Cellular Automata-Based Model for Simulation of Collective Pedestrian Dynamics in Indoor Environments with Surmountable Obstacles

Eduardo C. Silva[a], Gabriela S. Damazo[b], Gina M. B. Oliveira[c] and Luiz G. A. Martins[d]
Faculty of Computer Science, Federal University of Uberlândia, Uberlândia, MG 38408-100, Brazil
{eduardocassiano, gabriela.damazo, gina, lgamartins}@ufu.br

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Abstract: Understanding and predicting human behavior in normal and emergency situations is a difficult task that attracts the attention of many researchers. In this sense, modeling and simulation of collective pedestrian dynamics (CPD) is essential in society, as it is used in various scenarios, such as urban planning and public safety. Cellular Automata stand out as simple computational tools capable of identifying and reproducing the complexity of various patterns, such as pedestrian movement, especially during evacuation in emergency situations. Models of this type take several parameters into consideration, such as the strategy for choosing the floor, the interaction between pedestrians, social phenomena, such as panic and the tendency to follow crowds, among others. This work proposes a model based on cellular automata for modeling CPD, strongly based on the Varas Model, which combines three changes to bring the simulation closer to reality. These are: changing the movement dynamics, presenting the separation between surmountable and impassable obstacles, and changing the permission to pass between objects diagonally. These updates speed up the pedestrian evacuation process and increase the level of credibility of the simulations compared to reality.

1 INTRODUCTION

Collective pedestrian dynamics (CPD) models play a crucial role in enhancing public safety and improving urban planning strategies. These models use different computing approaches, including social force, fluid dynamics, agent-based, game theory and animal experimentation (Zheng et al., 2011). A notable method used in modelling CPD are the cellular automata (CA), that can be considered multi-agent systems. The CA are computational structures, which can interact with each other, presenting local connectivity, and result in emerging computing.

Three different factors can be considered when developing this CPD models. First, the space in which the simulation is conducted. Second, the representation of the pedestrians. Third, the situation described by the model. It is particularly interesting to model CPD in emergency situations because there are some human behaviors (e.g. panic, surpassing obstacles) that should be considered in the simulation in order to make it more trustworthy.

The literature contains several works using CA for CPD. Historically, the first studies using CAs to model human movement were published in the 1990s, for example the work of (Nagel and Schreckenberg, 1992), although it was focused on modeling vehicle traffic flow. During this period, contributions came from several studies involving pedestrian simulations through models based on social forces, such as (Helbing and Molnár, 1995; Helbing et al., 1997a; Helbing et al., 1997b; Helbing et al., 2000), in addition to the arrival of CA-based models focused on modeling bidirectional traffic (Blue and Adler, 1999a; Blue et al., 1997; Blue and Adler, 1999b; Blue and Adler, 2000). Then, CA models that simulated pedestrian traffic in multiple directions emerged, with emphasis on the Euclidean distance-based model of (Burstedde et al., 2001). The environments studied also changed over time, with emphasis on the internal scenarios of classrooms (Liu et al., 2009), elevators (Ma et al., 2012), theaters (Gao et al., 2020), restaurants (Eng Aik and Wee Choon, 2012), aircraft (Giitsidis et al., 2017), ships (Hu and Cai, 2020), among others (Li et al., 2019).

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[a] https://orcid.org/0000-0001-9042-2562
[b] https://orcid.org/0009-0007-3364-7029
[c] https://orcid.org/0000-0003-0384-1879
[d] https://orcid.org/0000-0003-0168-1293

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(Alizadeh, 2011) proposed a CDP model that incorporates the concept of a dynamic floor into the deterministic perspective, being built considering the distribution of pedestrians during the simulation and recalculated at each iteration, by checking the number of people on floors closest to an exit. (Mrowinski et al., 2012) proposed two approaches: individuals can move according to a probability between following the floor value or making random movements or pedestrians minimize the number of neighbors. (Shi et al., 2018a; Shi et al., 2018b) proposed a model that extends the static floor from the microscopic scale to the mesoscopic scale.

(Shi et al., 2019) proposed a model that calculates the dynamic impatience level considering both the self-growth and the impatience propagation among pedestrians. (Cariño and Garciano, 2020) used dynamics to develop a model of Evacuation safety index (ESI). (Huan-Huan et al., 2015) developed a model in which pedestrians are treated as the movable obstacles which will increase the value of the floor field.

(Alizadeh, 2011; Mrowinski et al., 2012; Shi et al., 2018a; Shi et al., 2018b; Shi et al., 2019; Cariño and Garciano, 2020; Huan-Huan et al., 2015) are models that share in common the static floor proposed by (Varas et al., 2007), that is, a simplified way of calculating the distances between the cells of the grid and the exit without disregarding the use of obstacles. This method offers an alternative to the static floor based on Euclidean distance (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Kirchner et al., 2003b; Kirchner et al., 2003a; Kirchner et al., 2004; Nishinari et al., 2004), in this model the reproduction of human behavior phenomena depends on the adjustment of several parameters. In contrast, using only the static floor field and rules for handling collisions with obstacles, the (Varas et al., 2007) model can reproduce simulations in complex scenarios. Finally, (Varas et al., 2007) also relies on the panic parameter, which makes the model non-deterministic.

The aim of this paper is to present a CA model for CPD, strongly based on the (Varas et al., 2007) model that improves the relationship of the pedestrian with the space of simulation, especially with the obstacles, changing the movement dynamics, presenting the difference between surmountable and insurmountable obstacles and modifying the permission to pass between insurmountable obstacles using the diagonal.

First, in Section 2, the reference model is described. Second, in Section 3, the changes we made in the model are presented. Third, in Section 4, we explain the results comparing the alterations with the reference model. Finally, in Section 5, we summarize and explain future research points.

2 THE MODEL

The prototype presented in this article is based on (Varas et al., 2007), a model that proposes a simplified method for calculating the distance from transition cells to exit cells (Mrowinski et al., 2012). In addition, the model supports obstacles, something that is usually present in real scenarios. The next subsections detail the main aspects of the explored model.

2.1 Floor Field Calculation

In the (Varas et al., 2007) model, the room is defined as a two-dimensional quadrangular lattice, so that each floor cell represents an area of $0.4 \times 0.4m^2$ and can assume one of the following states: pedestrian, obstacle or empty. The cell size represents a surface when occupied by a person in high-density situations (Li et al., 2019). In addition, the authors also defined that the pedestrian speed is approximately 1 m/s, thus $\Delta t = 0.4s$.

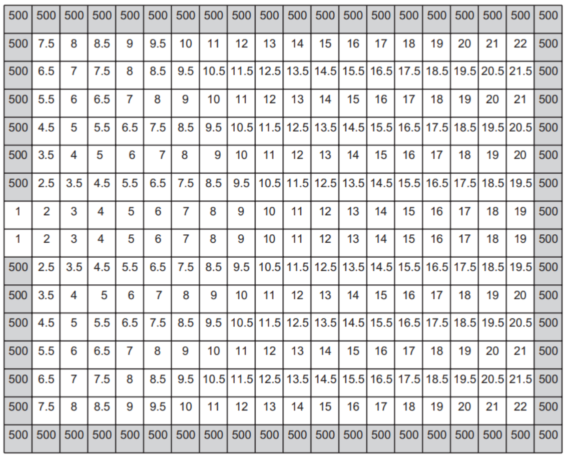
The initial grid is designed to determine the exit locations, the empty cells, the positions of the individuals and insurmountable obstacles. Each cell receives a constant value that represents the distance from that cell to the exit, so that the closer to the exit, the lower the value of the cell is (Alizadeh, 2011). The values of the cells of the initial grid are calculated as follows (Varas et al., 2007):

1. The exit cell receives a value of 1;
2. The cells adjacent to those with previously defined distances have their values calculated according to the following rules:
    - If the value of the cell is n, the adjacent cells vertically or horizontally will receive a value of $n+1$, while the adjacent cells on the diagonals will receive a value of $n+\lambda$, with $\lambda > 1$;
    - If there is a conflict of values, the lowest value is chosen for that cell;
3. Step 2 is repeated until all cells have their distances calculated;
4. Objects (walls, tables, chairs, etc.) receive a high value so that pedestrians do not try to pass through these cells.

The Figure 1 shows an initial grid representing the floor of a 16×20 room, in which the cell distances were calculated considering, $\lambda = 1.5$ and object with the constant value of 500.

2.2 Transition Rules

The movement and interaction between pedestrians is defined based on a transition rule that uses Moore



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500	5.5	6	6.5	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	500
500	4.5	5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	500
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500	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	500
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500	4.5	5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	500
500	5.5	6	6.5	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	500
500	6.5	7	7.5	8	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	500
500	7.5	8	8.5	9	9.5	10	11	12	13	14	15	16	17	18	19	20	21	22	500
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500

Figure 1: Calculation of the floor field of a 16×20 room grid (Varas et al., 2007).

neighborhood and radius 1. At each step of the CA evolution, all pedestrians move together to a cell closer to the exit. Figure 2, demonstrates the movement rules used, which are presented below (Alizadeh, 2011):

- Black circle: pedestrian moves to the cell with the lowest value in its neighborhood;
- White circles: if two pedestrians want to go to the same cell, this results in a conflict, resolved randomly. The winner moves and the loser remains still;
- Black triangle: if two or more cells in the neighborhood of a pedestrian have the same value, the pedestrian moves randomly to one of these spaces;
- White triangle: introduction of the panic characteristic. If a pedestrian panics at time t, he remains still.

The last three rules introduce probability to the model, so that it is not fully deterministic. It is worth mentioning that a pedestrian remains still when the cell he wants to move to is occupied. In this sense, the forms of interaction between pedestrians occur using this last information and the rule of the white circles.

3 NEW MODEL RULES

One of the contributions of the (Varas et al., 2007) model is the inclusion of obstacles in the simulations so that the environment resembles real situations, since it is more common for pedestrians to need to evacuate rooms with obstacles than completely empty rooms. However, there are a significant number of simulations in rooms without obstacles, for example (Zheng et al., 2017). In addition, this model allows the analysis of the influence of the location of doors and their respective sizes on the evacuation of simulated scenarios. During the implementation of this model, certain aspects were identified that could be changed to bring the work even closer to real environments. The modifications made will be detailed below.

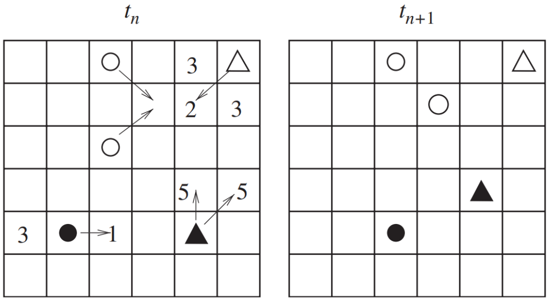


Figure 2: Rules of pedestrian movement (Varas et al., 2007).

3.1 Cell Selection Dynamics

In the (Varas et al., 2007) model, the pedestrian chooses to move to a cell with a lower value than the one he is currently in. In addition, the authors imposed some rules in which the pedestrian remains still. There are three cases:

1. If he loses in the dispute against another pedestrian who wants to go to the same cell as him;
2. If he panics at that moment of the simulation;
3. If he chooses to go to a cell that already has a pedestrian.

The first two items were demonstrated by the author in Figure 2. The original behavior of the third rule is shown in Figure 3(a). In the grid on the left, at $t = 0$, only a single pedestrian can move, while the other pedestrians wait for the cell with the best floor value to become available, which occurs at $t = 1$. Therefore, a different approach is presented in this work, which is also explored in other works, such as the model proposed by (Alizadeh, 2011). In it, the pedestrian always chooses the lowest empty floor, which often avoids stopping by the third rule. This choice-without-waiting (CWW) approach is presented in Figure 3(b). Therefore, when using the choice movement rule without waiting, all three pedestrians are able to move. On the other hand, in the choice with waiting, only one of the pedestrians moves.

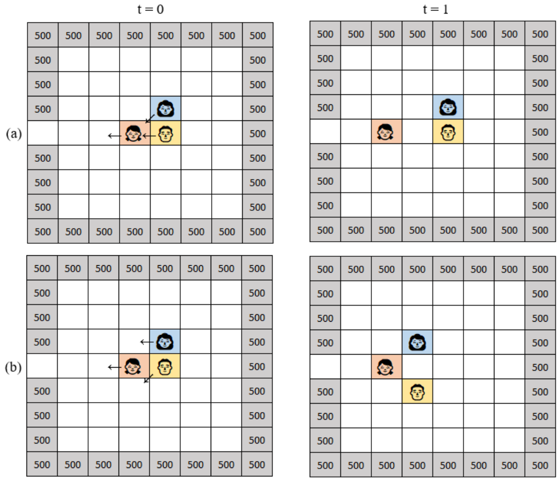


Figure 3: Comparison between pedestrian movement in a 9 × 8 room. (a) Choice of cell with waiting. (b) Choice of cell without waiting (CWW).

3.2 Surmountable Obstacles

The (Varas et al., 2007) model supports the simulation of obstacles in the simulation, in order to reproduce situations that are more faithful to reality. To model obstacles, the model defines cells with constant and unreachable values, making transitions to these cells unfeasible. Therefore, these objects are completely impassable, *i.e.*, regardless of the items it wanted to represent (walls, tables, chairs, etc.), pedestrians would not be able to overcome them.

The model proposed in this paper presents a distinction between two types of objects: impassable and passable. The impassable objects are the objects of the original (Varas et al., 2007; Alizadeh, 2011) models. The passable objects are introduced according to some rules:

1. They have no impact on the structure of the grid, that is, when the floor field values are calculated, the passable objects are ignored and their cells are treated as free and have their cost values calculated;
2. An overtaking rate z is defined at the beginning of the simulations, which indicates the probability of a pedestrian passing the object. It works as follows:
   - If the pedestrian ”wins” the overtaking, in the next time step, he will occupy the obstacle cell, representing a pedestrian on top of a chair or a table;
   - If the pedestrian ”loses” the overtaking, he remains still.

Figure 4 demonstrates the difference in pedestrian movement when considering the existence of surmountable obstacles (proposed approach) and the original model (with only insurmountable obstacles). Figure 4(b) shows the movement of a pedestrian in yellow, following the original version of (Varas et al., 2007). In it, obstacles and walls are not distinguished, therefore, to overcome the barrier, the pedestrian must go around it. In Figure 4(a), according to the proposed approach, the objects in blue represent surmountable objects, while the walls in gray are insurmountable. Assuming that at time $t = 0$, the pedestrian has gained the overtaking, at time $t = 1$, he is on top of the barrier. In the next time steps, he leaves the barrier floor and goes to a cell according to the value of the lattice and the transition rules.

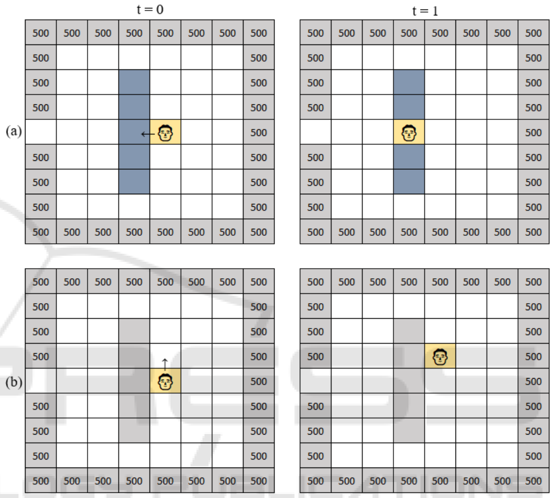


Figure 4: Pedestrian movement in environments with surmountable obstacles: (a) extended model and (b) original model.

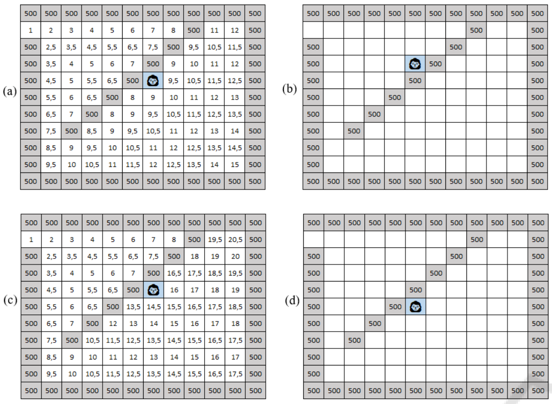
3.3 Changing Diagonal Movements

The (Varas et al., 2007) model allows pedestrians to move diagonally. This feature is addressed in the transition rules and in the floor field calculation. Despite this, when obstacles are positioned diagonally, the rules allow pedestrians to pass through the free space between the barrier.

Figure 5(a) shows an initial grid of a room that contains a diagonal barrier. As demonstrated, the floor field calculation performed by the original model considers the passage of obstacles through the free cells on the opposite diagonals, which makes it feasible for a pedestrian to move to such cells, illustrated in Figure 5(b).

A simple solution would be to use a double wall, so that the obstacles are also included in the map modeling. However, this representation may not be suitable for demonstrating real scenarios as it results in more crowded environments.

To solve this problem, the model improves the floor field calculation to avoid movements through barriers, *i.e.*, the floor calculation is not propagated to adjacent diagonal cells between obstacles. Figure 5(c) shows the initial grid generated from this new floor calculation strategy, resulting in the desired movement, as demonstrated in Figure 5(d).



(a)

500	500	500	500	500	500	500	500	500	500	500	500
1	2	3	4	5	6	7	8	500	11	12	500
500	2,5	3,5	4,5	5,5	6,5	7,5	500	9,5	10,5	11,5	500
500	3,5	4	5	6	7	500	9	10	11	12	500
500	4,5	5	5,5	6,5	500	☺	9,5	10,5	11,5	12,5	500
500	5,5	6	6,5	500	8	9	10	11	12	13	500
500	6,5	7	500	8	9	9,5	10,5	11,5	12,5	13,5	500
500	7,5	500	8,5	9	9,5	10,5	11	12	13	14	500
500	8,5	9	9,5	10	10,5	11	12	12,5	13,5	14,5	500
500	9,5	10	10,5	11	11,5	12	12,5	13,5	14	15	500
500	500	500	500	500	500	500	500	500	500	500	500

(b)

500	500	500	500	500	500	500	500	500	500	500	500
								500			500
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500				500							500
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500	500	500	500	500	500	500	500	500	500	500	500

(c)

500	500	500	500	500	500	500	500	500	500	500	500
1	2	3	4	5	6	7	8	500	19,5	20,5	500
500	2,5	3,5	4,5	5,5	6,5	7,5	500	18	19	20	500
500	3,5	4	5	6	7	500	16,5	17,5	18,5	19,5	500
500	4,5	5	5,5	6,5	500	☺	16	17	18	19	500
500	5,5	6	6,5	500	13,5	14,5	15,5	16,5	17,5	18,5	500
500	6,5	7	500	12	13	14	15	16	17	18	500
500	7,5	500	10,5	11,5	12,5	13,5	14,5	15,5	16,5	17,5	500
500	8,5	9	10	11	12	13	14	15	16	17	500
500	9,5	10	10,5	11,5	12,5	13,5	14,5	15,5	16,5	17,5	500
500	500	500	500	500	500	500	500	500	500	500	500

(d)

500	500	500	500	500	500	500	500	500	500	500	500
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500	500	500	500	500	500	500	500	500	500	500	500

Figure 5: Pedestrian movement in scenarios with obstacles arranged diagonally.

4 SIMULATION RESULTS

The analysis of CDS models involves several parameters that have a direct influence on the simulation results. The value of the diagonal rate was defined as $\lambda = 1.5$. Another important consideration is that, in all simulations, as in the paper by (Varas et al., 2007), the panic rate was adopted as 5%, that is, each pedestrian, at each time step, has a 5% chance of stopping due to having panicked. Another important characteristic is that, in this implementation, it was considered that a pedestrian, upon reaching the door, is no longer inside the room.

The prototype was developed using the JAVA language through an Integrated Development Environment (IDE). Simulations and data collection were performed through the tool's integrated console. A link to the repository with a copy of the source code for reproducing results can be found at appendix. Furthermore, 30 runs were performed for each simulation version and the values displayed refer to the average of these. Other important information will be presented for each map.

4.1 Evacuation Dynamics in an Empty Room

The grid used in the simulations to represent an obstacle-free environment can be seen in 6(a). It consists of a 16×20 room, with a cell-sized exit centered on the leftmost wall. In the simulation, pedestrians are randomly distributed. In the case of the image, fifty pedestrians were placed in the simulation. This map is used to compare the model of (Varas et al., 2007) and the CWW version.

The Figures 6(c) and 6(d) present two different instants ($t = 18$ and $t = 66$) of the simulation with the original version of the Varas Model. A queue formation phenomenon occurs, because pedestrians choose only the lowest floor value in their neighborhood and, until it is clear, they remain still. Since the door is located at a point further to the left of the room, the queue follows that direction.

The Figure 6(b) shows a simulation instant ($t = 18$) with the CWW version. The difference between the formations generated by the two models is clear. It is clear that in the new version, pedestrians accumulate closer to the exit and this causes them to leave the room faster.

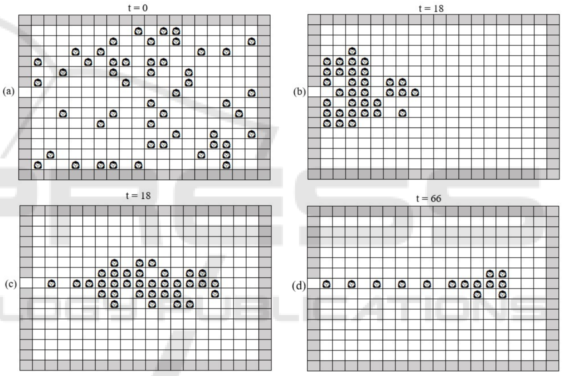

Figure 6: Comparison between the evacuation dynamics resulting from the original and greedy versions of the Varas model. (a) Initial lattice of a random simulation for 50 pedestrians in an empty room; (b) Lattice after 18 simulation steps with the model in the CWW version; (c) Lattice after 18 simulation steps with the model in the Original Varas configuration; and (d) Lattice after 66 time steps in the Original Varas configuration.

A quantitative analysis of this difference in behavior is presented in Figure 7. This figure shows the average number of simulation time steps required for the complete evacuation of pedestrians in the investigated environment, for different numbers of people (25, 50, 100, 150). This average was obtained from 30 simulations in each scenario (number of pedestrians) and for each model investigated (Original Varas and CWW version). The graph shows that the average number of time steps differs between the two models as the number of pedestrians increases. In the CWW version, pedestrians always look for a cell smaller than or equal to their value that is empty, which causes a potential reduction in the average waiting time. In the original version, they remain stationary until the cell they want is free, which results in a considerably longer waiting time, especially in traffic congestion situations.

Furthermore, it is important to consider that the observed discrepancy may also be influenced by the way the model is implemented, as previously mentioned. In the implemented version, a pedestrian at the door is no longer considered in the simulation. In this sense, if there is a crowd, pedestrians escape more quickly, since at each time step, a pedestrian can occupy the door cell. However, when considering scenarios without pedestrians accumulating around the exit, for example, in the formation of queues, pedestrians do not necessarily leave at each time step.

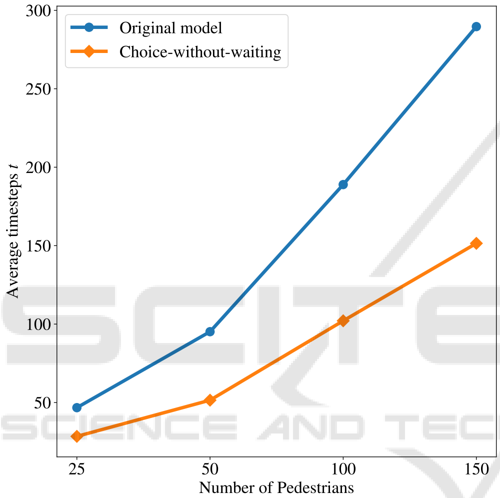

Figure 7: Comparison between the original and CWW versions of the Varas model, considering simulations for 25, 50, 100 and 150 pedestrians.

4.2 Evacuation Dynamics in Environments with Obstacles

To analyze the difference between surmountable and impassable obstacles, it was necessary to think of environments that use different types of obstacles. The map in Figure 8(a) was inspired by a university classroom. The room is 17×20. Adding up all the pedestrians in the simulation (students and teacher), this simulation has 49 people. In addition, 51 obstacles were modeled to represent the students' desks (1 cell per desk) and the teacher's desk (the only one that occupies 3 cells). The exit is located in the upper left corner.

Another environment used for this modeling was inspired by the university's computer labs. In this modeling, the grid is sized 14×20, with 60 traversable obstacles (representing the computer benches) and 60 pedestrians. The exit is located in the upper right corner (Figure 8).

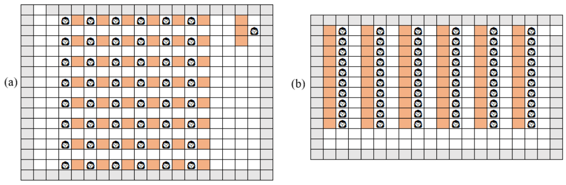

Figure 8: Maps of the classroom (17×20 with 51 obstacles) and computer lab (14×20 with 60 obstacles).

For both maps, an overtaking rate of 70% was used. Figures 9 and 10 show the graphs corresponding to the simulations performed for these maps. These two configurations demonstrate that the arrangement of pedestrians, objects and the exit of a map can directly affect the average number of simulation time steps.

When observing Figure 9, it is noticeable that the average times are very close. This is due to the arrangement of the grid. In the case of the classroom map, most pedestrians will prefer to walk diagonally, heading northwest and avoiding obstacles, even when they manage to overcome them, since the exit is located at the highest point and to the left of the map. In addition, the fact that the obstacles are of a single size prevents them from making it too difficult for pedestrians to move. Therefore, even though the original version of (Varas et al., 2007) takes, on average, more time steps, this difference is not so visible.

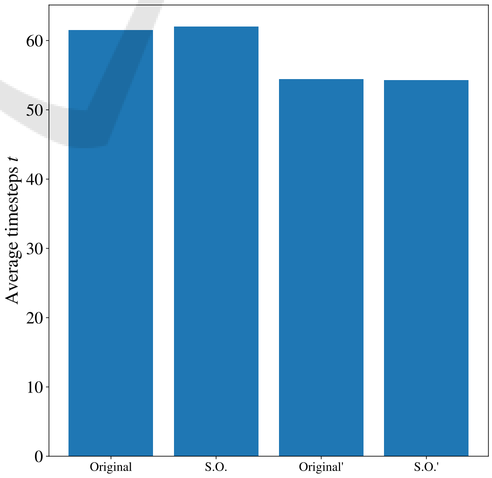

Figure 9: Average time steps for evacuation in the classroom environment.

In Figure 10, the average decreases from the original (Varas et al., 2007) model (slower) to the CWW version with traversable objects (faster). The door located in the upper right corner and the arrangement of the obstacles forming continuous barriers is what causes this discrepant difference between the two simulations.

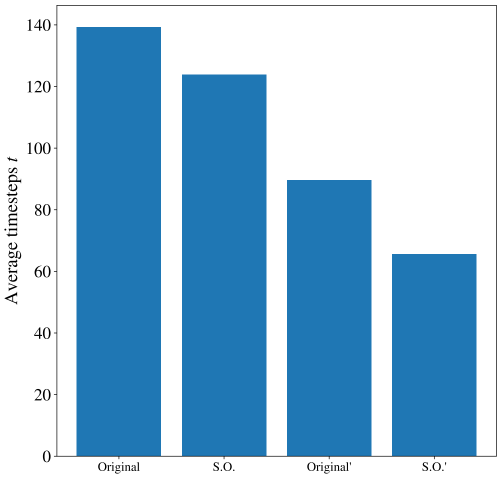

Figure 10: Average time steps for evacuation in the laboratory environment.

Figure 11(a) shows that, by making it impossible to pass through the objects, the only option for pedestrians is to follow the corridor, which creates a large crowd and, even with the CWW version, it is not possible to disperse these individuals to get closer to the exit. In the case of Figure 11(b), the traversable objects are connected, in this case, it is clear that pedestrians prefer to try to pass obstacles, rather than follow the corridor, which corresponds to the information in the graphs.

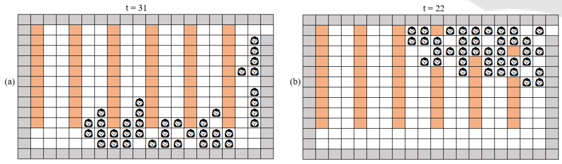

Figure 11: Laboratory evacuation dynamics according to the type of obstacle modeled. (a) Simulation of the CWW version with only insurmountable obstacles ($t = 31$); and (b) Simulation of the CWW version model with both surmountable and insurmountable obstacles ($t = 22$).

4.3 Evacuation Dynamics in an Environment with Diagonal Wall

In order to assess the non-crossing of insurmountable barriers diagonally, a map similar to the one shown in Figure 5 was used. It has dimensions of 16×20 and pedestrians are randomly allocated in the room.

Figure 12 shows two simulations that demonstrate the difference in pedestrian flow when allowing or not allowing the crossing of walls by free cells on the diagonals. These simulations were generated from the original version of the Varas model and through the CWW version, varying the way in which the distances of the grid cells are calculated. In Figure 12(b), the floor calculation of the original model was adopted, which considers the adjacency between the diagonal cells positioned on opposite sides of the wall. As can be seen, in this simulation, pedestrians quickly gathered at the exit, since they were able to cross the barriers. On the other hand, in the situation shown in Figure 12(c), the improved floor calculation was adopted, which disregards the adjacency between diagonal cells on opposite sides of the walls, so that pedestrians need to go around to reach the exit.

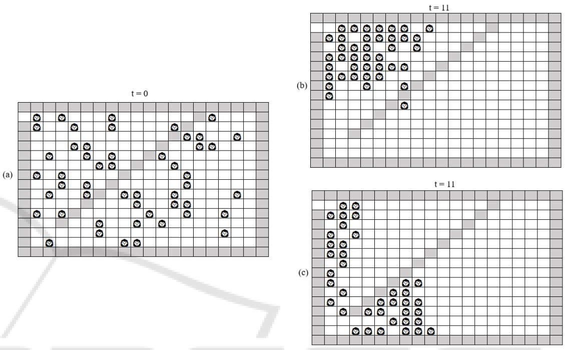

Figure 12: Pedestrian flow as a function of the strategy used in the floor calculation. (a) Lattice at time $t = 0$ with 50 random pedestrians. (b) Simulation of the greedy strategy model using the original floor calculation, at time $t = 11$. (c) Simulation of the greedy strategy model using the adapted floor calculation, at time $t = 11$.

By allowing this overtaking, the simulation becomes a little faster, since individuals do not need to go around the wall. Despite this, as mentioned in previous sections, this behavior does not come close to reality. Furthermore, as can be seen in the graph in Figure 13, the average number of steps does not change significantly when using the CWW version of the model.

Another noticeable result when analyzing the graph is that using the ”double wall” version or the ”no diagonals” version does not affect the average number of simulation steps, whether in the simulation of the original model or the CWW version. Despite this, removing the double wall frees up some cells on the map, which allows more pedestrians or obstacles to be represented in those locations.

5 CONCLUSION

Cellular automata-based CPD models are widely used in this research area because they can effectively

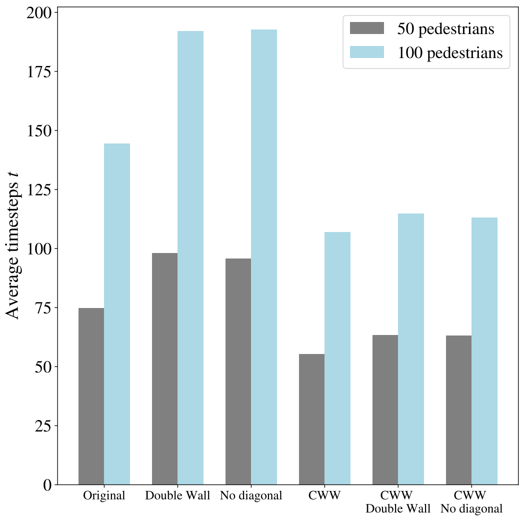

Figure 13: Comparison between simulations of the Room with Diagonal Wall Map.

and simply represent complex pedestrian behaviors in normal and emergency situations. In this sense, this work implemented a precursor model in the area, which is well known and used by several researchers, the (Varas et al., 2007) model. In addition, changes were made to this model: in the movement dynamics, by presenting surmountable obstacles and by prohibiting diagonal movements between impassable objects.

These modifications, when compared to the original model, produced different results. The CWW version significantly improves the average simulation time steps as the number of pedestrians increases. The second modification presents a separation between surmountable and impassable obstacles. In this case, it was observed that the room configuration produces very different results for each simulation. Once these obstacles were separated, the third modification prevents people from passing through the diagonal between two impassable objects. This modification did not demonstrate a significant difference in the average simulation time steps, but it is a more realistic behavior when people encounter a diagonal wall. In the original model, since it is possible to calculate the cost of a neighboring diagonal cell, pedestrians can pass through walls, which does not reflect reality.

These changes are an initial step towards refining the model (Varas et al., 2007). In future work, this research will be used to enhance the model's ability to represent real environments. One idea is to add a dynamic floor so that pedestrians do not congregate in one location, but can instead look for other exits (Alizadeh, 2011; Xiao and Li, 2021; Strongylis et al., 2019). Another investigation aims to further distinguish between surmountable obstacles, presenting different difficulties for overcoming. Furthermore, one proposal is to add characteristics of external environments, so that the model can be used in different environments and can assist in the evacuation of pedestrians in these locations (Zheng et al., 2011; Zheng et al., 2017; Zhou et al., 2019).

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APPENDIX

A copy of the source code used in the simulations was made available in a remote repository at (https://github.com/eduardocassiano-ufu/Cellular-Automata-with-Surmountable-Obstacles). Additional instructions on compilation steps, software dependencies and test execution are presented on the repository's home page.