COM3542: Modelling Forest Fire Spread With Cellular Automata

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Introduction & Background

Motivation, State of the Art / Existing Models,
Aims of the Project

Background: Motivation

Wildfires are increasing - in size, intensity, frequency and destruction.

The effects extend to the stability of ecosystems & wildlife, the integrity of infrastructure and the potential loss of human lives.

Modelling and simulations are vital tools in helping us to understand and predict wildfires and make effective decisions, strategies and solutions on how we deal with their threat.

Cellular Automata (CA) provides a biologically inspired approach for understanding and modeling forest fires.

First we describe our aims, objectives and the model we will create in order to investigate these.

Then, we will provide an overview of some of the current state of the art existing models using CA.

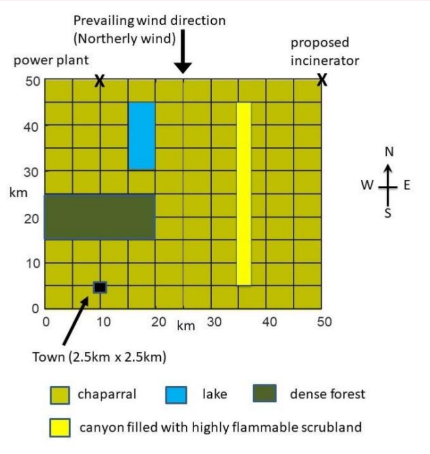
Background : Aims & Objectives

A Town in the USA, concerned with the potential risk of wildfires from a power plant and a waste incinerator, has tasked our team with creating a model to investigate the following objectives:

- The relative **time for a fire** starting at the power plant and incinerator **to reach the town** assuming a prevailing wind direction.
- How **time to reach the town** from the incinerator would **change** depending on the **wind direction**.
- Planning of **short-term intervention** - specifically in the case of the incinerator through aerially dropping water.
- Planning of **long-term interventions** - extending areas of dense forest is mentioned.

Background: Aims and Objectives

The schematic of the region surrounding the town is demonstrated below:



Varying terrain in the region has differing effects for potential wildfires, these described here:

- **Chaparral :** Easily Flammable, Burns for up to Several Days
- **Canyon :** Very Easily Flammable, Burns for up to a Few Hours
- **Dense Forest :** Harder to Ignite, Burns for up to a Month
- **Lake :** Acts as a Natural Fire Break

Background: State of the Art and Existing Models

Almeida & Macau (2011) set up a two-dimensional cellular automata model, using four states to represent cells as either empty, vegetation, burning, or burnt.

First the lattice is initialised, with cells randomly assigned as vegetation or empty, to represent the heterogeneity of fuel conditions across the landscape, and some to burning, to begin the fire.

It introduces probabilities for both the ignition from a burning cell to a neighbouring vegetation cell and the probability that a burning cell will change to a burnt cell.

This then captures the stochasticity of fire spread across the landscape, incorporating randomness or probability that simulates the inherent uncertainty present in real-world fire dynamics.

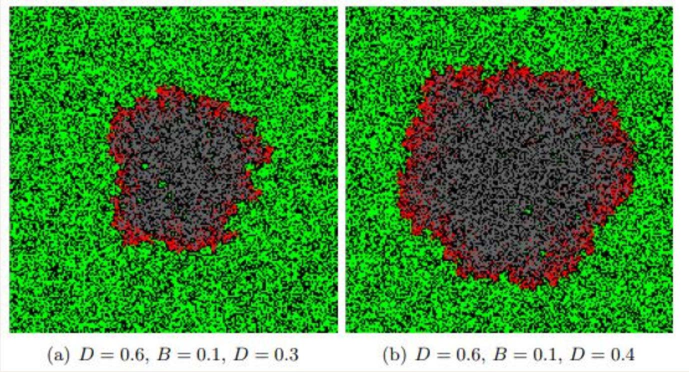


Image from (Almeida and Macau, 2011)

Background: State of the Art and Existing Models

Almeida & Macau (2011)'s model however is limited in its approach regarding meteorological, vegetation and topographical factors.

In particular it does not present an approach for modelling wind direction, and does not consider differences in vegetation across the landscape.

Mutthulakshmi et al. (2019) define another stochastic CA model that considers these parameters through setting fire propagation parameters associated with the density of vegetation, the type of vegetation, and the wind speed.

In Mutthulakshmi's model wind will increase the spread of the fire in the direction it is blowing in, but will slow the fire spread in directions against the wind. The manner of which this is implemented will inspire our design.

For the propagation of fire across different vegetation types, we will approach this through constant values for each type, instead of investigating the water content and density of vegetation by area as this approach does.

Mutthulakshmi's model also investigates the use of fire breaks / lines to limit the spread of the fire, which may inspire our long-term intervention strategies.

Background: State of the Art and Existing Models

Another recent state of the art approach to modelling fire spread we investigated was Zheng et al. (2017). This study introduced an innovative approach to fire spread modeling, departing from traditional cellular automaton (CA) methods. **Instead of manually defining local transition rules**, they integrated an Extreme Learning Machine (ELM) into the CA framework. ELM, a popular **data-driven learning model,** generated local evolution rules based on **historical training data**. This integration simplifies the CA modeling process, eliminating the need for complex theoretical considerations and numerous physical parameters.

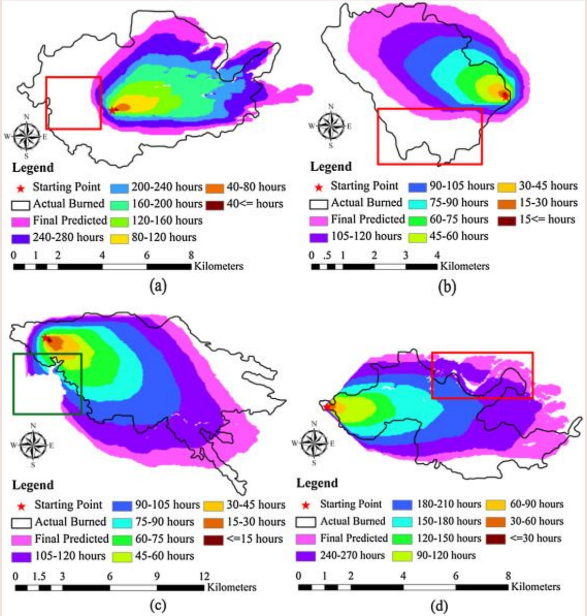


Image from (Zheng , 2017)

02

Model Description & Methodology

Stochastic cellular automata model with wind effect

Overview of Methodology

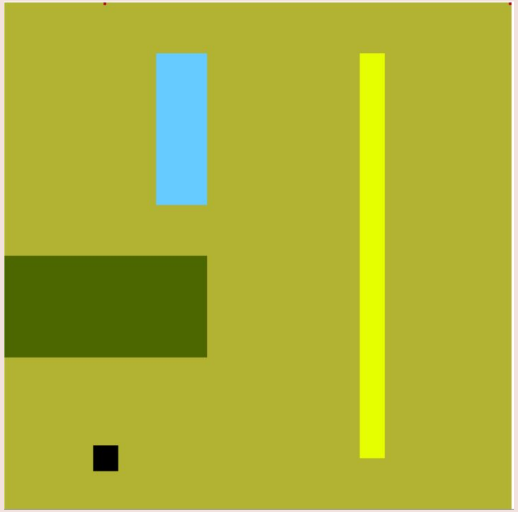
The model in the provided code is a stochastic cellular automaton that simulates the spread of a forest fire.

Spatial Representation:

- The landscape is represented as a two-dimensional lattice (grid) of dimensions 200x200.
- Each cell in the lattice has discrete coordinates (i, j), where i = 0, ..., 199 denotes the column, and j = 0, ..., 199 denotes the row.
- The cells have internal states represented by integers (0 to 6), where each state denotes a different condition, such as vegetation, burning cell, burned cell, etc.

Neighborhood:

- The Moore neighborhood is used, consisting of eight cells surrounding a central cell, as defined by N(i, j).



Initial grid, generation 0.

Overview of Methodology

Transition Rules:

- The transition rules for each cell are determined by a local rule function (`transition_func`).
- The model takes into account the amount of combustible material (fuel) is in each cell of the landscape. The amount of fuel influences how easily a cell can catch fire and sustain combustion. (`setup_fuel_grid`)
- The model includes inherent ignition probabilities for different terrain types (chaparral, canyon, forest, lake, town). (`setup_ignite_probabilities_grid`)

*If a cell is burning (state 5), it will be completely burned down (state 6) after number of steps equal to the amount of fuel for the cell.

```
# Update burning cells and fuel grid
burning_cells = (grid == 5)
fuel_grid[burning_cells] -= 1
```

```
# Identify cells which ran out of fuel
# and set them to dead state
dead_cells = (fuel_grid == 0)
grid[dead_cells] = 6
```

Methodology behind the Wind Effect

The wind effect is a crucial factor in fire spread. The wind direction and velocity affect the ignition probabilities of neighboring cells.

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Wind Direction and Cosine Values:

- The wind direction is specified using the variable `WIND_DIR`, which can be adjusted to represent the cardinal direction from which the wind is blowing (e.g., 'N' for north, 'S' for south).
- The code includes precomputed cosine values (`COS_VALS`) corresponding to different wind directions. These cosine values are used in calculations to determine the influence of wind on fire spread in specific directions.

```
COS_VALS = {'NW': [1.0, 0.707107, 0, 0.707107, -0.707107, 0, -0.707107, -1.0],
            'N': [0.707107, 1.0, 0.707107, 0, 0, -0.707107, -1.0, -0.707107],
            'NE': [0, 0.707107, 1.0, -0.707107, 0.707107, -1.0, -0.707107, 0],
```

Methodology behind the Wind Effect

Wind Effect Constants:

- Two constants, `C_1` and `C_2`, are defined in the code (C_1 = 0.045 and C_2 = 0.131). These constants control the impact of wind on the probability of fire spread.
- The wind effect on the probability of ignition is calculated using the formula:

```
wind_prob_grid[curr_direction_burning] += math.exp(V * (C_1 + C_2 * (cos_a - 1)))
```

- `V` is the wind velocity (which can be adjusted).
- `curr_direction_burning` is a boolean array indicating whether the corresponding cell is currently burning.
- `cos_a` is the cosine value corresponding to the angle between the wind direction and the direction of the burning cell.

Methodology behind the Wind Effect

Calculation of Wind Effect:

- The `calculate_wind_effect` function takes the current grid state and the states of neighboring cells as input.
- For each direction, the cosine value is taken based on the wind direction.
- The wind effect on ignition probabilities is computed for cells that are currently burning (`curr_direction_burning`).
- The wind effect is added to the `wind_prob_grid` for those burning cells.

Note: if a cell doesn't have any burning neighbours, then it will have value zero in `wind_prob_grid`, so it will also zero its value in `ignite_prob_grid` after the multiplication below, so we don't multiply base burn probabilities by summed `P_W` from each direction.

```
    # Calculate wind effect
    wind_prob_grid = calculate_wind_effect(grid, neighbourstates)

    # Update ignite probabilities grid based on wind effect
    ignite_prob_grid *= wind_prob_grid
```

Overview of Methodology

Stochasticity:

- The model incorporates stochasticity, introducing **randomness** in the ignition process.
- First it generates a grid (`random_grid`) of random numbers between 0 and 1, each element representing a random probability.
- Then it creates a boolean mask (`cells_to_ignite`) comparing each element of the random_grid with the corresponding element in the grid with already calculated ignite probabilities (`ignite_prob_grid`). The result is True where the random number is less than the ignition probability and False otherwise.
- Finally, the main grid is updated by setting the cells where the ignition should occur (if it gives `True` in the `cells_to_ignite`) to the burning state(value 5).

This process simulates a stochastic ignition process where each cell has a probability of catching fire based on the `ignite_prob_grid` and the randomness is introduced by comparing random numbers with these ignition probabilities. This randomness adds variability to the simulation, reflecting the inherent uncertainty in real-world fire spread processes.

Assumptions and Parameterisation

- The model uses discrete time steps, with each generation representing 4 hours.
- The burn durations for different terrain types are deterministic and fixed:
    - Chaparral takes 7 days to burn (42 gen.)
    - Dense forest takes 30 days to burn (180 gen.)
    - Canyon takes 12 hours to burn (3 gen.)
    - Lake does not burn.
- This number of burn generations are set as parameters in `setup_fuel_grid` . For the lake this is set to -1.0.
- The model formulation includes only fire spread dynamics under flat terrain.
- Ignition probabilities are assumed to be constant for each terrain type throughout the simulation.

Assumptions and Parameterisation

- The burn durations for different terrain types are assumed to be uniform and constant across all instances of that terrain type.

- Wind conditions are assumed to be constant throughout the simulation. The velocity and direction of which are set as a constant value.

- The fuel grid is initialized based on terrain types, but the model does not account for dynamic changes in fuel load over time due to factors such as vegetation growth or decay.

- We assume the weather is stable with no rain, difference in temperatures or extreme weather conditions.

Methodology for Short Term Intervention

We've decided to explore a short-term intervention involving aerially dropping water to extinguish or slow down the spread of the fire to the town from the newly built incinerator, the two locations we have explored for this are:

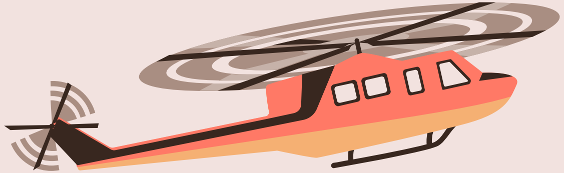
- Directly on top of the incinerator
- In front of the town

There is a limited quantity of $12.5km^2$ of water available to drop, this is the equivalent of 200 cells in our CA Grid.

The Model will allow us to drop these short-term interventions at chosen time-stamps.

We will model these drops of water as 14x14 square of cells to explore how this affects the spread of the fire, we will set the state of these cells to the same state as the lake, in order to extinguish the fire.

It is important to note that when dropping on top of the incinerator, it must be done within enough generations so that the fire has not spread further than the 14x14 square to drop, otherwise the intervention will not stop the spread the fire.



Methodology for Long Term Intervention

We have decided to explore two avenues of long term interventions, these being firstly extending the area of dense forest to slow the spread of fire to the town, and secondly using fire breaks – a common strategy used by wildfire fighters involving cleared areas or barriers devoid of vegetation, created to stop the advance of a wildfire, serving as a containment measure to prevent its uncontrolled spread.

We have explored where to extending the area of dense forest in three areas, these being:

1. An extension of the already existing area to cover the east side of the town.
2. New areas surrounding the waste incinerator, to slow the initial burning.
3. New areas surrounding the fast burning canyon scrubland, to offset the speed of burning.

Each of these will have the same area of new dense forest to explore the efficiency of each.

As our second long term intervention, we have decided to implement the fire breaks surrounding the waste incinerator, to halt the spread of the fire close to the source. These will be modelled by a new state that is inflammable.

Methodology for Long Term Intervention

Image of Model using
Dense Forest Extension 1

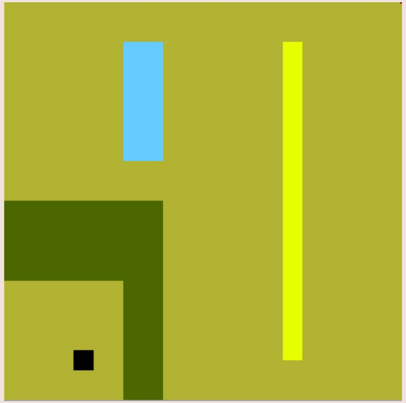


Image of Model using
Dense Forest Extension 2

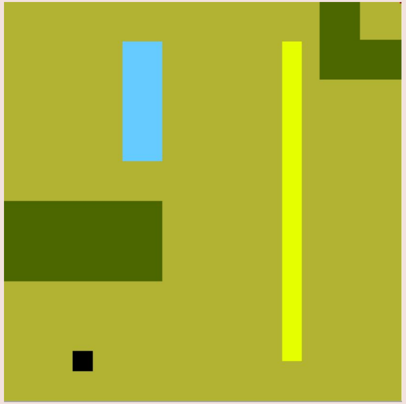
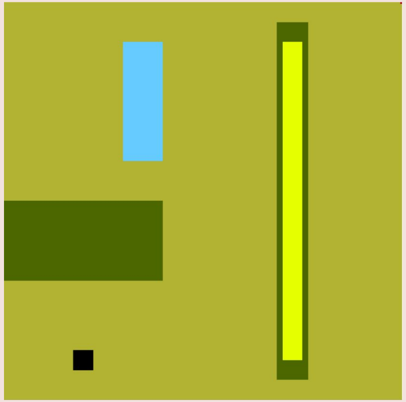


Image of Model using
Dense Forest Extension 3



All Models at
Timestamp: 0

03

Results of Model

Results for Each Task, With Some Discussion

Task 1 : Relative Time to Reach Town

Time to Reach Town from **Power Plant** :

336.2 Generations
Equivalent to **56.03 Days** *(1 d.p.)*

Time to Reach Town from **Waste Incinerator**:

369.6 Generations
Equivalent to **61.6 Days** *(1 d.p.)*

Both of these results are taken from an average of 5 runs of the model - assuming a prevailing wind direction (Generation results are rounded to the nearest whole integer).

The Fire reaches the Town from the Power Plant 33.4 Generations quicker than the Town from the Waste Incinerator.

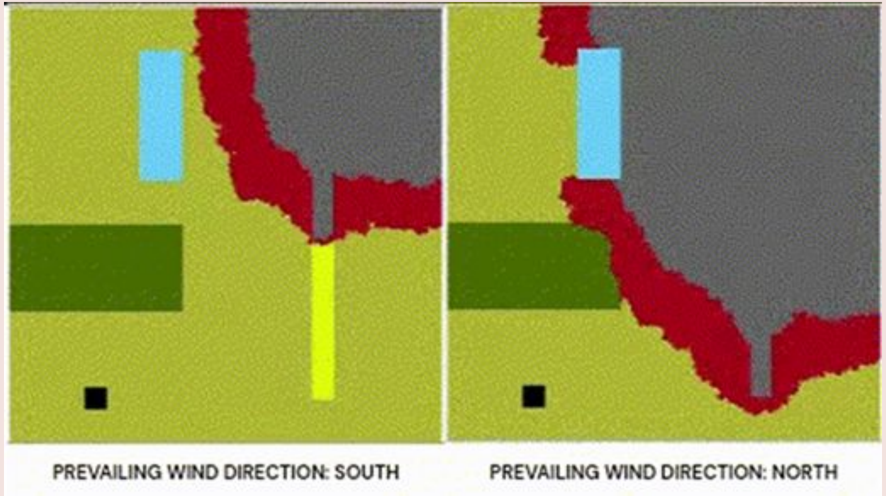
This is equivalent to 5.6 *(1 d.p.)* **days.**

And a 9.11% Difference in Time from the Waste Incinerator compared to the Power Plant.

Task 2 : Change of Time to Reach Town With Wind Direction

The next slide details the table of results for fire spread from the incinerator to the town with differing wind directions. Taking an average of 5 Trials, with a constant wind velocity of 1.0.

Changing the velocity of the wind can further be used to model the effects of extreme weather conditions.



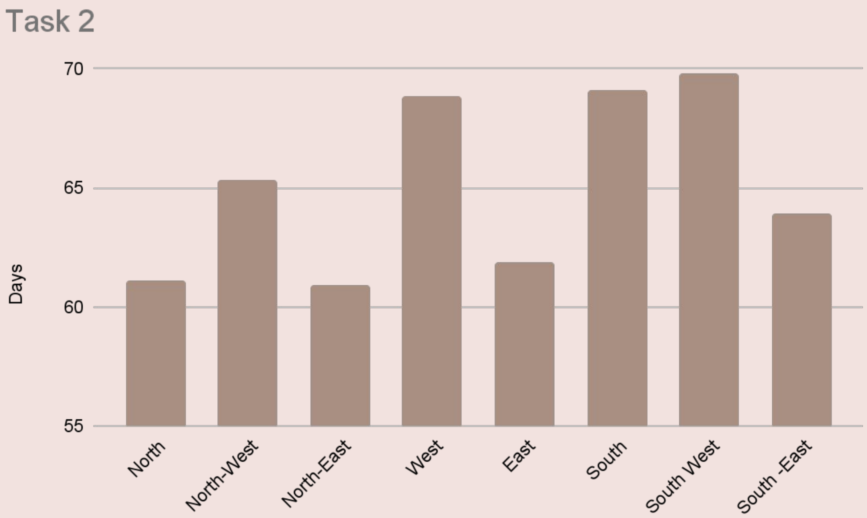
Comparing the difference of the fire spreading in real time between north and south wind

Wind Direction	1 trial (Generations taken to reach the town)	2 trial (Generations taken to reach the town)	3 trial (Generations taken to reach the town)	4 trial (Generations taken to reach the town)	5 trial (Generations taken to reach the town)	Mean value (Generations taken to reach the town)
North	367	373	351	362	380	366.6 (61.1 days)
North – West	393	402	388	375	402	392.0 (65.3 days)
North – East	363	372	365	364	364	365.6 (60.9 days)
West	422	415	403	410	416	413.2 (68.83 days)
East	366	377	371	378	367	371.8 (61.9 days)
South	417	411	407	418	421	414.8 (69.1 days)
South – West	419	413	413	419	430	418.8 (69.8 days)
South – East	379	383	375	401	380	383.6 (63.9 days)

Task 2 : Change of Time to Reach Town With Wind Direction

When the fire ignites from the waste incinerator; we can see that the wind direction has a significant effect on the speed in which it spreads to the town.

Wind originating from the prevailing wind direction of the North, blowing the fire southward towards the town blows the fire at a faster rate than wind originating from the south; it is also seen with the fire spread originating from the East compared to the West, wind originating from the East blowing the fire to the town much quicker than a wind blowing in from the West



Task 3 : Short Term Intervention

Time to Reach Town from **Incinerator** using **Aerial Drop on Incinerator** :

Does Not Reach / Fire Extinguished
If Intervention is Timed at Generation 15

Time to Reach Town from **Incinerator** using **Aerial Drop in Front of Town (At 300 Generations)**:

391.2 Generations
Equivalent to **65.9 Days** *(1 d.p.)*
Change of **24.6 Gens / 4.1 Days** *(1 d.p.)* ***To No Intervention***

Both of these results are taken from an average of 5 runs of the model - assuming a prevailing wind direction (Generation results are rounded to the nearest whole integer).

Maximum Number of Generations that Aerial Drop on Incinerator must be Completed in:

Approx. 24 Generations

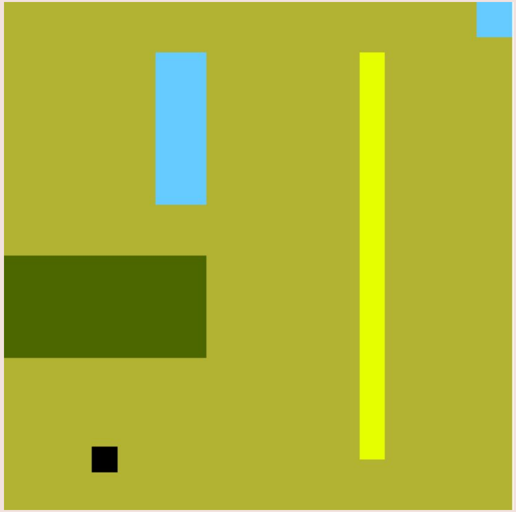
This is equivalent to 4.0 *(1 d.p.)* **days.**

Taken from running the model with interventions at different timestamps; would be advised to take action before this deadline. 25 Generations was the only timestamp where we saw it fail, however due to the stochastic nature of the solution it is possible to fail at 24 Generations.

This was tested at a wind velocity setting of 1.0, with a wind direction of North, higher values may affect the results.

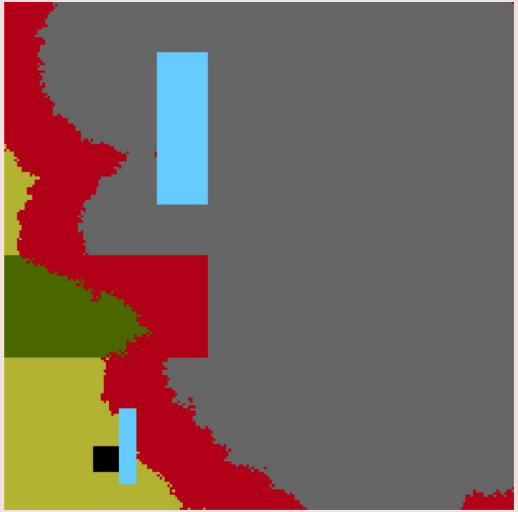
Task 3 : Short Term Intervention

Image of Model using **Aerial Drop on Incinerator** (Water in Top Right Corner) :



Timestamp: 20

Image of Model using **Aerial Drop in Front of Town** :



Timestamp: 300

Task 4 : Long Term Intervention

Time to Reach Town from **Incinerator** using **Dense Forest Extension 1 (Extension from Existing)** :

410.8 Generations
Equivalent to **68.5 Days** *(1 d.p.)*

Time to Reach Town from **Incinerator** using **Dense Forest Extension 2 (Extension Surrounding Canyon)** :

404.2 Generations
Equivalent to **67.4 Days** *(1 d.p.)*

Time to Reach Town from **Incinerator** using **Dense Forest Extension 3 (Extension around Incinerator)** :

380.2 Generations
Equivalent to **63.4 Days** *(1 d.p.)*

Time to Reach Town from **Incinerator** using **Fire Breaks Surrounding Incinerator**:

Does Not Reach / Fire Extinguished
This Assumes a Perfect Fire Break

These results are taken from an average of 5 runs of the model – assuming a prevailing wind direction (Generation results are rounded to the nearest whole integer).

04

Discussion and Conclusion

Model : Discussion & Conclusion

Our CA Model has simulated the spread of a forest fire in the given region surrounding a town in the USA; it takes into account the stochastic nature of the spread of fire, the effects of wind velocity and direction on this spread, as well as the fuel and flammability differences in terrain in the region.

It has been used successfully to meet our client's requirements, giving some firm answers to the aims and objectives set out at the start of the study. These successes and their limitations, as well as an outline of future work that could be undertaken will be detailed in this section.

Limitations of our general model include a lack of topographical features and models; lack of meteorological conditions other than wind; as well as potential regrowth of vegetation, which is especially true for quickly regrowing chaparral which may reignite.

Model : Limitations

Topographical Limitations:
Topographical model features including elevation, or height, of terrain; as well as any roads or existing structures other than the town, could in real-life impact the spread of fire in ways not explored here. For example: mountains, and other changes in elevations such as the canyon, could halt the spread of fire; as could roads, which could act as fire breaks similar to the one explored in our long-term intervention.

Terrain Regrowth Limitations:
Conditions considering our terrain could also impact the realism of our wildfire model, chaparral and shrubland as a terrain regrows quickly after burning; and so considering probabilities for the potential regrowth and reignition of burnt cells could allow for more accurate results.

Meteorological Limitations:
Meteorological conditions could further impact the real-life scenario of a wildfire, levels of rain and humidity in the area may either limit the spread of fire, or cause drier wood more likely to be flammable; this is also similar with average temperatures in the region, high temperatures may lead to a faster than expected spread of fire, lower the opposite. It is also possible that the change of seasons could affect this further.

Short Term Intervention : Discussion and Conclusion

Our CA model for the planning of a Short Term Intervention demonstrated two potential methods that could be used when aerially dropping water to halt the spread of the fire.

Targeting the incinerator as immediately as possible after the ignition of the fire demonstrated it may be possible to completely halt the spread of the fire to the town. However it was seen that this depends heavily on having a quick response time to the ignition of the fire; according to the model this response time has to be within 4.0 days to prove effective.

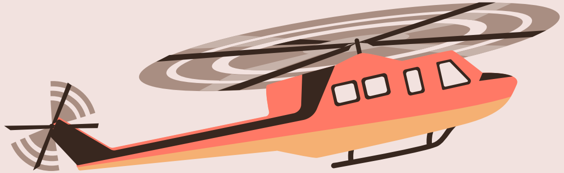
Using a method where the water was dropped near the town to slow the spread of fire, may be more appropriate where this rapid response time is not possible, it was shown according to our model to slow the spread by 4.1 days, whilst not completely extinguishing the fire like the previous method this may allow for crucial time to perform critical evacuation and other protective measures.

Short Term Intervention : Limitations

Limitations:
However, it is worth noting that our Model of potential Short Term Interventions comes with some limitations when considering the realism of an actual wildfire.

Our Model assumes an aerial drop of water will perfectly extinguish the fire within a cell, and not allow for the reignition of a cell when it has been extinguished; in a real life scenario this may not be possible, one of the reasons for this it is common that the heat from an actual wildfire may cause the water to dissipate before it reaches the fire.

Future Work:
It may be possible to model this dissipation of water by introducing stoicism to the aerially dropped water state, for example introducing a ~5% chance that the water will not extinguish the fire.



Long Term Intervention - Dense Forest : Discussion, Conclusions & Limitations

Our CA model for the planning of a Long Term Intervention demonstrated two potential methods that could be used.

Firstly, the method of extending the dense forest was explored in three different areas; we found that extending the forest from its original area was the most effective approach, followed by surrounding the canyon, and then extending the forest near the incinerator.

We tried to keep the area of dense forest constant throughout the experiment to analyse the effectiveness regarding cost, however the canyon approach required 80 additional cells, constituting an extra $5km^2$; this may have an effect on these results.

Limitations:
When considering real life situations, we can demonstrate that extending the area of dense forest in this manner would in fact slow the spread of the fire to the town.

However increasing the area of dense forest to the extent shown in the model may prove extremely costly, and a very long-term solution as dense forest can takes years, if not decades, to grow - it could also potentially impact the local ecosystem and environment in unexpected ways.

Long Term Intervention - Fire Break Lines : Discussion, Conclusions & Limitations

Secondly, we also proposed the idea of using fire break lines as a way to halt the spread of the fire, these were modelled as cells that did not allow for the spread of the fire. We modelled these close to the incinerator, demonstrating from this that fire break lines could halt the spread of the fire completely.

Our model suggests strongly that fire break lines could be used as a effective, efficient and robust long term intervention.

However it is worth noting that our fire breaks have been modelled as completely perfect fire breaks, and do not allow for potential real-life mistakes, or overlooked areas that could allow for the fire still to spread.

Real-life scenarios have shown that unremoved, or rather regrown, vegetation have in the past allowed the fire to jump across fire breaks, especially when considering potential floating embers carried by winds across the fire breaks.

Future work / models could be improved by modelling this impact, potentially introducing stochasticity by giving a small probability each timestep for a cell in the firebreak to fail. This would then still demonstrate that a firebreak may slow the spread of a fire, but not allow for it to be modelled as a perfect solution. Then it may be more efficient to create layers of multiple fire breaks, to allow for each one to halt the spread the fire.

Final Conclusion

In Conclusion, our CA Model has provided a platform to investigate the spread of a forest fire, in particular within the given region.

It has allowed us to investigate the speed of the spread of the fire from different ignition sources, and compare these with considerations for wind direction and velocity. As well as begin to investigate the potential implementation of short and long term intervention plans.

We have demonstrated ways in which these intervention plans can be implemented; using aerially dropped water, extensions of slower burning dense forests, and fire breaks.

As discussed there other considerations that could be added, and improved upon, with our Model to create a more comprehensive solution that would allow for a better understanding to be gathered. These include:

- Topographical, Meteorological and other Vegetational Considerations
- Improved Mechanics of Aerially Dropped Water
- Improved Fire Break Mechanics

It is also possible that future state of the art models could differ in their approach and include either ELM models such as Zheng et al. (2017); or OpenStreet data such as with Mutthulakshmi et al. (2019).

06 References

Almeida, R.M. and Macau, E.E.N. (2011). Stochastic cellular automata model for wildland fire spread dynamics. *Journal of Physics: Conference Series*, 285, p.012038.

K. Mutthulakshmi, Megan Rui En Wee, Yew Chong Kester Wong, Joel Weijia Lai, Jin Ming Koh, U. Rajendra Acharya, Kang Hao Cheong, Simulating forest fire spread and fire-fighting using cellular automata,Chinese Journal of Physics, Volume 65, 2020, Pages 642-650, ISSN 0577-9073,, https://doi.org/10.1016/j.cjph.2020.04.001.

Zheng, Z., Huang, W., Li, S. and Zeng, Y. (2017). Forest fire spread simulating model using cellular automaton with extreme learning machine. Ecological Modelling, 348, pp.33–43. doi:https://doi.org/10.1016/j.ecolmodel.2016.12.022 .

Thanks for watching!