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Abstract: The Forest Fire Fighting Training Simulator (3FTS) is an interactive, real time simulation software designed to improve organization, coordination and firefighting capabilities of the different level fire managers in fighting forest fires. 3FTS uses a high fidelity fire propagation model to simulate fire behaviour, and a fire suppression model to introduce the effects of the firefighting actions taken by the virtual firefighting crew or equipment in a synthetic environment. In this study, fire propagation model of 3FTS was explained first, describing how the factors that affect fire behaviour such as weather, fuel and topography were incorporated into the model. Then, the fire propagation results of the 3FTS were compared with those of the Fire Area Simulator (FARSITE), a fire behaviour prediction model accepted globally as one of the main fire simulation systems that uses a semi-empirical fire propagation model. The comparison was made in terms of the total size and the shape of the perimeter of the burned area. Finally, the results of the experiments were evaluated considering uncertainty of modelling a fire as a complex task and some suggestions were made.

***Keywords**: forest fire; fire propagation model; fire behaviour*

1 INTRODUCTION

Fire behaviour modelling is handled as a numerical simulation and targets understanding and predicting fire propagation over time. In 3FTS this task is done in real time providing a scenario for the actors in which they can participate in suppression activities for training purposes.

Within a 3FTS simulation basic factors affecting fire behaviour are wind, fuel characteristics and topography. These factors are applied as numeric parameters to the fire model. A realistic fire model depends heavily on the variety and amount of data gathered to calculate these parameters. The data collected to calculate the fuel model parameters are statistical.

3FTS is used in training of fire fighters to improve their coordination and organization capabilities. Each trainee can participate in a training scenario with a certain commander role, observe the situation in real time and carry out their fire suppression tasks of through their virtual crew.

An elliptical fire model, which is propagated on a grid of 2mx2m cells, is used in the simulation. This means that the resulting shape of a fire is elliptic. In the beginning of a scenario execution, the fire is started at an ignition point which resides in a fire cell. At discrete time intervals calculations are made to specify the burning time of the adjacent cells, so that the fire is propagated along the fire cells in the grid. The direction and speed of fire changes depending on the underlying topographic, atmospheric and fuel characteristics. In this paper 3FTS fire model is explained and compared to the FARSITE fire model using the results of 2 hour fire simulations.

2. THE FIRE MODEL OF 3FTS

2.1 3FTS Fire Model Rate of Spread Calculation

Inside the 3FTS fire model the basic principle is calculating the rate of spread from an ignited cell to adjacent cells. Furthermore the overall spread shape is considered to be elliptical under homogeneous conditions. The rate of spread is calculated as in the formula (1) below.

$$\text{Rate of Spread: } ROS = a[1 - e^{(-bBF)}]^c \qquad (1)$$

In the formula a, b, c parameters represent the fuel characteristics, the burning factor BF is calculated depending on the wind speed W (kph) and dead fuel moisture DFM as shown in the formula (2).

$$BF = 20 \times e^{(-0,090 \times DFM)} \times e^{(0,04 \times W)} \qquad (2)$$

Dead fuel moisture DFM is crucial in calculating the fire behaviour. Simply drier fuel increases rate of spread and fuel consumption. DFM is calculated using the formula (3) below. Parameters used in the formula are the temperature factor TF, rain in the last 24 hours R, conditional moisture M (%) and the wind speed W (kph).

$$DFM = e^{(0,475+0,738 \times TF+0,195 \times \ln(R)+0,01136M-0,02126 \times W)} \qquad (3)$$

TF value used in the DFM formula is the temperature factor which is calculated based on the air temperature (C°), the number of days after last rain D as in formula (4).

$$TF = 3,123 + 0,028 \times T - 0,002 \times T^2 + 0,429 \times \ln(D) - 0,235 \times D^2 \qquad (4)$$

The ROS formula for the fire propagation model denotes an S shaped curve. The parameters a, b and c depend on the fuel type and the BF propagation factor is calculated based on the weather conditions.

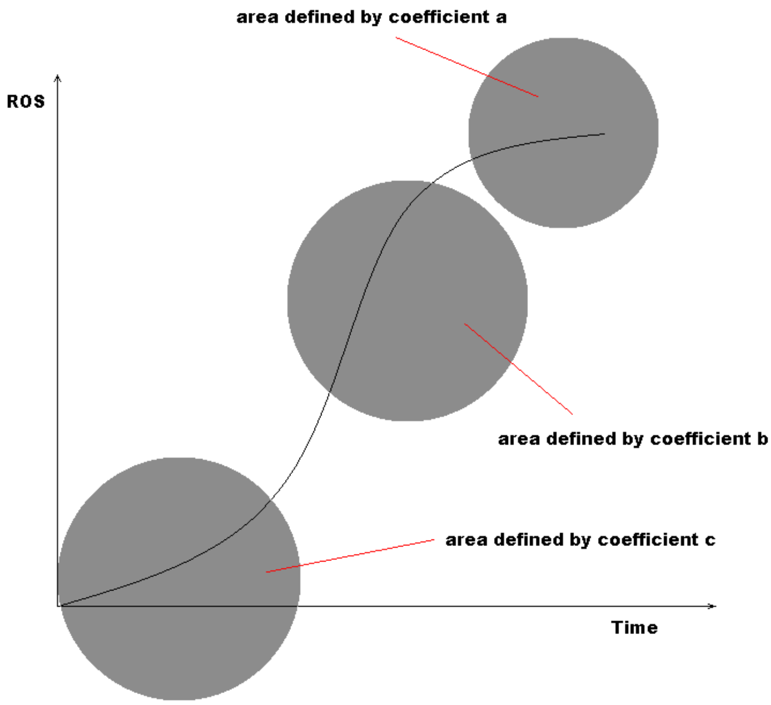

Figure 1: ROS values graph with a, b and c coefficients

2.2 Elliptical Fire Propagation in 3FTS

3FTS fire model is based on elliptical fire propagation which means fire spread will form an elliptical shape under homogeneous conditions such as fuel characteristics, atmospheric conditions and topography. Elliptical formula is used to calculate ROS at each point on the ellipse. Below the elliptical formula (5) is shown for an ellipse with the focal point F.

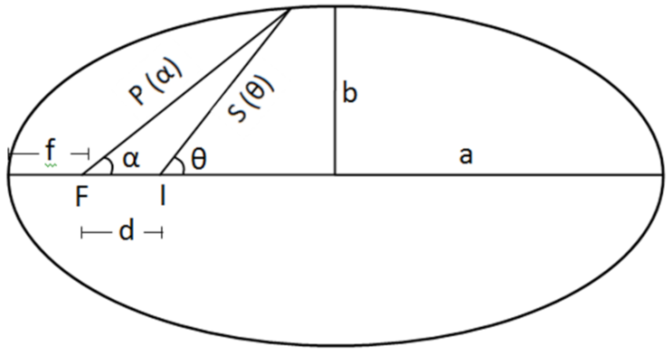

Figure 2: Polar formula for an ellipse with its origin at point F as the focal point

$$P(\alpha) = (a - e \times c) / (1 - e \times \cos(\alpha)) \qquad (5)$$

In Figure 2 above a and b represent the major and minor axis respectively. So length to breadth ratio LB is calculated as in the formula (6) below.

$$LB = a / b \qquad (6)$$

Considering the ignition point, polar coordinates of the ellipse (θ and S(θ)) can be calculated as in formula (7) below.

$$S^2 = P^2 + d^2 - 2 \times P \times d \times \cos\theta \qquad (7)$$

Using ROS values for head fire and back fire, half values for major and minor axis are calculated. Note that back fire spread rate is calculated using the same ROS formula (1) using the wind value of 0 kph.

$$a = (ROS^{back\ fire} + ROS^{head\ fire}) / 2 \qquad (5)$$

$$b = (ROS^{back\ fire} + ROS^{head\ fire}) / 2LB \qquad (6)$$

$$c^2 = a^2 - b^2 \qquad (7)$$

$$d = ROS^{back\ fire} - a + c \qquad (8)$$

$$e = c / a \qquad (9)$$

$$f = a - c \qquad (10)$$

Using these parameters to be able to calculate the coordinate values according to the ignition point I, the distance d between the ignition point I and focus point F must be calculated. Afterwards polar coordinates (θ ve S(θ)) can be calculated.

S(θ) value calculated will be the ROS value of any point on the ellipse with an angle θ to the fire starting point. Finally the actual ROS will be calculated by multiplying this value with the head fire ROS value. The unit of ROS value is meters per minute.

With these calculations for a single point ROS values for each angle are calculated on the ellipse which are adjacent points for an ignition as the fire starting point. So a point whose ignition time is reached in a simulation time interval is ignited and the calculations above are made. An elliptic fire shape is formed as the result of this chain reaction. Theoretically time of arrival from an ignition to a point on the ellipse can be calculated with S(θ) value. For instance with a resolution of 1 degree, a number of 360 S values will be calculated like S(1), S(2), S(3), ..., S(360).

2.3 Simulating Cellular Propagation

To apply the rate of spread calculations to a real time simulation smallest unit of area in a scenario has been determined as 2mX2m square cell. This is the size of an area which can be treated as an ignition point and the calculations for adjacent cells can be carried out. Also this atomic unit of area is either burning or not burning so there is no partial burning for any given cell. Fire propagation using a cellular model is possible with the use of cell schemes. These schemes can be either symmetrical as in Figure 3 or asymmetrical as in Figure 4. Selection of a scheme determines the number of S(θ) calculations from the central cell. In 3FTS fire model only one scheme is applied throughout the simulation for consistency. It was observed that the main difference between schemes is the total shape of fire. And the main criteria for a scheme selection can be summarized as “more cells more calculations”.

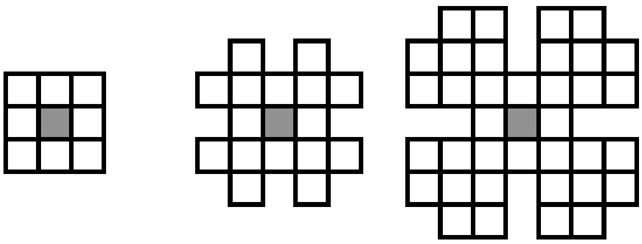

Figure 3: Symmetrical Cellular Schemes with 8, 16 and 32 cells

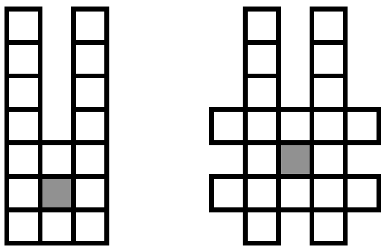

Figure 4: Asymmetrical Cellular Schemes with 16 and 20 cells

The ideal elliptical shape of fire can be achieved by using as many cells as possible in a scheme. However, the more cells in the scheme the more calculations needed in the simulation. In 3FTS, as a trade-off between the ideal elliptical shape of fire and the performance, the asymmetric cellular scheme with 20 cells was selected. The number and direction of calculations is shown in Figure 5 below.

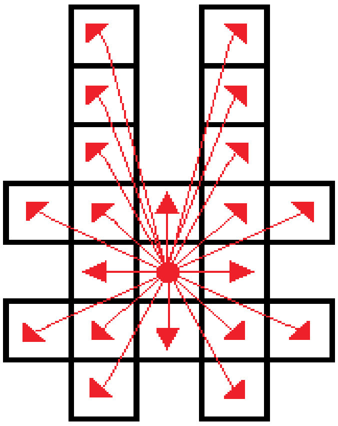

Figure 5: Calculation for the neighbouring cells within 20 cells asymmetric scheme

Figure 6 below shows the fire propagation over time (in 60 seconds). It can be observed that the total shape tends to form elliptical shape over time.

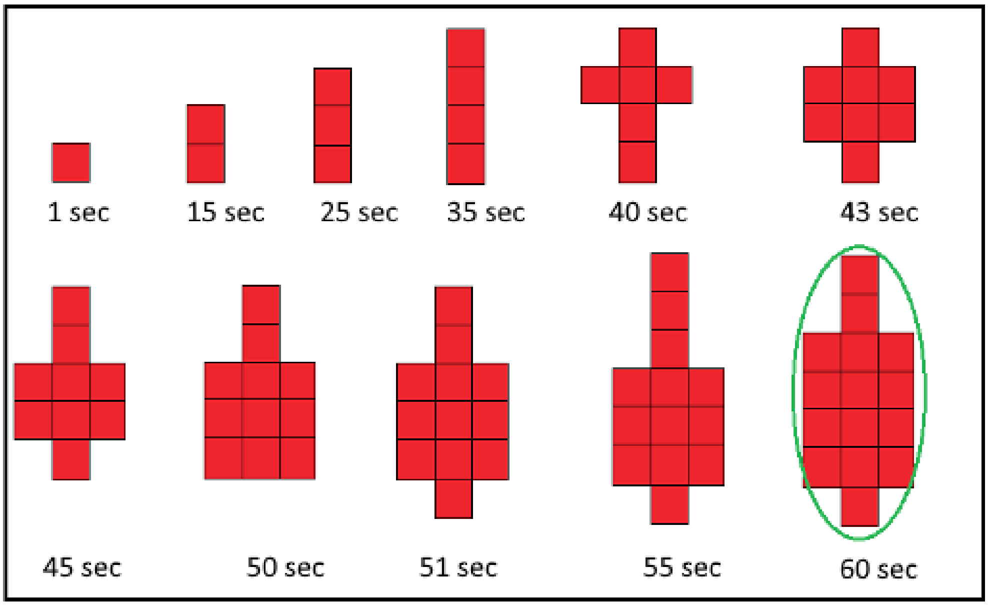

Figure 6: Fire propagation in real time

The example propagation above depicts a straight direction to the north. It is obvious that when the direction of fire has an angle between two straight directions, propagation of burnt cells will not be as precise as in the above figure. Table below shows the area differences for the same propagation with different angles of direction. 0 degrees to the north is accepted as the reference value.

Table 1: Burnt area results for fire propagation in different angles

Angle	Running Time (min)	Burnt area (m^2)	Difference (m^2)
0 degrees	30	105032	0
17 degrees	30	104540	-492

112 degrees	30	104220	-812
135 degrees	30	103540	-1492
213 degrees	30	104052	-980
291 degrees	30	104340	-692

2.4 Fuel Characteristics of 3FTS

Fuel type, age and closure are the basic fuel characteristics in 3FTS fire model. Type represents the classification of the plant with specific code assigned like Cz for red pine, Dy for maquis, etc. The age of plantation follows this code represented by the letters a, b, c, d, e. Plants with diameter smaller than 8 cm are assigned the letter a, diameters between 8 cm and 19.9 cm are assigned the letter b, 20 cm – 35.9 cm are assigned c, 36 cm – 51.9 cm are assigned d and plants with diameters greater than 52 cm are assigned e. Last part of the code denotes the closure property of fuel using numbers 1 for %11-40, 2 for %41-70, 3 for %71-100. When applied to the model closure values are accepted as %25 for 1, %55 for 2 and %85 for 3. Fuel types evaluated in this paper are Czb1 and Dy which are commonly used for training purposes in 3FTS.

3 EVALUATION OF 3FTS USING FARSITE

FARSITE is used to evaluate the results of 3FTS fire model according to the burnt area and shape of fire. FARSITE simulator is developed by the US Forest Service and its fire model is based on Huygens principle. It simulates the speed and growth of a propagating wild land fire. For evaluation purposes under the same conditions basic elliptic fire scenarios have been executed in both simulators. The inputs representing the spatial and temporal conditions are homogeneous within a hypothetical simulation area. That means a singular value for each of fuel type, wind speed and moisture conditions which will apply to the whole terrain. The results are calculated as burnt area in hectares.

Table 2: Burnt area evaluation between FARSITE and 3FTS fire models

Fuel type (3FTS / FARSITE)	Temperature (C°)	Wind Speed (kmph)	Moisture (%)	3FTS Burnt Area (ha) in 2 hours	FARSITE Burnt Area (ha) in 2 hours
Czb1/SH8	25	30	10	448.1	382.1
	25	30	20	377.68	316
	35	30	10	652.83	361.7
	35	30	20	589.63	311.9
Dy/SH5 (Maquis)	25	30	10	297.26	459
	25	30	20	238.62	385.1
	35	30	10	492.82	440.1
	35	30	20	428.63	381.3
Dy/SH7 (Maquis)	25	30	10	297.26	418.3
	25	30	20	238.62	348.4
	35	30	10	492.82	397
	35	30	20	428.63	343.9

4 CONCLUSIONS

3FTS and FARSITE burnt areas in 2 hours have been compared in similar homogeneous conditions. When FARSITE simulates fire growth as a spreading elliptical wave, the fire is propagated over a finite time step using points, that define the fire front, as independent sources of small elliptical wavelets. On the other hand 3FTS fire model makes its calculations to spread as an ellipse from an ignition point which resides in a cell with 2x2 meters dimensions. Propagation from a point (FARSITE) and cellular propagation (3FTS) cause a difference in total burnt area while forming a similar elliptical pattern. Cellular resolution in 3FTS makes it possible to simulate the fire in real time and allows interactive suppression activities at any time step. Basic principle is applying suppression materials (water, foam, etc.) to a burning cell and calculating the suppression effect on the cell. The suppression effect decreases the rate of spread for that cell and depending on a ROS threshold value, it either stops burning or continues to burn with a lower ROS.

Furthermore 3FTS fire model can detect if it can pass across roads and other kinds of barriers depending on the number of cells allowed as a minimum limit of road or barrier thickness in meters. This feature is frequently used in training sessions to suppress fire with a backfire. In this scenario a barrier wider than the threshold thickness is created and backfire is started between the barrier and the actual fire. Here, the goal is to clear the fuel before the actual fire reaches that carefully selected area and going out of control.

Atmospheric conditions (temperature and moisture) change the fire behaviour in both models. For different moisture conditions 3FTS and FARSITE fire models show similar behaviour which is a decrease in burnt area as the moisture value increases. This can be explained as the rate of spread in both models decreases as the humidity increases which makes the fuels burn more slowly. But as far as the temperature is concerned, there is an inverse correlation between the two models. 3FTS fire model basically calculates a higher rate of spread value for higher temperature values while FARSITE fire model decreases rate of spread as the temperature increases.

Temperature, wind speed and moisture are the constant parameters for the two models and they are applied homogeneously throughout the terrain to obtain a smooth elliptical fire spread. But the available fuel characteristics for two models are different so there is no exact same fuel type to use as an input for both models. Among 3FTS fuel types Czb1 was accepted to be similar to SH8 fuel type in FARSITE which is defined as high load, humid climate shrub. And for 3FTS's Dy (maquis) fuel type, SH5 and SH7 fuel types of FARSITE were accepted to have similar characteristics. Furthermore canopy cover, stand height and crown base height values were used as the same values for both models. For Czb1/SH8 fuel types stand height is 6.2 meters, canopy cover is %25 and crown base height is 1.2 meters. For Dy/SH5/SH7 fuel types stand height is 2 meters, canopy cover is %25 and crown base height is 1 meter. As it can be seen from the burnt area results fuel characteristics depend heavily on the statistical data gathered for the fire model and cause the difference of fire spread between the two models.

There is also a difference between the two fire models when handling of wind speed. In 3FTS open wind speed is used directly in the model calculations while in FARSITE mid flame speed is calculated from open wind speed which is assumed to be 10 metres above the ground. In FARSITE the mid flame wind speed is reduced from the open wind speed depending on the canopy information and fuel characteristics.

Fire model development is a continuous and complex task in an effort to get closer results to a real fire. To remove uncertainties more data should be gathered about fuel characteristics and real fire rate of spread values so that simulation inputs can be tuned to match actual results. 3FTS is currently being used for training purposes and provides a fire simulation for its trainees to carry out suppression activities. Further development goals for the 3FTS fire model include providing quick analysis to predict spread direction and speed of a real fire as an aid for real suppression activities. To accomplish this purpose more data from real fires must be gathered. This data is expected to be as detailed as possible including topographic and spatial conditions on the terrain and rate of spread results. Obviously this data can only be gathered observing the real fire and recording it. Also careful measurements at the time of fire for atmospheric conditions must be obtained.

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