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Fire-Evac Model ODD Protocol (Overview, Design Concepts, and Details)

1. Purpose

With rising population in urban areas, sprawl has become a part of most large urban areas across our country. However, with this influx of urban-sprawl, these areas have begun to encroach on the urban-wildland interface, causing some issues to arise. The urban-wildland interface can be defined as the zone of transition between unoccupied land and human development. These developments stand the risk of wildfires due to their proximity to the undeveloped (highly vegetated areas). With these issues, there is need to model how communities that fall within this designation will be able to evacuate in case of a wildfire. For our group's final project, we created a wildfire and evacuation model of a selected location within Eagle Mountain, Utah. Within our overall model there are two different sub-models. The first is a percolation model of the wildfire spread throughout the model landscape and the second is an agent based model of the evacuation of housing developments in the model domain. Using this model, we were able to test how fire spread effects an evacuation of a community within an area along the urban-wildland interface.

2. Entities, state variables, scales

Within this model, a number of different entities are represented. These are the wildfire, the road network, the vehicles, and the patches of different types of vegetation and landcover. Each of these entities have variables that help characterized them. These ranged from proximity to the wildfire and the model exit points, to landcover/vegetation type, overall fire-threat, elevation, and ignition and extinction parameters. The main agent used where the vehicles fleeing during the evacuation. The movement of these vehicles is determined by the proximity of the wildfire to the neighborhood, as well as their distance to the closest exit point. These agents reacted the fire differently depending on the levels of each of the variables and the amount of stochasticity. There were many different state variables that are used within this model. The global variables consisted of:

- projection
- ignition
- initial-trees
- burned-trees
- currently-burning
- veg-density-dataset
- fire-threat-dataset
- elev-dataset
- nodes-dataset
- node-name
- subdivisions
- p1 p2 full-list

- burned-cars
- exited-cars
- evacuated?
- temp
- time0 time1 time2 time3 time4 time5 time6 time7 time8 time9

While the local variables included:

- min-veg-density
- max-veg-density
- evac-time
- min-elev
- max-elev
- dxnode distance
- first-node
- previous-node
- location
- chance random float
- current elev

Scale-wise this model could be seen as unrealistic. This is mainly due in part that the road network does not include traffic effects and the model itself had to be resized to 10m to allow the model to function easier. The extent of the model is 409x230 patches, which meets the dimensions of the real landscape of the region we used. The length of one time step is assumed to be 1 second, meaning the vehicle agents are moving at 23 mph while the model is running. Similarly, the fire can spread at up to 23 mph, which is likely a few times higher than a realistic fire would spread. As the model begins, it often takes around 40-50 ticks for the evacuation procedure to start and this continues until the model is completed around 600-700 ticks (varies with model parameters). The length of the fire spread is mainly dependent on the other variables within the model; such as vegetation density, elevation, wind direction and extinction.

3. Process overview and scheduling

The main processes that change the overall characteristics of the model entities are the extinction rate of the wildfire, the ignition probabilities based on direction of the wildfire, and the level of stochasticity of the vehicles in making wrong turns. The extinction rate of the fire determines how long the fire is burning. The longer the fire is burning the higher the chances of a vehicle being caught within the fire itself. With the direction of ignition, this simulates the wind direction, in which the fire is being moved. Depending on the direction in relation to the community this could cause more vehicles to be caught within the fire or none at all. Finally, depending on the level of stochasticity, the vehicles could simulate one or more evacuees not knowing where the safe exit locations are or all evacuees knowing where to go in a wildfire situation.

As the model begins, the fire originates within the model domain and begins to spread. Dependent on the wind direction, extinction, elevation, and vegetation density levels the fire spread will continue. When the wildfire reaches the proximity buffer, this begins the evacuation of vehicles. On each time step the fire will continue to spread throughout the model and the vehicles will move one patch-length along the road network. At each intersection the vehicles will move towards the exits, unless stochasticity has been increased (q value lowered) and a wrong turn is made. Vehicles that reach the exit points are deemed safe, while vehicles that become caught in the wildfire are considered to be burned or killed. The model is stopped once all living vehicles exit the model or the fire burns out.

4. Design concepts (only include what's applicable for our model)

- *Basic principles* - There are two basic principles to this model. The first principle is to use a percolation model to simulate the ignition and spread of wildfire near the Eagle Mountain community of Utah. The general concept behind this portion of the model is that fire spread can be affected by vegetation density, extinction rate, wind speed/direction, and elevation. These parameters are modeled to impact the rate of fire spread and areal coverage based on their values and the interaction among them.
- The second principle is to use an agent-based model to simulate neighborhood evacuation once the wildfire model enters a buffer around the neighborhood. Each car is considered as an agent here which will traverse through a modified road network of the study area. Two evacuation exits are selected considering their proximity of urbanized areas. Once the fire reaches the neighbourhood, cars will start to evacuate the area toward their nearest exit using the shortest route.
- *Emergence* - The fire spread rate and pattern emerges based on the interplay between fire threat, vegetation density, directional ignition parameters related to "wind," elevation, and extinction rate. A change in any one of these values can affect how the fire behaves.
- The evacuation process of the cars will start from the nodes. There are thirty nodes in the road network. So, around ten cars will start to evacuate initially which are randomly generated from the nodes. Then the next 10 cars will start to move at every ten time steps. In this way, the model facilitates evacuation for around 50 cars.
- *Adaptation* - Adaptive behavior is modeled in the fire spread by reproducing some of the behavior seen in the real world, where fires are more likely to spread into dense vegetation, down wind, and into higher elevations. The model emulates this spread by incorporating vegetation, elevation, and simulated wind direction data. Fire spread is maximized in areas of high vegetation density, high elevation, and high directional ignition probability (which represents wind direction).
- A disaster evacuation usually produces a large volume of traffic and therefore reduces the speed of movement. Considering this phenomenon, the initial evacuation model was set with a lower car speed of 23 mph. This value can then be increased by an order to observe the impact of speed on the evacuation time and the percentage of burnt cars.
- *Objectives* - The only real objective in the model is that each car placed on the road during the evacuation phase has an "objective" to exit the model domain. The cars move toward the exit by choosing the node at each intersection that will get them closest to an exit.

Over several "decisions" at intersections, this results in the cars moving toward the exit and achieving their objective. The cars can also be prevented from reaching their objective if they make wrong turns or get burned by the fire.

- *Learning* - Learning is not explicitly considered in this model.
- *Prediction* - Prediction is not explicitly considered in this model.
- *Sensing* - The fire is assumed to sense the vegetation density and elevation of neighboring cells within the model. Wind direction is also "sensed" by the probability of fire ignition increasing in directions set by the user in the sliders on the model interface.

- The cars start to evacuate by sensing the fire within the buffer zone. However, this model instigates all cars to move at the same time irrespective of their distance to the fire. Therefore, a separate buffer for each neighborhood would have made this fire sensing process more accurate.

- *Interaction* - True interaction does not exist within the fire spread portion of the model, but there is some indirect interaction that impacts how the fire can spread in the future. The fire is only able to spread to vegetated cells that are previously unburnt, so the active fire spread is impacted by cells in the area that may have previously burned and are no longer available to ignite.

- In the evacuation portion of the model, the vehicles do not explicitly interact with each other while traversing the road network. It is also assumed that the cars will move at a constant speed without causing any delay at the intersections or crossings. However, there is some interaction between the fire and the cars. If a car encounters a burning cell, it will become "burned," stop, and no longer be able to evacuate the area. This event also adds to the burned cars count.

- *Stochasticity* - Several stochastic parameters are used in the fire spread portion of the model. First, the location of initial fire ignition is randomly chosen among cells that have a fire threat greater than 0.8. Then, the probability of fire spread itself is based on a combination of vegetation density, elevation, and a directional component representing wind. The resulting value, between 0 and 1, represents the probability that fire will spread into the adjacent cell in question. Finally, the extinction of an actively burning cell is dependent on the probability set by a slider on the model interface tab, which is 0.30 by default. Each of these 3 components adds stochasticity to the fire spread model that results in non-deterministic behavior to represent natural variability in fire spread each time the model is run.

- A stochastic behavior is also added in this model considering the possibility of cars not choosing the shortest route. Initially this value was set to 1 assuming that all cars will make the right decision about their route choice. Then it was changed in an decreasing manner to observe the changes in evacuation time. It is expected that a lower value of q will increase the total evacuation time assuming the greater chance of evacuees not taking the right route. Hence, it may also significantly impact the number of burned cars.

- *Collectives* - No collectives are used in this model.
- *Observation* - A few outputs are used to observe the fire spread portion of the model in order to provide an understanding for how the simulation played out and determine the spatial extent of the fire spread. The "percent-burned" variable is used to report the total percentage of the landscape that was burned by the fire. This is captured to provide a comparison between model simulations to determine how the fire size is affected by the parameters controlling fire

spread. The "current-burn" variable reports the number of patches that are burning at the current time step. This allows the fire to be monitored to determine if its areal extent is increasing or decreasing in size throughout the simulation.

- The evacuation portion of the model generates two outputs: burned cars and exited cars. The "burned-cars" variable represents the number of cars affected by the fire, whereas the "exited-cars" variable represents the number of cars that survived during the fire evacuation. Initialization of the model sets both of these values to zero. As the model proceeds, any car traversing through a currently burning patch will be added to the "burned-cars" count. Besides, once a car reaches within a 5 meter radius of the exits, it will be counted as "exited-cars".

5. Initialization

The model world is an area spanning approximately 3.5 x 2.5 kilometers with grid cells at about 10-meter spatial resolution (then projected to WGS84) set to a world envelope according to the vegetation density dataset. At setup, the vegetation patch colors are displayed in shades of white to dark green according to their respective vegetation densities. Cells with a vegetation density less than 0.1 are set to black. Elevation is set on a scale from black to white where black indicates low elevation and white indicates higher elevation. The user has the ability to switch between a display of the vegetation or elevation. Because the number of burned-cars, exited-cars, number of cars-evacuated and burned-trees cannot take place until the fire model has been initiated, each is respectively set to 0,0, false, and 0 at initiation. Subdivision borders are drawn with a fixed color of blue. The road network is created with the make-links procedure creating links to nodes and nodes are assigned distances to their nearest node and exit nodes. Both Exit Nodes (node 20 and 14) are set to color blue and remaining Nodes are scaled from white to black depending upon their distance to both Exit Nodes.

The initialization of the agent-based model is dependent upon the fire portion of the model. The x patch coordinate 225 and y patch coordinate 12 are set to ignite at the start of the model run. Fire can also be randomly ignited on a patch with fire threat > 0.8, vegetation density > 0.05 and pxcor/pycor < 50 to introduce stochasticity. The user is also provided the option to manipulate the initial values of two parameters according to his/her choosing which the fire spread is conditional upon. These parameters are displayed as a series of adjustable sliders located on the models interface. These adjustable parameters include:

- Fire extinction probability labeled as "extinction". A scale from 0.0 to 1.0 probability of a cell's fire extinguishing at every timestep.
- Ignition of fire caused by wind travel in four cardinal directions:
    - Northward wind direction labeled "ignitionN" and scaled from 0.00 – 1.00
    - Eastward wind direction labeled "ignitionE" and scaled from 0.00 – 1.00
    - Westward wind direction labeled "ignitionW" and scaled from 0.00 – 1.00
    - Southward wind direction labeled "ignitionS" and scaled from 0.00 – 1.00

The final slider for parameter "q" controls the probability of an agent making the correct choice at an intersection and traveling to the node nearest to the exit. This parameter, similar to the previous two, is also scaled from 0.0 – 1.00.

No agents are present when model is initialized. However, agents are initiated dependent upon if and when the wildfire touches the designated buffer. In the instance that agents are initialized, only 10 total agents begin evacuating and at random single node locations. 10 additional agents are then added every 10 time steps until a total of 50 agents are moving about in the model.

6. Input data

- The fire evacuation model for Eagle Mountain City requires input data from 5 sources that include:

1.) A land cover and vegetation density dataset in ASCII-delimited file format originally provided at 10-meter spatial resolution and titled “veg_frac_10m_wgs84.asc” . This dataset is used to set fire ignition probabilities to patches and was acquired from the Utah Department of Natural Resources (DNR). The dataset includes 9 original classifications of vegetation type local to the Eagle Mountain area, which include; agriculture, barren, developed, grassland, exotic herb, pinyon-juniper, desert scrub, shrubland and sage shrub. Each DNR vegetation type corresponds to an accompanying density value.

2.) A fire threat probability raster dataset in ASCII-delimited file format at 10-meter spatial resolution and titled, “threat_prob_5m_wgs84.asc”. This dataset was also provided by the Utah DNR via their Wildfire Risk Assessment Portal. The wildfire threat dataset originally provides 11 categorized measurements for the likelihood of a fire starting and spreading to a location. These likelihood categories include 1.) Urban, Agriculture, Barren or Water 2.) Very Very Low, 3.) Very Low, 4.) 5.) Low, 6.) Low-Moderate 7.) Moderate, 8.) Moderate-High, 9.) High, 10.) Very High, and 10.) Extreme. The have been scaled to a value between 0 - 1.0 for use in the model.

3.) A digital elevation model (DEM) in ASCII-delimited file format at 10-meter spatial resolution and titled, “dem_ut_5m_wgs84.asc”. The DEM dataset is used to augment wildfire spread and was also acquired from the DNR Wildfire Risk Assessment Portal.

4.) A user created nodes point shapefile titled, “nodes_new.shp” that generalizes the roads and intersections layout of Eagle Mountain City for maintaining model simplicity and efficiency. The nodes shapefile consists of two primary categories of nodes which include:

- Link Nodes: Nodes that provide links for successive agent movement towards closest exit
- Exit Nodes: The nodes representing exits to safety from the evacuation area.

5.) A subdivision boundaries vector shapefile titled, “Subdivision.shp”: Subdivisions were provided by the engineering department of Eagle Mountain City and generalized for purposes of maintaining model efficiency. The subdivisions serve as a spatial context for where members of the community live and and the nodes by which agents will initialize for evacuation.

- All ASCII-text files and point/vector shapefiles were individually set and loaded using the WGS84 coordinate system. The evacuation of all agents from neighborhoods is a response to fire in the case that the fire does not extinguish before reaching the designated evacuation buffer. If at any instance the traveling fire reaches a point of contact with an actively evacuating agent, that agent will be considered ‘dead’ and no longer engaged with the process of traveling towards the nearest exit node. Agents are exclusively restricted to movement towards exit nodes only according to the road network links connected to nodes and exit nodes.

7. Submodels

- "To setup" is designed to prepare the model landscape and agents for the simulation. It resets all values, loads the GIS datasets and applies them to the model world, sets up the road network and ignites the initial fire.
- "To display-elevation" colors the patches of the model world to display their elevation value in a black to white scale -- only invoked by the button on the model interface.
- "To display-vegetation-in-patches" sets up the model world to display colors based on vegetation density from white to green. It also adds the fire threat and elevation values to each patch.
- "To match-cells-to-patches" ensures that the GIS envelope aligns with the vegetation density dataset.
- "To ignite" is run on cells where fire has spread to and updates their color to red, sets their "burning?" boolean to true, and adds 1 to the "burned-trees" count.
- "To go" is the procedure that runs the model each time step. It removes cars that reach the road network exits and stops cars that get "burned" by the fire, adding them to the burned-cars count. This module also calls the spread-fire routine and starts vehicle evacuations if the fire breaches the buffer around the neighborhoods. It also calls for cars to move, advances the time step clock, and stops the simulation if all cars have exited or stopped moving.
- "To move" provides moving directions for the cars. Each car generated at a node starts with facing at its link destination. Then it measures the distance between its location and link destination. If the distance is greater than a patch size, the car forwards itself by one patch and updates its current location and link destination.
- "To spread-fire" spreads the fire across the model landscape to queen's case neighbors (8) with a probability based on the following criteria:
    - For fire to spread to a neighboring patch, the patch must have a vegetation density greater than 0.05, and must not be currently burning or already burnt
    - Ignition probability is dependant on the the "wind direction" probability (e.g. "ignitionN") multiplied by the vegetation density of the patch
    - An additional probability modification depends on elevation of the neighboring patch. If uphill, probability is increased by 0.15. If downhill, probability is decreased by 0.15. If no elevation change, probability is not changed.
    - This sub-model also calls the extinguish routine for each patch
- "To extinguish" has patches that are on fire extinguish with a probability set by a slider. If extinguished, the patch's color is changed to dark red and the "burning?" boolean is set to false.
- "To-report percent-burned" calculates the percentage of patches that have been burned during the simulation.
- "To-report current-burn" calculates the total number of patches that are currently burning.

- “To make-road-network” uses the node point shapefile to create node turtles on each point. Each node has three variables: “dist-exit1”, “dist-exit2” and “dist-exit”. The first two variables measure distance to exit 1 and exit 2. The third variable picks the smaller distance between this two.
- “To make-links” creates link roads between the nodes, mimicking Eagle Mountain’s road network.
- “To assign distances” calculates a node variable “dist-exit” which refers to the distances between each node and its nearest exit point. First, it measures the distance of both exits from each node (“dist-exit0” and “dist-exit1”) to identify the nearest one and then assigns that value as the distance to exit.
- “To car-release-times” refers to the time steps (every 10 ticks) at which new cars will be created and start moving to evacuate the area.
- “To spawn-cars” is used to create the car agents. Cars are randomly generated at the nodes with three variables “current-location”, “link-dest” and “stopped?”. Initialization of a car sets the “current-location” as the node’s location, “link-dest” as the neighboring node with the minimum distance to exit and “stopped?” as false.

8. Group Roles

- Model Design - Entire Group
- Data/Literature search - Matt, Armita, and Erik
- Coding - Armita and Erik
- Testing - Entire Group
- Analysis - Entire Group