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Modeling Pedestrian Dynamics with Adaptive Cellular Automata

Djalma Padovani*, João José Neto, Paulo Roberto Massa Cereda

School of Engineering of the University of São Paulo, Av. Prof. Luciano Gualberto, 380 - 05508-010 - São Paulo – SP, Brazil

Abstract

This work presents a proposal for modeling pedestrian dynamics by means of Adaptive Cellular Automata, a dynamically adjustable approach that uses an underlying cellular automata and a set of adaptive functions intended to reconfigure the automata internal structure and behavior according to observable events and rules, making them adaptable to environment changes.

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Keywords: Self-Adaptive; Reconfiguration; Cellular Automata; Pedestrian Dynamics,

1. Introduction

Pedestrian crowd is a phenomenon that can be observed in several places in a large city, such as streets, intersections, squares, etc. Many researchers have been interested in studying this phenomenon because pedestrian crowd dynamics can cause accidents with deaths and injured people. It is noticed that the greater the population density, the greater the risks and consequences of possible disasters. The subject, however, poses serious research challenges, since conducting experiments involving people is difficult and costly, and it is virtually impossible to replicate real-world disaster situations involving crowd. Computational simulation is a very popular approach to

* Corresponding author. Tel.: +55-11-99909-8577.
E-mail address: djalma.padovani@usp.br

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study this type of phenomenon, since it makes possible to approximately reproduce disasters and allows the experimentation of different hypothesis without involving people. One promising approach followed the last decades is the use of models based on cellular automata, instead of simulating the dynamics of individuals in so-called agent-based models. Cellular automata models allow simple and fast implementation, but are criticized for lacking realism because these models limit the pedestrian spatial movement to checkerboard and turns it difficult to model changing pedestrian velocities and to simulate heterogeneous pedestrian behaviors.

Adaptive automata emerge as an alternative to bypass such limitations. An adaptive automaton is a state machine that successively changes its own structure in response to the application of so-called adaptive actions associated to the application of transition rules by the automaton. Adaptive rules may be organized by constituting an adaptive layer attached to non-adaptive devices. In that way, adaptivity can provide an adaptive layer for cellular automata, so that environment modifications such as those referring to pedestrian velocities and heterogeneous behavior can be identified and used as input to modify the structure and behavior of the cellular automata itself, making their behavior closer to that of real-world pedestrian dynamics.

The remaining of this paper is organized as follows: firstly the basics of pedestrian dynamics is explained, afterwards an overview about cellular automata and their application to pedestrian dynamics is given, then the concepts of adaptive cellular automaton and the algorithms proposed for the modeling of pedestrian dynamics are explained and exemplified. Finally a brief conclusion is presented and future work is proposed.

2. Pedestrian Dynamics

In general one must consider pedestrians as individuals with different targets. If several pedestrians have the same target they may try to reach it following different routes. Every pedestrian has an individual velocity that is strongly influenced by interactions with other pedestrians. These interactions can reduce this velocity or even stop completely the movement, e.g. in jams. In the following, the major properties of pedestrian dynamics will be shortly summarized[1].

Individual pedestrians try to minimize their effort to reach their target. Deviations or even movements against the preferred direction are avoided. If the target is not reachable directly, pedestrians choose a series of intermediate targets for which they aim straight for[2]. Therefore, the route of pedestrians can be approximated by a polygon[3]. Although pedestrians tend to use existing routes, trails between existing routes can be formed as shortcuts[4]. The favorite speed of individual pedestrians can be described as Gaussian distribution with the average of 1.34 m/s and a standard deviation of 0.26m/s. Variations of this preferred speed can also exist because of external influences. An example for this is the reduction of the average velocity with higher temperatures[5].

Pedestrians try to keep a safety distance from other pedestrians and from walls or obstacles. As described in[3], the space requested during movement is significantly bigger than the space requested in rest, because a larger safety distance is necessary in case of a sudden slowdown and because of the pendulum motion of legs and arms during the movements. At small pedestrian densities, pedestrians tend to move in their individual favorite speed. As the density increases, pedestrians tend to have stronger interactions with others and their speed decreases. Observations[1] showed that there is no movement at densities larger than 5.4 pedestrians/ m^2.

Although pedestrians act independently, some interesting phenomena can be observed in crowds. One of them is the lane formation, motivated by the fact that lanes reduce the collisions between pedestrians and allow higher flow. This effect is even amplified if there are obstacles in the middle of the corridor. Similar to the effect of lane formation, striations can occur when two flows of pedestrians cross each other. Striations minimize the interactions between pedestrians of different groups and are temporarily, whereas lanes separate pedestrians spatially. Lanes has also the characteristic of collapsing above a certain critical density, leaving groups of pedestrians with different targets so close to each other so that they are no longer able to move at all[1].

Other interesting phenomena observed in crowds are the oscillations of the flow in bottlenecks, for example, when pedestrians have to pass a door to get out of a closed space. In this situation, pedestrians show an increasing impatience and start to put pressure on the door. If the pressure on one side of the door gets above a certain threshold, this group will dominate the movement. The direction flow switches only if a reversed situation sets in.

The frequency of the changing direction decreases with increasing length, because at longer bottlenecks pedestrians have more difficulties to get an overview of the situation and tend to be more patient[4].

3. Cellular Automata

Crowd simulation models can be classified into two categories: macroscopic and microscopic. Macroscopic approaches include regression models and dynamic flow models. Microscopic approaches include cellular automata models and agent-based models. The macroscopic approaches simulate the behavior of the crowd as a whole. They do not consider individual features such as physical abilities, direction of movement, and individual positioning. On the other hand, the microscopic approaches are interested in the behaviors, actions, and decisions of each pedestrian as well as interactions with others, giving more realistic outputs of simulation[6].

Cellular Automata are collections of cells on a grid[7, 8, 9]. Each cell contains a state chosen among a finite set and can change over time. The grid has to be regular, which means that it is made of regular polygons. There are three possible types of grids: triangular, rectangular and hexagonal. Since pedestrians are often approximated by a circle, the hexagon is the best choice to represent pedestrians. A rectangular grid is perfectly suited for walls, because most rooms are rectangular. Hexagonal and triangular grids are not appropriate to represent straight walls, but are more flexible for obstacles with complex shapes[1]. The states of the cells change based on the awareness of the environment and the possibility to move to the state of its neighboring cells. Two common neighborhood definitions are used: Von-Neumann neighborhood, where just the neighboring cells that share one side with the basic cell are taken into account; Moore neighborhood, where all cells sharing at least one corner with the basic cell are considered as neighbors [3].

Pedestrians move from one state to another based on the awareness of the environment and the possibility to move to the state of its neighboring cells. Changes of cells state are based on a set of rules that produce a new generation of cells depending entirely on the previous generation. Generally, it is necessary to distinguish between parallel and sequential update rules. By using parallel update rules all pedestrians move simultaneously. In this case there might be conflicts if two or more pedestrians want to enter the same target cell. Only the winner of the conflict is allowed to move; the others have to stay in their cells. By using sequential update rules, pedestrians proceed one by one. There are no conflicts, so a higher flow might be generated. Rules can also be classified as stochastic or deterministic. The class of stochastic rules includes all parallel update rules based on statistical processes; in contrast to stochastic, deterministic parallel update rules do not use random numbers and the system is totally predictable for a given starting configuration[1,10].

4. Adaptive Cellular Automata

Adaptive automaton is a state machine that successively changes its structure according to the application of adaptive actions associated with the rules of transitions performed by the automaton[11]. In this way, states and transitions can be eliminated or incorporated into the automaton as a result of each of the steps performed during the input analysis. In general, the Adaptive Automaton is formed by a conventional, non-adaptive device, and a set of adaptive mechanisms responsible for the self-modification of the system. The conventional device may be a grammar, an automaton, or any other device that respects a finite set of static rules. This device has a collection of rules, usually in the form of if-then clauses, which test the current situation against a specific configuration and take the device to its next situation. If no rule is applicable, an error condition is reported and operation of the device is discontinued. If there is a single rule applicable to the current situation, the next situation of the device is determined by the rule in question. If more than one rule adheres to the current situation of the device, all possible situations are handled in parallel and the device will display a non-deterministic operation. Adaptive mechanisms are formed by three types of elementary adaptive actions: consultation (inspection of the set of rules that define the device), exclusion (removal of some rule) and inclusion (addition of a new rule).

We introduce the concept of Adaptive Cellular Automaton as an adaptive device composed by a static and a dynamic configuration. The static configuration is formed by the quadruple <Environment, Pedestrians, Rules,

Time>. The first element is used to describe the environment: space, obstacles, walls, riots, main and secondary exits, and main entrance cells. The second element is used to describe pedestrians: the position in the space, the neighbourhood, the path to the target and the group they belongs. The third element is used to describe the rules applied to the system: type of neighbourhood, path to target rule, conflict target resolution, maximum number of pedestrians in the system and type of movement. The fourth element indicates the interval time applied for iterations. The static configuration is detailed in the paragraphs below.

a) Environment
The environment is composed by squared cells with fixed width, obtaining a two-dimensional grid. The space is discretized into small cells that can be occupied by exactly one pedestrian. At a discrete time it possible to analyse the state of the system by observing the state of each cell. For simplicity, the environment described here is static, which means that it does not evolve with time and it is not influenced by the behavior of pedestrians, following the concept of static floor field described in[12]. The environment is characterized by the triple <celId, celType, celState, celOverhead>. The attribute celId identifies the cell position in the grid. The attribute celType identifies whether the cell is a free walking space or occupied by a barrier or an obstacle. Specific celTypes are used to identify exits and entrances. The attribute celState identifies the state of each cell, i.e. free cells are identified by zeros; pedestrian cells are identified by ones. Non free cells, such as walls, barriers and riots are identified with the corresponding integer numbers. Main and secondary exits are identified as free cells. The attribute celOverhead is used to inform any penalizations pedestrians take when choosing the cell.

b) Pedestrians
Pedestrians are characterized by the quadruple <pedId, groupId, neigbId, nextcellId >. The attribute pedId identifies pedestrians in the system. The attribute groupId identifies the group pedestrians belong. It can assume a null value if the pedestrian does not belong to any group. The attribute neigbId is used to identify the coordinates of all possible neighbourhoods of the cell occupied by the pedestrian (north, northeast, east, southeast, south, southwest, west, northwest). The attribute nextcellId is used to identify the coordinates of the next cell the pedestrian has to occupy in order to achieve the target in a shortest path.

c) Rules
Rules are characterized by the quintuple < neigbTp, distanceTp, updateTp, maxPed, movTp>. The attribute neigbTp is used to identify the type of neighbourhood – Moore, Von Neumann or a randomized version of both. The distanceTp defines the kind of calculation used to obtain the distance between the cell occupied by the pedestrian and the target (i.e. Euclidean or Manhattan). The attribute updateTp is used to indicate if the system uses parallel or sequential update rules. The parallel option indicates the pedestrian has to verify if the chosen cell has already been reserved by another pedestrian at the same step. If not, the pedestrian can occupy the cell, otherwise he has to choose another one or stay at the current cell. The sequential option indicates pedestrians have to verify only if the chosen cell is free, since there are no conflicts for the same cell. The attribute maxPed indicates the maximum number of pedestrians allowed in the environment under analysis. The attribute movTp is derived from the Observation Fan proposed in[13], through which pedestrians can observe the environment before deciding which path to take. In our model, it indicates whether the pedestrian should verify the availability of current cells before deciding the movement, so that the next movement is made only through current free cells.

d) Time
The iteration time is a parameter than can be adjusted to reflect the average velocity of a pedestrian. Considering a square cell of 40X40 cm^2 and an average velocity of 1.34 m/s, as explained in session 2, the corresponding time scale is 0,3sec of real time.

The dynamic configuration is used to describe the behavior of the pedestrian, considering the static configuration of the system and the events that pedestrians are subject to. Formally, a cellular automaton C is defined as $C = (d, S, r, f)$, such that $d \in \mathbb{N}$ is the dimension, S is a finite set of states, $r \in \mathbb{N}$ is the neighborhood radius and $f \subseteq S^{(2r+1)^d} \mapsto S$ is the rule set. A configuration $c \in S^{\mathbb{Z}^d}$ is a coloring of $\mathbb{Z}^d$ by S, and a global mapping $G: S^{\mathbb{Z}^d} \mapsto S^{\mathbb{Z}^d}$ applies f uniformly and locally, such that $\forall\, c \in S^{\mathbb{Z}}, \forall\, z \in \mathbb{Z}^d, f(c(z-r), \dots, c(z+r))$.

An adaptive cellular automata A is defined as $A = (C, M)$, where C is the underlying non-adaptive cellular automaton and M is the adaptive mechanism. For our specific scenario, the rule set f is extended in order to consider additional facts, such that $f \subseteq S^{(2r+1)^d} \times E \times P \times T \mapsto S$, where E, P and T are property maps about the environment itself, general pedestrian behavior and time constraints, respectively. Adaptive functions are triggered whenever planned yet unexpected configurations are reached, as a means to improve the ongoing pedestrian dynamics and mitigate effects of high density crowds and insurgent riots. For instance, consider a scenario in which the number of exits is insufficient to meet the growing demand of pedestrians. The model will eventually collapse unless new exits are programmatically provided as time goes by. Let there be a helper adaptive function $\mathcal{P}$, defined as follows, that decides upon the instantiation of new exits based on a population growth threshold $\gamma \in \mathbb{R}$:

$$\mathcal{P} = \frac{\{ a = \left(\left| \{ s \mid s \in S^d \text{ is a pedestrian} \} \right| \div \left| \{ s \mid s \in S^d \text{ is an exit} \} \right) \right.}{|S^d|} > \gamma,$$
$$a \text{ and } s \mid s \in S \text{ is empty} \Rightarrow s \leftarrow \text{exit} \}$$

Conceptually, every pedestrian chooses the shortest path from origin to target. However, when in a crowd, strictly optimal paths will potentially collide and thus compromise the flow, as pedestrians cannot share the same positions simultaneously. The general rule ignores positions other than optimal, thus leaving the pedestrian in a stationary position waiting for an opening. From a behavioral point of view, deliberate stops constitute an issue, as the model identifies the waiting pedestrian as an obstacle rather than a moving entity. As a workaround, we introduce an adaptive function Q, defined as follows, that detects a potential stationary pedestrian scenario and changes the rule for suboptimal paths as well:

$$\begin{aligned}
&Q(a) = \{ v_1 = \{ s \mid s \in S^d \text{ is empty} \} \\
&v_2 = s \in v_1 \cap neighbours(a) \\
&?(a, ?x) \mapsto ?y \\
&-(a, ?x) \mapsto ?y \\
&+(a, ?x) \mapsto v_2 \}
\end{aligned}$$

Weather conditions might significantly impact on pedestrian dynamics to the point of influencing their own behavior as individuals and crowd. For instance, consider a scenario where pedestrians might reject or offer resistance of traversing under heavy rain conditions; we introduce an adaptive function $\mathcal{V}$, defined as follows, that adds an uncertainty factor to pedestrians under rough weather conditions:

$$\begin{aligned}
&\mathcal{V}(a) = \{ v_1 = \{ s \mid s \in S^d \text{ is empty} \} \\
&v_2 = s \in v_1 \cap neighbors(a) \\
&?(a, ?x) \mapsto ?y \\
&-(a, ?x) \mapsto ?y \\
&+(a, ?x) \mapsto s \in \{v_2, ?x\} \}
\end{aligned}$$

5. Simulations

In this session we describe the results of simulations of three typical situations: the evacuation of a large room with a single exit; the effect of a barrier positioned near the exit of the room; and the effect of opening a secondary exit in an opposite direction of the first exit. The room consists of a square of 20 meters side and cells of 40 cm side, corresponding to 50 cells for each side. Firstly, we investigated the capability of the model to represent pedestrian simulations, evaluating density and velocity of pedestrians. Since the velocity of pedestrians is inversely proportional to the density, when the density increases, the velocity decreases[13,14]. In our simulations, pedestrians got into the room from the southwest side, through an area of 10 by 10 cells, and got out the room at the northeast edge, through a unique cell, at coordinate (50,50).

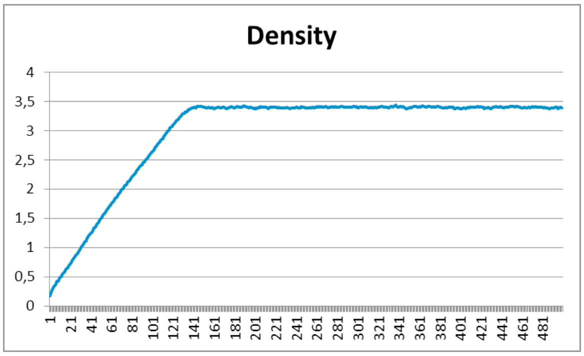

Fig.1: Pedestrian density of the room after 500 iterations.

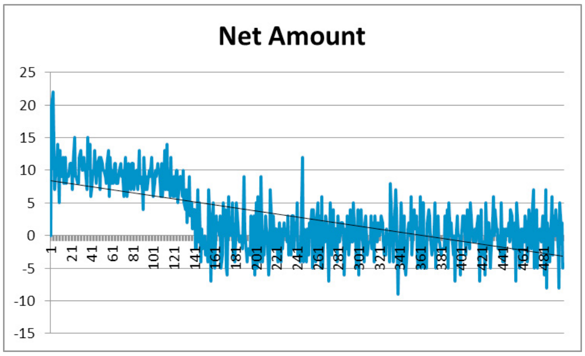

Fig.2: Net amount of pedestrians after 500 iterations.

The system was configured to verify the entrance cells states and if they were not free, the system did not allow new entries. It was expected that the system would stabilize after reaching a threshold density, because the capacity to leave the room was significantly lower than the capacity to enter the room. Fig.1 shows the pedestrian density of the system after 500 iterations in pedestrians/m^2. As expected, density increases steadily until it reaches a threshold value, then it stabilizes. Fig.2 shows that the net amount of pedestrians (amount of pedestrians in current iteration minus amount of pedestrians in previous iteration) is decreasing steadily towards zero, which means that, after reaching the threshold density, the system is in equilibrium and only allows new pedestrians after current pedestrians leave. Therefore, our model represented correctly the nature of pedestrian dynamics.

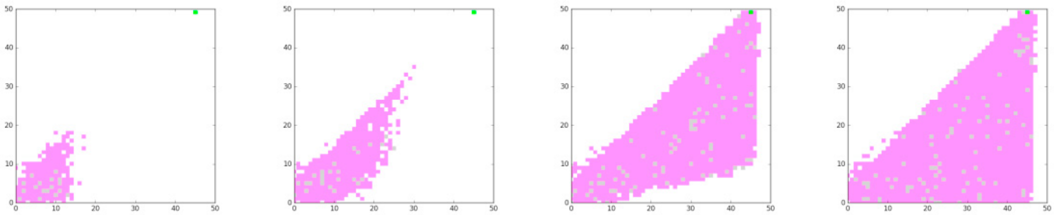

Fig. 3: State of simulation of room evacuation in 4 different steps.

We also performed qualitative observations from the simulations. Fig.3 shows, at four different steps, the state of the simulation in the scenario of evacuating room with a single exit. In this simulation, there were configured two different groups: one representing people in general (magenta) and another, smaller, representing elderly and children (grey). The exit was represented by a single cell in green. To give more realism, the neighbourhood was configured as a randomized option of Moore and Von Neumann and the Euclidean Distance method was used to calculate the distance from the cells to the target. The last state shows clearly the influence of bottleneck created by a single door, given the throughput of new entries.

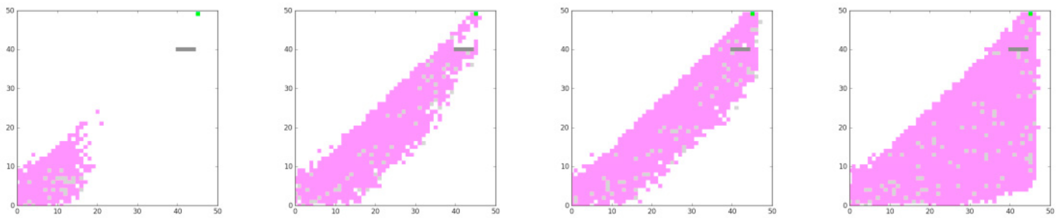

Fig.4: State of simulation of room evacuation with a barrier in 4 different steps.

A second simulation has been done to analyse the impact of a barrier in the pedestrians flow. Fig.4 shows the results obtained at four different steps. In this scenario it is possible to observe that the barrier (dark grey) has to be overcome by the pedestrians so that they can reach the target. Again, the throughput of new entries outperforms the capacity of evacuation, and after a threshold, a very similar bottleneck has been formed. Our model was able to detect the barrier and made pedestrians go around it using all available cells so that pedestrians could reach the target taking the shortest path.

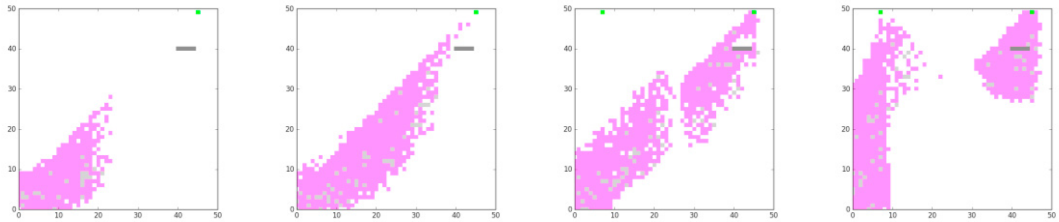

Fig.5: State of simulation of room evacuation with a barrier and a new exit in 4 different steps.

A third simulation has been done to analyse the impact of a new exit barrier in the pedestrians flow. Fig.5 shows the results obtained at four different steps. In this scenario it is observed that new exit attracts part of the pedestrians that are going to the main exit and help to form a lane after reaching a steady point. This scenario was also used to test the adaptive layer of our model. The new exit is open automatically based on the number of pedestrians in the room and on a set of events that indicates the room cannot afford more pedestrians. The Adaptive Cellular Automaton was also capable to set an overhead to a new door, so that the system could regulate pedestrians flow to avoid destabilization over the new door, as it is nearer the entrance cells.

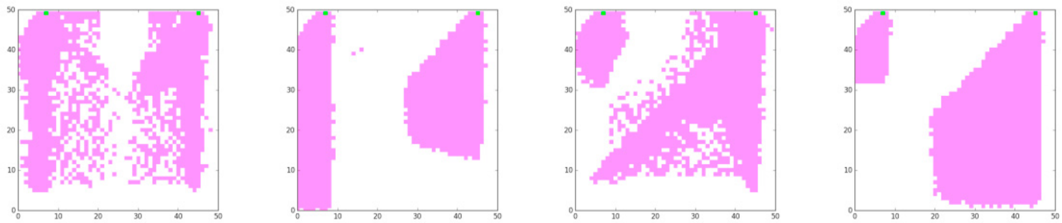

Fig.6: Simulation of room evacuation with 2 exits. In the first two figures, there is no overhead, whereas in the last two, the left door was set with an overhead.

We have also performed another experiment in order to validate the behavior of the model in a situation where new exits are reachable only with through an overhead, that represents the scenario where pedestrians have to choose between the affordability of a new exit versus some discomfort associated with it, for example when it is raining and the new exit has no coverage. Fig.6 shows the comparative results of the pedestrian dynamics with and without overhead. In the first two figures both exits have no overhead, whereas in last two the exit on the left side was set with an overhead. It is observed that with overhead, many pedestrians have chosen the right door even though on the left one there was a smaller queue, whereas without overhead pedestrians distribution have been more balanced over the two doors.

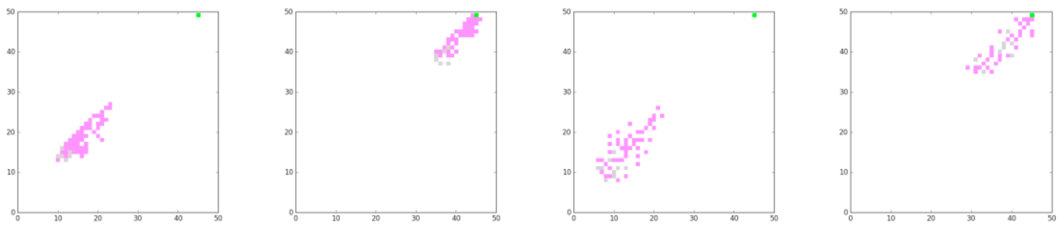

Fig.7: Simulation of room evacuation with 2 exits. In the first two figures, pedestrians go through optimal paths whereas in the last two they can go through suboptimal ones.

Finally, we have tested the scenario where pedestrian can go through a suboptimal path and compare it with an optimal one. Fig. 7 shows the comparative results of the pedestrian dynamics in both suboptimal and optimal configurations. In the first two figures pedestrians went through an optimal path, whereas in last two they went through a suboptimal one. It is observed that in the suboptimal scenario there is a broader scattering of pedestrians, which is expected since in this configuration pedestrian should be in movement most of the time, even if they go through longer distances to the target.

6. Conclusions

This paper presented a proposal for modeling pedestrian dynamics by means of an abstract device called Adaptive Cellular Automata, a dynamically adjustable approach that uses traditional cellular automata and a set of extensions for enabling them to reconfigure their own internal structure and behavior according to observable events and rules, allowing them to adapt and respond to environment changes. The model has been explained and simulations of density and velocity have been performed, with results that are in tune with the existing literature of the topic. The adaptive layer of the model has also been tested, bringing initial results that encourage us to follow the investigations. Future works include validating the model against real data and extending the rules to make the model suitable for a broader range of scenarios such as: exits and paths dedicated to people with special needs, such as governors, elderly and children; dynamic floor fields to indicate diffusion and decay; customizations for individuals with different weigh, velocities, and targets.

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