Evaluating Geographic Influences on Pedestrian Evacuation Using Cellular Automata: a Case Study of Sete Cidades National Park in Wildfire Scenarios

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Abstract. *The study of pedestrian evacuation dynamics is a field of much relevance for risk assessment and formation of plans aiming to minimize negative impacts in emergency situations. In this work, our objective is to create computational simulations using cellular automata around the pedestrian evacuation behavior on the Sete Cidades National Park, considering its high tourist activity. To this end, different geographical features were abstracted, with emphasis on the heterogenous vegetation and various relief altitudes, in order to evaluate the impact on evacuation times and routes. Additionally, wildfire propagation was also included in the model, introducing a realistic aspect for safety analysis on distinct regions of the park. Through this study, we sought to assist in the definition of evacuation policies on the target location, thus helping guarantee safe interactions between society and the environment*[1].

1. Introduction

The rising frequency of environmental disasters, whether natural or anthropogenic, has stimulated the search for alternatives that lower the social impact brought by such events. This has led to the development of evacuation plans for pedestrians, particularly for outdoor environments like forest parks, where the risk of emergencies, such as wildfires, is elevated. In order to contribute to environmental policy-making, various computational models describing pedestrian dynamics inside forest systems have been proposed, and the use of cellular automata to this end is specially appealing, considering the parallelism contained in crowd behavior and the simplicity of this mathematical tool [Varas et al. 2007].

The Sete Cidades National Park, located in northeastern Brazil, is renowned for its geological formations and presence of rock art, and has been the focus of numerous studies, due to its status as an integral federal conservation unit and a priority area for preservation [Matos and Felfili 2010]. In what pertains to the local tourism index, the year 2024 stood out as a visitation record, with over fifty thousand visitors by the month of October, according to data published by the Piauí state government [Setur 2024]. Given the park's ecological and cultural significance, along with rising tourist numbers, this study uses its detailed map to assess how vegetation density and topography affect pedestrian evacuation during wildfires.

Therefore, this study aims to understand the dynamics of pedestrian evacuation

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in the Sete Cidades National Park considering the influence of its geographical features through computational simulations and geoprocessing-based data collection and analysis. The modeling of pedestrian movement and fire spread was grounded on the mathematical theory of cellular automata. Additionally, after the execution of simulations with the proposed model, the acquired data will be used for numerical and qualitative analyses of how vegetation and relief impact in the evacuation time and routes, simultaneously analyzing the formation of bottlenecks at exits. Furthermore, based on the environment fire spread and the positioning of pedestrians in distinct regions, multiple evacuation rates will be calculated, identifying areas within the park suited for safe occupation.

2. Theoretical foundation

The Sete Cidades National Park is a conservation unit managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio) and located at the state of Piauí, spanning the cities of Piracuruca and Brasileira. Its surface covers approximately 6221 hectares, with a perimeter of 36 kilometers. Furthermore, the park lies at the transition between the Cerrado and Caatinga biomes, featuring a complex mosaic of vegetation types, being considered a priority preservation area [Instituto Chico Mendes de Conservação da Biodiversidade 2023]. The park's relief, situated on a sedimentary basin, consists of a pediplain surface with altitude ranging from 100 to 300 meters. Its hydrography comprises small interior streams that converge at the periphery to form the Piracuruca river [Matos and Felfili 2010]. Additionally, the PI-111 highway, which cuts through the park, serves as both a vital refuge and a key pedestrian evacuation route in this study.

Furthermore, the pedestrian evacuation and fire propagation model was based on cellular automata (CA) tools. The mathematician John von Neumann pioneered the discussion of CA from his studies on the understanding of autonomous systems' self-reproduction. In his work, von Neumman described five self-replicating models, the cellular automaton model present among them, which consists of a matrix of square cells that can assume a finite number of states during the process via communication with neighboring cells [Von Neumann et al. 1966]. Thus, the neighborhood concept can be applied in two distinct ways: the von Neumann neighborhood, that only considers as neighbors the four continuous cells corresponding to the cardinal directions, and the Moore neighborhood, proposed by Edwards Forrest Moore, and used in this work, that covers all of the cell's eight neighbors, including those in diagonal directions [Moore 1962].

The theory of cellular automaton is applied in the modeling of many different phenomena and complex systems, such as robotics, cryptography, fire spread and pedestrian traffic, the last two being the focus of this study. Within scientific literature, several precursor studies informed the characteristics of the proposed model. In this sense, the rules for modeling floor fields were strongly influenced by the approaches of [Varas et al. 2007] and [Alizadeh 2011]. Many of these studies focus on buildings environments, while [Gao et al. 2023] examine decision-making behavioral in evacuation situations. Furthermore, the work by [Wang et al. 2013], which incorporates topography into the evacuation process, inspired the inclusion of this parameter here, along the vegetation.

Additionally, various studies simulate the occurrence of emergency situations alongside evacuation processes, such as [Li et al. 2019], which models a flood scenario and analyzes its evacuation rates, and [Zheng et al. 2011], that resembles this work by incorporating fire spread into its implementation. On this matter, the fire propagation model is based on the papers of [Brasiel and Lima 2023] and [Brasiel and Lima 2024], which account for the vegetational heterogeneity of the Cerrado biome, with the latter specifically using the Sete Cidades National Park as a simulation environment. Similarly, the observations done in [Santos and Lima 2024], studying the same park, examines the effects of hydrography as an obstacle in the event of pedestrian evacuation.

3. Materials and methods

In this section, the methodology and materials used in this study will be discussed. Specifically, details about the evacuation model will be presented, covering the vegetation and relief mapping, the definition of floor fields, and fire propagation.

3.1. Diversity in vegetation and relief

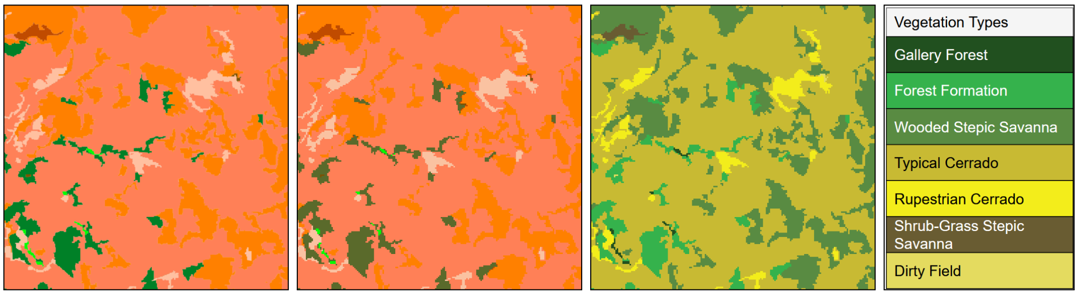
In the implemented model, key geographical characteristics of the Sete Cidades National Park were considered, including hydrographic courses, as studied in [Santos and Lima 2024], and different types of vegetation and relief. This subsection describes the methods employed in the modeling of the last two. Note that Figures 1(a), 2(a) and 2(b), as well as the data used in this process, were obtained from the Brazilian Geographical Information System "TerraBrasilis" [2].

Initially, to identify the park's floristic composition, the program applied the k-means clustering algorithm to the collected Figure 1(a), in order to group similar pixels. Therefore, seven types of vegetation were identified and assigned RGB (red, green, blue) colors as centroids. From this, each pixel was replaced by the nearest centroid based on the Euclidean distance between its RGB values and the seven centroids. The clustering result is presented in the Figure 1(b). For better visualization, the clustered image colors were replaced with more visually distinct ones, as seen in Figure 1(c). Furthermore, the legend of Figure 1(d) maps the vegetation types to their corresponding colors.

Sequentially, each vegetation type was assigned an occupation probability based on the vegetation's physical characteristics, such as density and terrain irregularity, which hinder pedestrian traversal. The values established were: 0.8 - Gallery Forest, 0.6 - Forest Formation, 0.3 - Wooded Stepic Savanna, 0.4 - Typical Cerrado, 0.5 - Rupestrian Cerrado, 0.2 - Shrub-Grass Stepic Savanna and 0.1 - Dirty Field. It should be noted that a lower occupation index indicates easier pedestrian traversal. After that, the 200×200 vegetation probability matrix was initialized, with each cell storing the probability corresponding to the pixel color in the image.

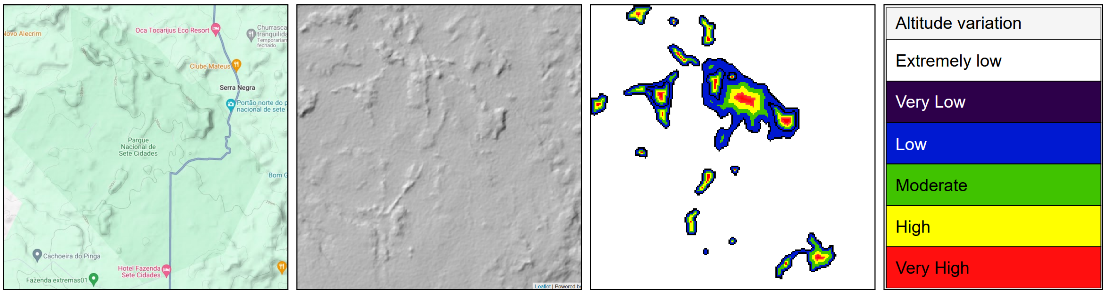
For the modeling of the park's relief, a visual representation was created using data from the terrain map and the shaded relief (Figures 2(a) and 2(b) respectively), as shown in Figure 2(c). The process included identifying high-altitude areas, delineating them, and assigning colors to represent the varying elevations. This approach defined central regions within each shape and gradually decreased the elevation in a radial pattern towards the shape's periphery. The legend in Figure 2(d) conceptually illustrates altitude variations. Each category was assigned a pedestrian movement likelihood percentage through it: Extremely Low - 100%, Very Low - 50%, Low - 40%, Moderate - 30%, High - 20% and Very High - 10%. Similar to the vegetation model, a 200×200 relief probability matrix was created, with each pixel assigned its corresponding percentage.

[2]TerraBrasilis portal is developed by INPE: `https://terrabrasilis.dpi.inpe.br/`.



(a) Original Image. (b) Clustered Image. (c) Image with visually distinct colors. (d) Legend.

Figure 1. Image segmentation process and vegetation data collection in the park.



(a) Map from Google Terrain. (b) Shaded relief (c) Relief representation. (d) Legend.

Figure 2. Data collection process around the park's relief and the creation of a simplified representation for algorithm analysis.

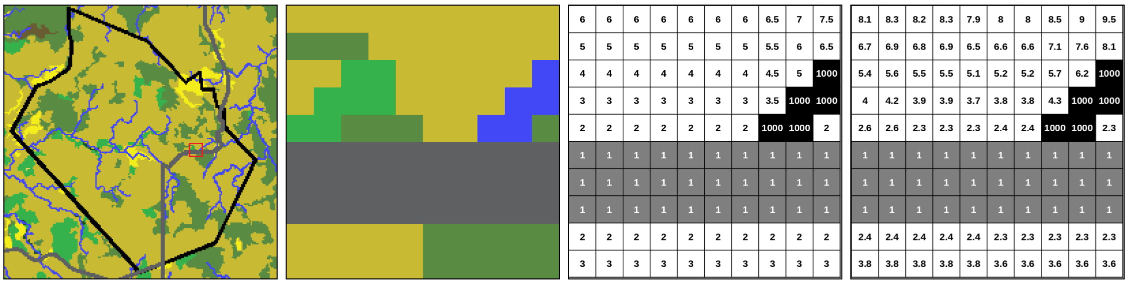
3.2. Floor fields and pedestrian movement

In order to guide pedestrian evacuation, two floor fields were modeled using cellular automata: the first to direct the pedestrian to the internal exit, represented by highway PI-111 cells, and the second to guide them from the highway to the park exits. Cell values in the floor fields were established adopting the rules defined by [Varas et al. 2007], as follows:

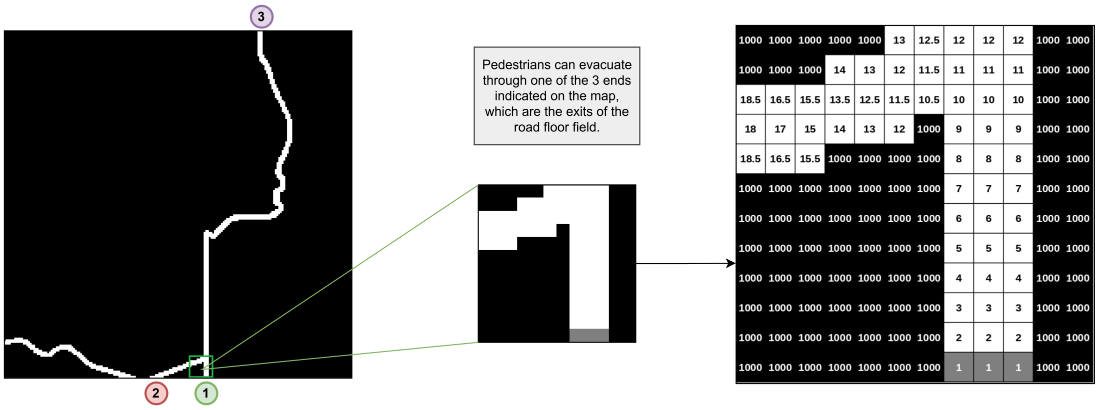
- For cells that cannot be occupied, such as hydrography and park boundaries on the first floor field and all non-highway cells in the second, the value is 1000;
- For cells that represent the exits in both floor fields, the value is 1;
- For the remaining cells, considering a cell with floor value N and value in the vegetation matrix M, the value is calculated as $N + M + 1$ for those vertically or horizontally adjacent, and $N + M + 1.5$ for those diagonally adjacent, reflecting the higher cost of diagonal movement, however, a cell is only updated if the new value is lower then its previous one.

The park map used to model the floor fields can be seen in Figure 3(a), highlighting the area used to illustrate the general floor field's functioning, amplified in Figure 3(b). Figures 3(c) and 3(d) compare the floor values with and without the vegetation probability matrix. Thus, cells with dense vegetation and a higher probabilities, even near the exits, have increased floor value, reducing the likelihood of pedestrian movement through them during evacuation. Figure 3(e) illustrates the highway's floor field, demonstrating the program's designated exits as final evacuation points for pedestrians.

Once the floor fields have been defined, pedestrian movement needs to be ad-



(a) Park's map with highlighted area. (b) Area for floor field analysis. (c) Floor field disregarding vegetation. (d) Floor field including vegetation.



(e) Map indicating the exits and road floor field analysis.

Figure 3. Sampling to illustrate the functioning and definition of the floor fields.

dressed. For this purpose, in each iteration, pedestrians choose a new cell to occupy, considering probabilistic factors to enhance the model's realism. Thus, for each pedestrian, the program will:

1. Identify the neighboring cell with the lowest floor value that is unoccupied;
2. Check if the identified cell has higher altitude then the current one. If it does, the program generates a random number (1 to 100) and compares it to the relief probability matrix value for that cell. If the generated value is lower, the pedestrian occupies the cell; otherwise, the program reverts to the previous step, searching for a new neighboring cell.
3. Store the target position, and if multiple pedestrians target the same cell, the program randomly selects one of the them to move, while the others stay immobile.

Furthermore, a difficulty factor was added for locomotion through dense and rugged vegetation (e.g., Rupestrian Cerrado, Forest Formation, Gallery Forest) and for transitions from lower to higher altitude cells. Therefore, in both these cases, movement requiring one iteration will instead take two, reflecting the additional time added from these geographical features during the evacuation process. Likewise, reaching the highway, pedestrians switch from the general floor field to the highway's floor field, guided to the official park exits, located at the park's three extremities.

3.3. Introducing fire focus

In order to simulate pedestrian evacuation during emergencies and enable the planning of safe evacuation routes, this work models fire propagation in the Sete Cidades National

Park, as studied by [Brasiel and Lima 2024]. The parameters considered include hydrography and vegetation, also using a cellular automata (CA) model. While the hydrographic courses represent static obstacles in the general floor field, the inflamed cells represent dynamic obstacles, which propagate over time. It is important to note that the fire propagates at one-tenth the speed of average pedestrian movement, following a 1:10 ratio (fire:pedestrians).

Furthermore, a fire matrix was created to store cell states, following the definition in [Brasiel and Lima 2024]: alive, burning (in four intensity stages, depending on how long the vegetation has been burning), and dead. Only 'alive' cells can be occupied by pedestrians, and cells corresponding to hydrography, park boundaries and the highway are non-flammable. Additionally, neighbors of a burning cell vary in flammability based on vegetation type. Therefore, using the park's floristic mapping, each vegetation type was assigned a burning probability, with denser, more humid forests being less vulnerable, and dry, sparse vegetation more likely to burn.

In addition, as a mechanism to distance pedestrians from the fire sources, an alert area was defined around each burning cell, covering a radius of five cells in vertical, horizontal and diagonal directions. As such, even if the fire is in the area near the park's exits, the pedestrian will be forced to trace a new route away from the spreading flames. Figure 4 depicts the fire propagation across the map, and it also shows the functioning of the alert zones surrounding the fire cells.

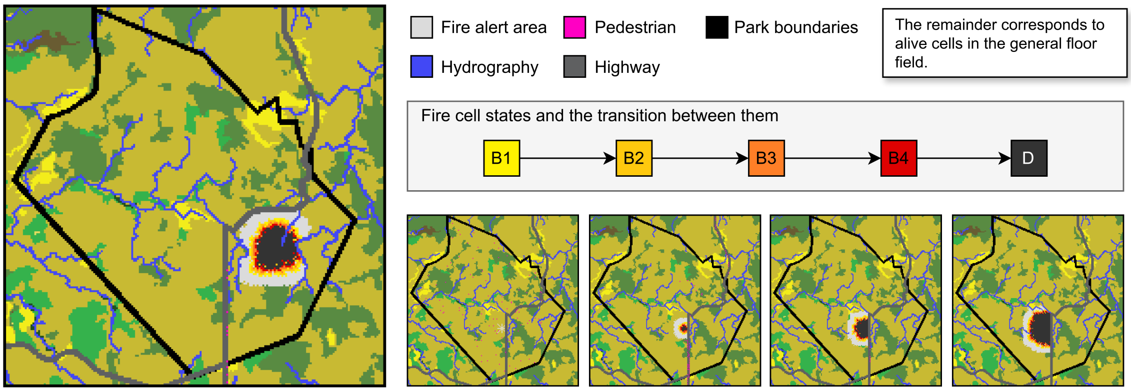


Figure 4. Storyboard illustrating fire spread combined with pedestrian evacuation over time and demonstration of the transition rules in the states of fire cells.

4. Experimental Results

The experimental results presented in this study were obtained through simulations using the proposed model. For illustrative purposes, Figure 5 displays the algorithm's operation during each simulation cycle, it is important to note that fire sources are only created in analyses that include fire propagation, and that the placement of 100 pedestrians represents a standardized value for analysis purposes, which can be adjusted as needed. In this context, it is worth mentioning that this research focuses on three lines of investigation: the first, quantitative, through graph analysis in order to discover the formation of chokepoints at specific exits and the numerical impact of vegetation and relief of the Sete Cidades National Park; the second, qualitative, aiming to analyze how these parameters impact the pedestrian evacuation routes via the representation in heatmaps; and lastly, the third, also quantitative, intends to assess the evacuation rates in different map areas, taking fire propagation into account.

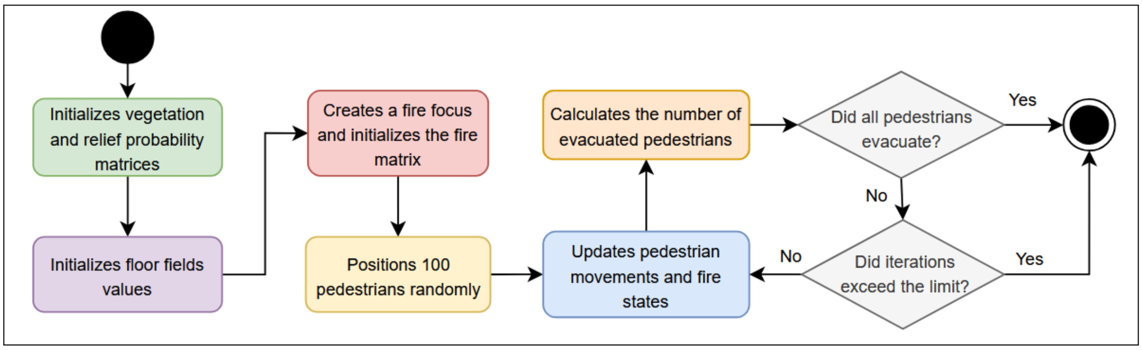
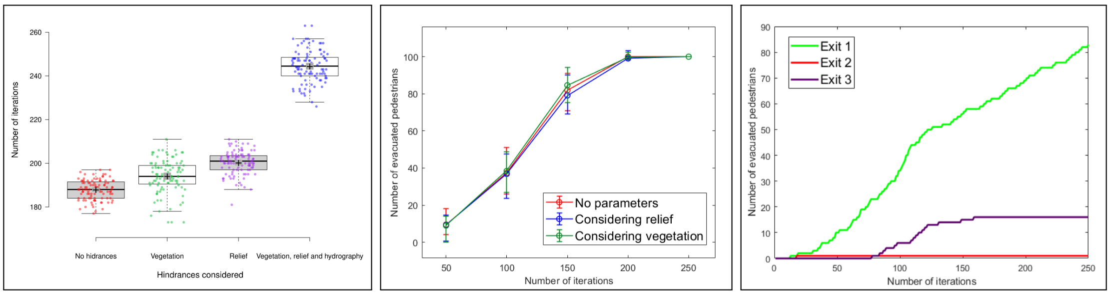


Figure 5. Simulation cycle steps based on the CA model for pedestrian evacuation.

For the first analysis, a comparative boxplot was developed, shown in Figure 6(a), which shows the number of iterations required for the evacuation of 100 distributed pedestrians. The graph shows that, when considered individually, both the vegetation and the relief significantly impact the evacuation time, an effect that is further amplified when combined with hydrography. Furthermore, the graph in Figure 6(b) illustrates, over 250 iterations, the evolution in the number of evacuated pedestrians comparing scenarios with vegetation, relief and no parameters added. The data used in both plots was obtained by running 100 simulation cycles for each considered scenario.

Additionally, the graph in Figure 6(c) compares the different park exits, presented in Figure 3(e), and the number of pedestrians evacuated through each one of them during a simulation cycle accounting for vegetation, relief and hydrography. From this representation, the predominance of exit 1 is visible in contrast to the others, suggesting potential bottlenecks and queues leading to this exit.

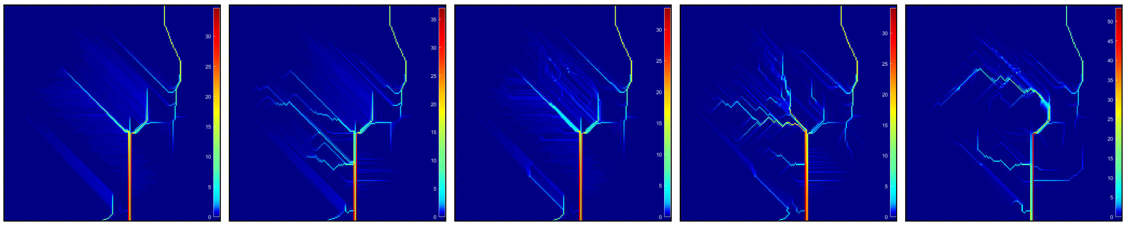
For visual analysis of the evacuation routes, heatmaps were generated, as shown



(a) Comparison of total evacuation time across different scenarios. (b) Tracking of the iterative process across different scenarios. (c) Comparison of pedestrians evacuated through each exit.

Figure 6. Graphs comparing the evacuation process' and exits distribution considering different parameters and impediments.

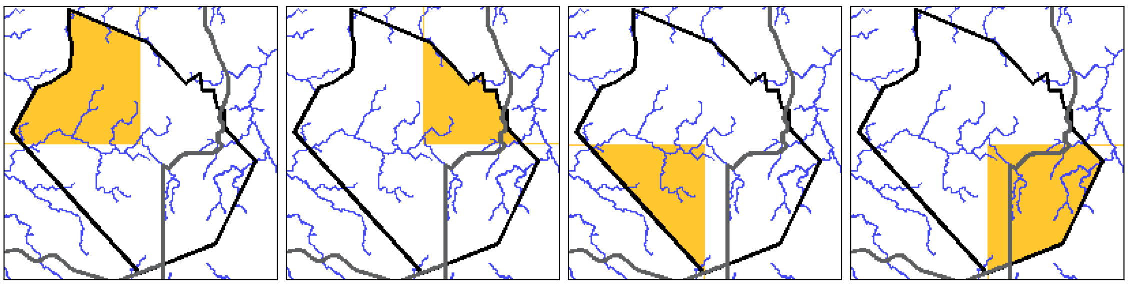
in Figure 7, using data tracking the average pedestrian presence in each cell across the park area over 100 simulation cycles. Figure 7(a) shows the pedestrian behavior in a scenario without additional parameters, in which straighter movement patterns are observed, that area altered in Figures 7(b) and 7(c), which account for vegetation and relief separately. When combined, these parameters exert a new visible impact on Figure 7(d) and in Figure 7(e), that includes the hydrography as an additional obstacle. As a result, it is possible to observe the distortion in the evacuation routes when accounting for these geographical characteristics. Moreover, the color mapping of the highway cells matches the results shown in the graph of Figure 6(c), indicating the prevalence of exit 1 on pedestrian evacuation.



(a) No parameters. (b) Vegetation. (c) Relief. (d) Vegetation and relief. (e) Vegetation, relief and hydrography.

Figure 7. Heatmaps considering different parameters and indicating the pedestrians mean in each cell after 100 simulations.

For the third and final analysis, the fire propagation alongside pedestrian evacuation was considered to evaluate the performance across different map regions. To this end, the area was divided into four quadrants delineating regions shown in Figures 8(a), 8(b), 8(c) and 8(d). This segmentation facilitates a systematic analysis of evacuation performance across different geographic sectors allowing the assessment of spatial variations in pedestrian distribution and fire source positioning. Subsequently, a series of experiments were conducted to simulate all possible permutations of the pedestrians' initial positioning region and the fire source location. For each permutation, 100 simulation cycles were run, recording the number of evacuated and trapped pedestrians at the end of each cycle.



(a) Northwest. (b) Northeast. (c) Southwest. (d) Southeast.

Figure 8. Map regions considered for distribution of pedestrians and fire sources.

Finally, the average evacuation rate of each scenario was computed, with the results presented in Table 1, displaying the percentage of evacuated pedestrians for each combination of pedestrian distribution and initial fire location. From the data, it reveals that the northwest region exhibits the lowest evacuation rates considering all fire source scenarios, particularly when it originates in the northeast region, with fewer than half of pedestrians reaching any exit. In contrast, scenarios with southeast pedestrian distribution show the highest evacuation rates, indicating greater safety for occupants in this area.

Table 1. Evacuation Rate based on Pedestrian distribution × Fire source.

Pedestrians \ Fire source	Northwest	Northeast	Southwest	Southeast
Northwest	35,31%	28,12%	36,55%	36,14%
Northeast	93,10%	83,71%	93,25%	92,46%
Southwest	86,83%	86,14%	77,59%	82,80%
Southeast	99,88%	99,84%	99,87%	97,17%

5. Conclusion and future works

Overall, this study presented a cellular automata model for pedestrian evacuation along wildfire propagation in the Sete Cidades National Park. To enhance realism in the simulations and quantify the impact of vegetation and relief, the model incorporates these geographical features, including hydrography, using data from a geoprocessing system.

Data collected from the simulations revealed that both the vegetation and the relief exert significant impact in the total evacuation time, particularly in scenarios where hydrography acts as a static obstacle, and alter the routes leading to highway PI-111, the exit for the first floor field. Additionally, another finding was the uneven distribution of pedestrians among the highway exits during simulations, with exit 3 concentrating a disproportionately large share of the pedestrian total, suggesting potential queue formation. Finally, simulations tested evacuation rates by varying pedestrian and fire source locations across park regions. The results revealed that between all sub-regions, pedestrians positioned on the northwest had noticeably lower evacuation rate compared to the other areas, while the southeast region achieved nearly 100% evacuation rates.

From this study, it was possible to identify the preferred evacuation routes, as well as the safer areas for tourist activity within the park, and consider that the creation of new exits, particularly in the northwest region, could mitigate its' lower evacuation problem, due to its distance to the main highway. In this regard, this work has important contributions to the development of evacuation policies for the Sete Cidades National Park, particularly for the National Policy on Integrated Fire Management, established by Law No. 14,944. Furthermore, the model can be easily adapted to simulate scenarios in other larger or smaller forested touristic environments by adjusting the RGB colors of the map elements (e.g., exits, boundaries, vegetation).

However, it is important to highlight the model's limitations, particularly in terrain representation, which extrapolates GIS data to adopt a more computationally intuitive approach. Additionally, fire propagation considers only vegetation heterogeneity, without accounting for the influence of terrain. For future works, beyond improving these limitations, the implementation of human behavioral tendencies during evacuation could be an alternative, such as panic factor, aggressiveness or even leadership and grouping, increasing model complexity and further approximating real-world scenarios.

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