: Evacuation of a large room: Typical configuration at an intermediate time (left) and the dynamical floor field created by the people leaving the room (right).

One interesting result of these simulations concerns the influence of the attractive interaction of the pedestrians. We have found that fluctuations in the measured evacuation times become much more dominant if the coupling to the static field is small \[2\]. In this case they mainly follow the trace of other people in the hope that they know the way towards the exit. This corresponds to a situation where the exit can not be seen, e.g. due to failing lights or if the room is smoke-filled. This shows that for the interpretation of evacuation simulations just studying average evacuation times might lead to wrong conclusions.

### 3.2 Evacuation in Complex Geometries: Lecture Hall

The typical feature of a lecture hall is its compartmentation through large tiers, which act as non-traversable obstacles for the audience. Starting point for the simulations at \( t = 0 \) is a fully occupied lecture hall, i.e. all available seats are taken (see Fig. 11). The audience then tries to leave the hall through a single door at the front of the room. As in the simpler example of Sec. 3.1 the main guidance in the direction of the door is accomplished by the static floor field described above. The rather complicated geometrical structure of the situation
involves some sophisticated problems in the definition of this field. On the one hand, people have to orientate themselves into the direction of the door. On the other hand, they have first to leave the tiers (which is always possible in two directions). Without going into detail one can say that these problems can be solved by the superposition of different suitable static fields. The resulting field is shown in Fig. 11.

Figure 11: Lecture hall at $t = 0$ (left) and the static floor field used in the simulations (right).

The size of the lattice is $33 \times 33$ cells with 312 particles on it. Fig. 12 shows typical stages of the dynamics of the model (the left picture displays the hall after 134 and the right picture after 590 timesteps). In this example we have neglected the coupling to the dynamical floor field and therefore the whole evacuation process is driven solely by the static field.

Figure 12: Typical configurations at later times.
As one can see in these pictures the model is able to describe such a complex evacuation procedure in a very realistic way. The majority tries to leave the hall through the main corridor in the middle of the room. Therefore it is very crowded and the typical jammed motion is easy to spot. However some people try to reach the front door by detouring through the smaller corridors at the sides of the hall, as in reality.

The whole evacuation process takes about 650 timesteps which corresponds to approximately 3 minutes of real time. This seems to be a rather realistic result which has been obtained without any fine-tuning of parameter values.

This simple example already shows that our model is able to describe rather complex behaviour in complicated geometries. Therefore it can play its part in the field of the management of evacuation processes. An example for this will be given in the next section.

3.3 Optimization of Evacuation Times

In this subsection we present a simple application of our model in the field of risk analysis for the design of large buildings. Due to the high speed of a single simulation one is able to average over a large number of different evacuation scenarios (which are realised through different sets of random numbers). Therefore it is possible to make predictions about average evacuation times (and its fluctuations!) of different building geometries. As an example for such measurements we choose a slightly different situation then presented in the last subsection. Starting point is again a stylized fully occupied lecture hall, but now with two doors. In the first floor plane the doors are located at the front and the bottom of the hall (this geometry will be named "hall A"). In the second floor plane they are placed at the right and left side ("hall B"). These two different geometries are pictured in Fig. 13. We have measured the evacuation times for the 312

![Figure 13: The two floor planes for hall A (left) and hall B (right).](image)
people of the fully occupied rooms. The values for the mean evacuation times $T$ and the corresponding variances $\sigma$ are listed in the table below (in update steps).

| hall  | $T$  | $\sigma$ |
|-------|------|----------|
| A     | 560  | 85       |
| B     | 363  | 24       |

Though this result seems to be rather obvious through common sense, this example shows nevertheless that our model and its rich variations are very well suited to contribute to investigations in the field of risk analysis of evacuation processes.

4 Conclusions

We have presented simple examples for applications of a new two-dimensional cellular automaton model for pedestrian dynamics. In contrast to other CA approaches the model is able to reproduce the collective effects which are characteristic for pedestrian motion.

We can determine the complete statistical properties (including variances) of observables like evacuation times. This knowledge is of major importance if one wants to establish risk management techniques that are nowadays used for the hedging of financial assets all over the world [6].

Due to the high computational speed (simulations can be run 10 to 100 times faster than real time) our model is applicable to time-critical tasks like emergency management.

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