Predictive model for wildfires simulation based on cellular automata and stochastic rules

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Abstract. A significant increase in the occurrence of large wildfire has been observed in the last decades. Several works seek ways to attenuate the side effects from this great challenge. In this work, it is proposed the elaboration of a simulation model for wildfires based on cellular automata e stochastic rules. Its main objective is to understand the dynamics of these fires, which would make it possible to predict what would be the leading actions to be taken by firefighters teams. The model presents different states for the fire, simulating different fire intensities, and wind currents that direct the flames. In addition, a vegetation regrowth function was proposed, which brings the model closer to the real characteristics of a natural system. According to the results obtained, it was possible to conclude that the model achieves the expected objectives, satisfactorily simulating the analysed phenomenon.

Keywords: Cellular automata · Wildfire · Predictive model · Stochastic rules · Simulation · Firefighting efficiency · Complex phenomena.

1 Introduction

Spontaneous wildfires occur in nature and these are part of the natural cycle necessary for the conservation of some biomes [15]. However, in the last decades, the impacts of climate changes, indiscriminate exploitation and extraction increased the occurrence of these events throughout the planet [7]. Since this increase is not part of an environment's natural cycle, in most cases this environment ends up collapsing. In addition to the loss of the fauna and flora, which are irreparable, these wildfires can advance to areas of human occupation [11], especially those of marginalised populations (e.g., indigenous tribes, *quilombolas*, riverside dwellers and *favelas*) where there is no ideal physical infrastructure.

In order to mitigate negative effects, many works propose fire simulation models [14], seeking to understand the behaviour of the flames as a means to recommend countermeasures, strengthening the capacity to prevent and suppress wildfires while protecting human lives, nature itself and property.

The Cellular Automata (CA) [12] stand out as a simulation technique due to their simplicity of implementation and high correspondence with natural behaviour. Among the most common models that use CA, we can highlight models for urban growth [1], pedestrian evacuation [3], coordination of swarm of robots [17], epidemic prediction [13], etc. Considering that a wildfire can be categorised as a complex phenomenon, the application of CA facilitates its simulation, since the CA are discretised both in time and in space [4]. On the other hand, the implementation of continuous systems for the propagation of fire would demand a greater computational processing. Furthermore, since the cells evolve independently, it is easily adaptable for multiprocessing, allowing the exploration of high-performance simulations.

Therefore, considering the points raised, this work propose a computational model to simulate wildfires as a way to predict their general behaviour and, thereby, enabling a greater efficiency for management and firefighting forces. The model is based in CA with stochastic rules for fire propagation. Applied in regions with vegetation, the model does not only take into account the burning time in the cells, but other important characteristics during a wildfire, such as the fire intensity, the presence of wind currents and obstacles. The model was implemented in the game engine GameMaker [6], in which it was possible to simulate and validate the expected behaviour.

This work is organised as follows: Section 2 presents a brief review of the literature related to wildfire simulation using cellular automata. The simulation model proposed in this work is defined in Section 3. Regarding the model assessment, Section 4 describes the simulations and analysis performed. Finally, Section 5 presents the main conclusions and future works.

2 Brief Literature Review

This section describes a brief literature review that includes some works related to the application of cellular automata in wildfires simulation. At the end of this review, a table is presented in order to compare key characteristics of the model described by these works with our proposed model.

In the work by Dilão [5], a simplified model was implemented to simulate forest fires. The model has three states: vegetation, fire and burnt cell. In addition to these states, the author tested the influence of wind in his simulations. The results showed that, despite being simple, the model confirmed the effectiveness of CA in predicting the temporal evolution of real-time systems.

Exploring solutions for Geographic Information Systems (GIS), in the work of Yassemi et al. [2], the authors proposed the integration of CA and GIS for the simulation of forest fires. Focusing on modelling the environment, the system presents different options for terrain, vegetation and weather. According to the authors, the results presented are promising and the proposed model can be adapted to other CA-based spatio-temporal modelling applications.

In the same year, the work of Louzada et al. [10] presented important results in the propagation of wildfires. Through the application of CA, the authors were able to reach the conclusion that periodicity of small forest fires is important to prevent the occurrence of large wildfires.

Bringing the models closer to reality, a case study related to a forest fire (Spetses Island, 1990) was carried out in the work of Alexandridis et al. [2]. The authors proposed a simulation model using a non-linear optimisation approach to approximate its behaviour to that of the analysed event. The simulation results were promising in terms of the predictive capacity of the model.

More current works still present ACs as an important tool for fire simulation models. In the work of Lima and Lima [9], the authors proposed a model for the simulation of forest fires based on CA, which took into account a series of important environmental factors, such as wind direction and speed, and the flammability and intensity of the fire. Preliminary results show that the model is promising compared to real-world forest fires.

In the work by Xuehua et al. [18], the authors evaluated a set of factors that influence the spread of flames in forest fires. Among the analysed factors, the authors highlight combustible materials, wind, temperature, and terrain. Implemented through CA rules, the model demonstrate to be able to satisfactorily simulate the flame spread trends under different conditions.

Finally, in the work of Sun et al. [16] a model for simulating forest fires was proposed by combining different techniques, including CA. The main objective of the authors was to improve the accuracy of the model in relation to the spread speed of the flames. According to the results, the model was able to simulate and predict the spread of forest fires, ensuring the accuracy of spread simulation.

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3 Model Description

The fire simulation model proposed in this work is totally based on CA. Inspired on the work of [9], in our work we have proposed a different set of states for the cells of the CA, and a novel regrowth function for the burnt cells.

Figure 1 illustrates the possible states of the CA cells. The "vegetation" state (green), represent the cells that have fuel material. It is a state that does not influence the others, but can be influenced by the fire states. State "water" (blue), is a state defined at the beginning of the simulation, and does not interact with any other state, but it can serve as a barrier if a fire takes its direction. States "initial-fire", "stable-fire" and "ember" (orange, red and dark-red, respectively) represent the fire states, where each one represents a different fire intensity. Finally, when the fire is over, the cells change to the state "ash" (grey). In this state, there is no likelihood of spreading fire to other cells or catching fire again, unless vegetation in this position recovers.

Cells change state through transition rules, which we call here fire propagation rules. The fire propagation rules are defined through a combustion probability matrix. This matrix defines the probability of a cell ignite through the propagation of fire by the cells that are in its neighbourhood, whether these cells are already in some state of fire. An example of a combustion probability matrix can be seen in Figure 2a. The figure shows a central cell in the "vegetation" state, i.e., capable of ignite, and its neighbourhood in a fire state. Using Moore's

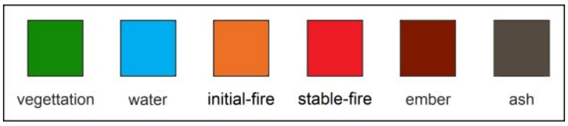
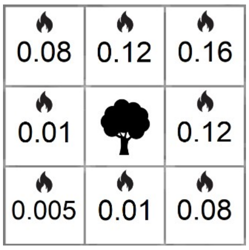
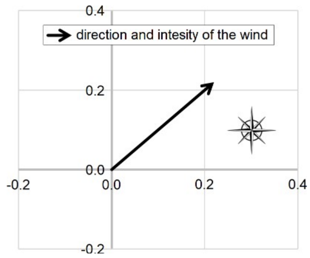


Fig. 1: Possible states for the cells of the AC described by different colours.



(a) Combustion matrix



(b) Wind power vector

Fig. 2: Combustion probability: Figure 2a presents the combustion matrix and Figure 2b the vector with the direction and intensity of the combustion.

Neighborhood, each cell has a probability of propagating the fire to the central cell. For example, the cell to the right of the central cell has a probability of 12% of propagation. It is worth mentioning that, at first glance, the applied probabilities seem to be low, however, the central cell is influenced by all the cells in its neighbourhood and the total burning time of a cell lasts a few time steps. These factors, accumulated, increase the probability of ignition.

The ignition probability can change according to some factors, for example, the position of the cell that is burning in relation to the central cell. This is due to the fact that some factors can influence the spread of fire. In this work, the wind was defined as an influencing factor. Still in the example of Figure 2a, one can see that the upper right cell has a higher probability of propagation (16%) in comparison to the lower left cell (0.5%). This difference in the probability is due to the presence of the wind force. In this example, there is a wind current going from the Northeast to the Southwest. In order to facilitate the visualisation, Figure 2b presents the wind influence through a force vector. This vector constitutes the influence composition of all cells that are in the neighbourhood of the central cell. As a result, we have the wind direction and its intensity, where the latter is represented by the size of the force vector.

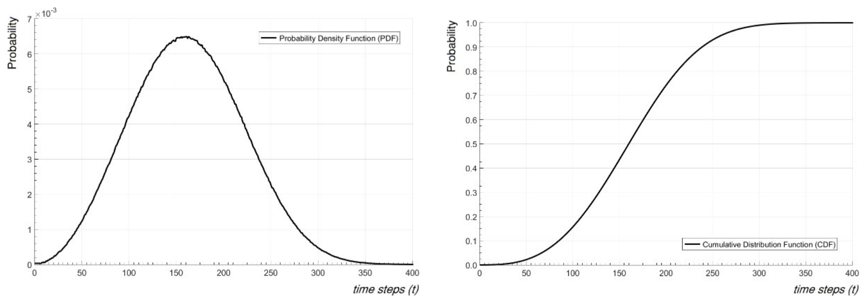
In addition to the fire propagation rules, the model also implements a transition rule for the regrowth of burnt vegetation. That is, unlike the other models of the literature presented in Section 2, in our model, a cell that is burnt, i.e., in the state "ash", can return to be a cell in the state "vegetation". Described by the Generating Function (GF) in Equation 1, it defines the probability of a cell change state, assuming it is completely burnt.

Equation 1 defines that the probability of regrowth $P_{regrowth}$ of a cell x, in the coordinates ij of the two-dimensional grid of the CA. If a time of idleness is defined, i.e., a time just after the burn where no regrowth of vegetation occurs, then the probability is zero. Otherwise, the probability is equal to the square of the current time step t over a power of 10. Defined by the variable a, this exponential represents the longitudinal extent of the probability distribution.

$$P_{regrowth}(x_{ij}) = \begin{cases} 0.0, & \text{if } idle \\ {t^2}/{10^a}, & \text{otherwise, such that } t \geq 1 \ and \ a \geq 1 \end{cases} \tag{1}$$

In order to take the model closer to reality, the GF is defined as an exponential, in which the applied probability is proportional to the number of time steps, i.e., cells that have been burnt for a long time are more likely to change state. Other types of functions would not print the desired behaviour. On the one hand, a constant probability function would not have the temporal effect on the regrowth of the flora, i.e., it would not imply that the longer a cell is burnt, the more likely it is to be reborn. On the other hand, using a linear probability function, although the temporal characteristic is present, it would imply an accentuated probability of regrowth for cells that have just been burnt.

Figure 3 illustrates examples of the Probability Density Function (PDF) (Fig. 3a) and the Cumulative Distribution Function (CDF) (Fig. 3b), obtained through the GF (Eq. 1). The PDF and CDF curves were computed using a process derived from the Monte Carlo method [8]. In this process, the variable a was set to the value six ($a = 6$). According to these charts, the peak of the PDF curve is reached around the time step 160, which is the time step with the highest probability of a cell being reborn. In turn, the CDF shows that from the time step 300, the probability of a burnt cell being reborn is almost 100%, considering that the $\lim_{x\to\infty} CDF = 1.0$.



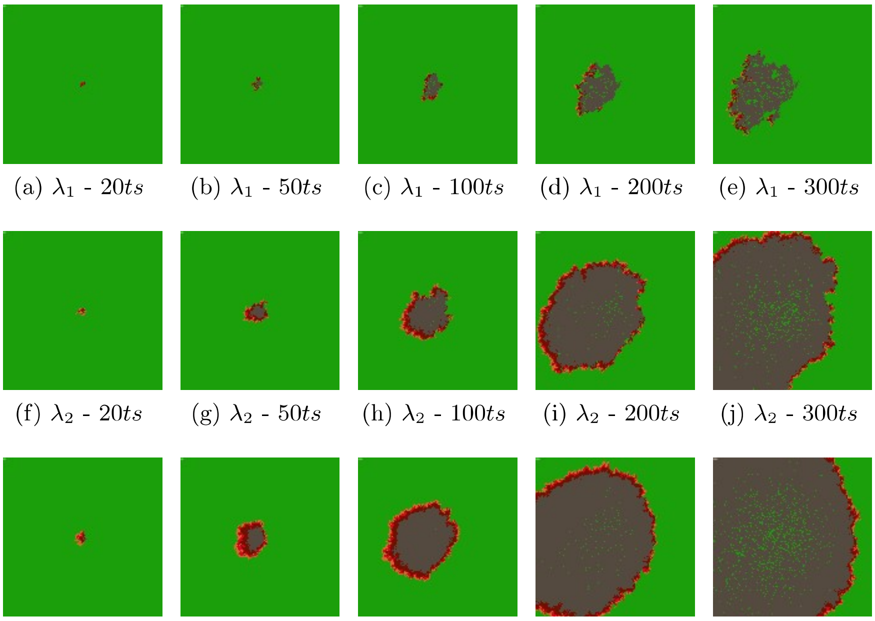
(a) Relative Probability (b) Cumulative Probability

Fig. 3: Probability distribution for the regrowth of cells after a complete burning.

4 Simulations and Analysis

This section describes the simulations and analyses performed with the proposed model. The simulations were performed in the game engine GameMaker [6], in CA grid with dimensions equal to (1024×1024). Each visual simulations was run for 300 time steps, while the quantitative simulations were run 100 times each, using different seeds to avoid outliers.

Figure 4 presents temporal screenshots of the wildfire simulation model proposed in this work. The main objective of these simulations is to, empirically, observe the evolution of the flames, so that it would be possible to calibrate the model and bring its behaviour closer to the characteristics of real wildfires.



(a) λ_1 - $20ts$ (b) λ_1 - $50ts$ (c) λ_1 - $100ts$ (d) λ_1 - $200ts$ (e) λ_1 - $300ts$

(f) λ_2 - $20ts$ (g) λ_2 - $50ts$ (h) λ_2 - $100ts$ (i) λ_2 - $200ts$ (j) λ_2 - $300ts$

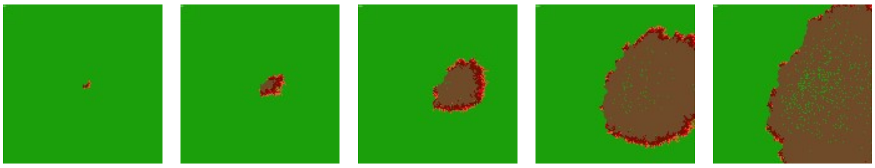
(k) λ_3 - $20ts$ (l) λ_3 - $50ts$ (m) λ_3 - $100ts$ (n) λ_3 - $200ts$ (o) λ_3 - $300ts$

Fig. 4: Evolução do modelo com vento norte sul $o \leftarrow l$

Three different scenarios (S1, S2 and S3) are illustrated, where the intensity of the fire (calories λ), is varied in each one to produce different scales of wildfires. In S1 (Figs. 4a-4e), the applied calorie was decreased by 50% ($\lambda = \lambda \times 0.5$); in S2 (Figs. 4f-4j), it was maintained with its initial value ($\lambda = \lambda \times 1.0$); and, finally, in S3 (Figs 4k-4o), it was increased by 50% ($\lambda = \lambda \times 1.5$). The evaluation of different calorie coefficients is extremely important, since momentary and permanent characteristics of a flora (e.g., type of vegetation, season of the year, humidity, temperature) influence how the flames behave if a possible fire occurs. For all three scenarios, screenshots are displayed within the same time step intervals, $ts : \{20, 50, 100, 200, 300\}$. In addition, each screenshot is composed of an AC grid, with dimensions equal to (1024×1024) cells.

Initially all cells are in state "vegetation" (cells in green). Intentionally, a spark is placed in the centre of the grid to start the fire. The propagation of fire takes place considering the probability matrix shown in Figure 2a. Besides, there is the presence of a wind current going from east to west. In the scenario S1, it is possible to observe that the propagation of the wildfire is slower compared to the other two scenarios. In S2 and S3, all cells within the wildfire radius went into combustion, differently from scenario S1. This was due to the fact that the calorie variable was weakened. Observing Figure 4e, there are several intact green areas within the burnt area, not resulting from the regrowth of flora. In scenarios S2 and S3, where the caloric variable is stronger, all cells ignited within the radius of the wildfire. In S0, in addition to the burning of all cells, it is possible to verify that the fire propagation speed is much faster than in the other scenarios, where, with 200 time steps, the burn radius is similar to the burn radius of S2 with 300 time steps.

EXPERIMENTOS COM OS QUADRANTES



(a) 20ts (b) 50ts (c) 100ts (d) 200ts (e) 300ts

Fig. 5: Evolução do modelo com vento norte sul

Finally, in a last simulation, an obstacle was built in the direction of the fire. Figure 6 presents this scenario, where the wildfire goes towards a lake (cells in blue). continuar

EXPERIMENTOS QUANTITATIVOS

5 Conclusion and Future Work

This work proposed a model for wildfire simulation through the application of cellular automata. Among its main characteristics, one can highlight (i) the presence of different states for the fire, which makes it possible to simulate different intensities of flames; (ii) the presence of wind currents that influence the fire direction; and, (iii) a regrowth function for the burnt vegetation.

According to the preliminary analysis and in comparison with other models of the literature, it was possible to conclude that the our model achieves

(a) $20ts$ (b) $50ts$ (c) $100ts$ (d) $200ts$ (e) $300ts$

Fig. 6: Evolução do modelo com vento norte sul

the expected behaviour. It was able to satisfactorily simulate, considering the characteristics presented, the behaviour of fire in the event of a wildfire. The spreading of the flames presented clear characteristics of a stochastic model, and the wind currents were able to direct these flames. Moreover, the proposition of a regrowth function allowed to print more realistic characteristics, mainly, compared to a random function, which, in turn, gave a high probability to the vegetation to grow in the time step subsequent to its burning.

Many paths emerged from the execution of this work. Thus, as a future work, we intend to add more states to the vegetation, bringing it closer to characteristics of the Cerrado, which represents the biome in our location and it frequently suffers from wildfires. Another important factor to be evaluated is the construction of a three-dimensional simulation model, which would allow the implementation of fire propagation by roots and wind. In addition, we intend to include the participation of a specialist in the field of wildfires, in order to validate the variables of the model, making it even more faithful to the reality.

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