FireStation - An integrated software system for the numerical simulation of fire spread on complex topography.

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Abstract

A software system aimed at the simulation of fire spread over complex topography is presented. The software implements a semi-empirical model for fire rate of spread, which takes as input local terrain slope, parameters describing fuel properties as well as the wind speed and direction. Fire shape is described with recourse to an ellipse-type model. Two different models are implemented for the simulation of the wind field. Both these models predict wind velocity and direction based on local observation taken at meteorological stations. The whole system was developed under a graphical interface, aiming at a better ease of use and output readability so as to facilitate its application under operational conditions. This work describes the mathematical models employed, provides an overview of the graphical interface and presents the results of some simulations tested against experimental data.

Keywords: Fire Simulation, Fuel Management, Fire Danger, Wind Simulation.

Name of the Software: FireStation

Hardware Requirements: laptop or desktop IBM-compatible PC, Pentium II or higher processor recommended, 64Mbytes of RAM minimum, VGA/SVGA color display.

Software Requirements: Microstation 95 or later. Microsoft Windows 95 or later.

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Software Availability: Contact the author for information.

Web page: http://adai.dem.uc.pt

1 - Introduction

Forest fires are a natural component of many ecosystems and are, thus, a necessary element in the complex chain for the maintenance of their delicate equilibrium. Nevertheless, forest fires may become a powerful source of destruction when the fire regime, fire frequency, size and severity, changes as the result of negligence and arson. Either from natural or human origin, the effects of large catastrophic forest fires can be devastating not only from the ecological standpoint but also from a socio-economic perspective. Large forest fires alter the availability of natural resources at a large scale with the consequent impact in the rural communities' lifestyle. The prediction of forest fire behavior is an essential component in land management at a landscape level in such fire adapted ecosystems, allowing a proactive fire management based on sound scientific principles, to mitigate fire hazard.

Forest fire prediction is a challenging task. The wide variety of primary physical phenomena affecting fire behavior makes it difficult to quantify the individual contribution from each factor. Furthermore, even possessing correct physical models, their application to real fire situations would always be subjected to errors due to limitations on the precision of the input data. This reasoning applies to vegetation characteristics, fuel moisture, wind field, etc. The estimation of some input parameters like fuel moisture and wind must be made with recourse to specific models for their calculation. This is, of course, another source of uncertainty introduced on the predictions. Bearing in mind the limitations pointed out, the results of such prediction tools should always be regarded as an estimate of reality, and be used according to that. From this reasoning it is expected that FireStation, or other systems, are most applicable to situations where the impact of possible errors is limited, such as training and fire management activities other than operational fire behavior prediction.

Over recent years, with the advances in computing speed, storage capacity and graphical capabilities, some fire prediction integrated systems have been developed. The different systems available differ in several aspects regarding the physical models implemented, the simulation technique, the intended use, etc. DYNAFIRE (Kalabokidis *et al.*, 1991) employs the BEHAVE fire prediction model (Rothermel, 1972, Andrews, 1986), using a grid-cell approach (*c.f.* section 2.3) for fire growth simulation.

FARSITE (Finney, 1998) is also based on the BEHAVE fire prediction model. It uses a wave propagation technique for fire growth simulation. FIREMAP (Ball and Guertin, 1991) conjugates the BEHAVE system with a cell-based approach for fire simulation. Unlike other simulation systems, EMBYR (Hargrove et al., 1993, cited by Albright and Meisner, 1999) is not designed to predict the hourly or daily behavior of a particular fire. Instead, it is a probabilistic model that attempts to predict potential burn patterns of large fires. A deeper discussion on the particular characteristics of the systems referred above may be found in Albright and Meisner (1999). Table 1, based on the review by these authors, synthesizes relevant information concerning sever systems, including FireStation.

According to the previous classification, FireStation fall in the BEHAVE coupled with the gridcell category. To the authors' knowledge, none of the previous systems incorporates any tool for wind field simulation, a feature that is available in FireStation and constitutes a major contribution for fire simulation quality.

An important issue when implementing models for operational use, is user friendliness. The interface

between the user and the models should be easy and intuitive. This applies not only to the input parameter specifications, but also to the display of results. In the present work, special care was put on this aspect. FireStation software was developed under the environment of the CAD application Microstation, from Bentley Company. The decision of developing the software within this environment was made on the grounds that Microstation provides a user-friendly interface and developing tools that proved to fulfill the needs for the development of the system. The underlying software was written in MDL, a specific C language of Microstation that has built-in subroutines for the design of window-based interfaces, generation of visualization elements in the 3D space, on top of the usual mathematical capabilities of the C language. The wind models are self-contained Fortran codes, which run as external programs.

The graphical environment of Microstation is three-dimensional. Thus the visualization process is allowed to employ, not only the normal top-view, but any other view perspectives as well, for map display and other visualization procedures. This is very important for interpretation purposes, since different visualization angles may provide a much clearer and correct interpretation of the data.

| Fire | Components | | Intended use | Input | | Output | Platform and |
|---|--|-----------------------------------|---|--|---|---|--|
| simulation system | Prediction model | Simulation technique | | GIS | Additional | | sontware |
| DYNAFIRE (Kalabokidis et al., 1991) | Physical- statistical (BEHAVE) | Cellular automation | To simulate the spread of low-to- moderate intensity surface fires | -Standard fuel types -Elevation -Slope -Aspect -Stream Network | -Temperature -Relative humidity -Fuel moisture -Windspeed -Wind direction | Maps of: -Fire perimeter -Fireline intensity -Average spread rate | -PC with MS- DOS and pMAP |
| EMBYR (Hargrove et al., 1995) | Probabilistic | Bond percolation | To simulate land- scape-scale burn patterns | -Vegetation classified by species and age | -Fuel moisture -Wind speed -Wind direction | Map of final burn pattern (50m resolution) | -UNIX workstation -FORTRAN compiler |
| FARSITE (Finney, 1998) | Physical- statistical (BEHAVE) | Elliptical wave propagation | To simulate the spread and behavior of wildland fire | -Standard/custom fuel types -Elevation -Slope -Aspect -Canopy cover | -Temperature -Relative humidity -Windspeed -Wind direction -Canopy characteristics | Maps of: -Fire Behavior -Fire perimeters (adjustable resolution) | -PC with Windows Operating System |
| FIREMAP (Ball and Guertin, 1992) | Physical- statistical (BEHAVE) | Cellular automation | To simulate the spread of low-to- moderate intensity surface fires | -Standard fuel types -Elevation -Slope -Aspect | -Temperature -Relative humidity -Fuel Moisture (optional) -Windspeed -Wind direction | Maps of: -Spread rate -Fireline intensity -Flame length -Heat/unit area -Reaction intensity -Fire perimeter | -UNIX workstation with PROMAP |
| WILDFIRE (Wallace, 1993) | Physical- statistical (FBP system) | Elliptical wave propagation | To simulate the spread of low-to- moderate intensity surface fires | -Standard fuel types -Elevation | -Wind Speed -Wind direction | Maps of: -Fire perimeters -Fire intensity (1m resolution) | -PC with MS- DOS |
| FireStation | Physical- statistical (BEHAVE) | Cellular automation | To simulate the spread of low-to- moderate intensity surface fires | -Standard/custom fuel types - Elevation | -Temperature -Relative humidity -Fuel moisture (optional) -Wind readings by meteo stations | Maps of: -Wind speed -Wind direction -Spread rate -Fireline intensity -Flame length -Heat/unit area -Reaction intensity -Fire perimeter -FWI indices | -PC with Windows Operating System -Microstation software |

Table. 1 – Comparison between different fire simulation systems (Albright and Meisner, 1999, except for FireStation data).

2 – The Mathematical Models

2.1 - Fire rate of spread

The fire behavior model is based on the Rothermel's surface fire spread model (Rothermel, 1972). The preference of such model to predict surface fire spread in one dimension within the system is based on the applicability of such model to any potential fuel complex throughout the world, such as logging slash (Brown 1972; Bevins and Martin 1978), grasslands (Sneeuwjagt and Frandsen 1977; Gould 1988; van Wilgen and Wills 1988) and shrublands (van Wilgen et al. 1985; Marsden-Smeley and Catchpole 1995; Cuinas et al. 1996, Cruz and Viegas 1998). In fact, other models are currently available, although with a more narrow range of applicability than the Rothermel's model. Empirically based models (e.g. Stocks 1987, Alexander et al. 1991, Fire Danger Group 1992, Van Wagner 1993, Marsden-Smeley and Catchpole 1995, Cheney et al. 1998, Fernandes et al. 2000) for fire spread have limited applicability to fuel complexes (and fire environment conditions) other than the original ones. Physically based models for fire spread (e.g. Albini 1985a,b, Albini 1996, Grishin 1997) have too high computation requirements to allow its use in software to support fire management decision-making. Besides that, most of these models have not been subjected to a thorough evaluation. For example, FARSITE and BEHAVEPLUS, software for fire behavior prediction used by the United States Forest Service (USFS), still rely on the Rothermel (1972) fire spread model. USFS fire researchers in conjunction with researchers from elsewhere are currently developing a fire-spread model to substitute the older Rothermel (1972) model (Andrews 1996, Catchpole et al. 1998). Major advances in forest fire behavior science since 1990 has been on characteristics other than surface fire spread, such as radiant heat fluxes from wildfires (Butler 1993), crown fire initiation (Alexander 1998), smoldering combustion (Frandsen 1991), crown fire spread (Albini 1996, Call and Albini 1997), residence times (Burrows 2001), and spotting distances (Albini 1999). These models, that are not required to predict surface fire spread, were not incorporated in the system because of the difficulty of estimating their input parameters in the field, the stochastic nature of the phenomena, and the high computation requirements.

Rothermel's model takes as input fire environment characteristics, *i.e.* fuel characteristics, wind speed and slope, and gives as output the surface fire spread rate along the main spread direction. This is a semiempirical model developed essentially from results obtained on a quite considerable amount of laboratorial experiments. This model has some limitations in what concerns the heat transmission mechanisms that are allowed. Thus, this model cannot predict fire spread occurring due to the projection of burning embers (spotting). The behavior of large fires (fires that modify in an appreciable way the surrounding environment), as well as crown fires, cannot be predicted.

The keystone of the model is eq. (1), which expresses an energy balance within a unit volume of the fuel ahead of the flame. It illustrates the concept that \vec{R} (the rate of spread) is the ratio between the rate of heating of the fuel and the energy required bringing that same fuel to ignition:

$$\vec{R} = \frac{I_r \pi \left(\vec{l} + \vec{\phi}_w + \vec{\phi}_s\right)}{\rho_b \epsilon Q_i}$$
(1)

where:

R - rate of spread [m/s].

 I_r - reaction intensity, i.e., heat release per unit area of the flame front $[J/(m^2s)]$.

 π - propagating flux ratio, i.e., fraction of heat release that is responsible for fuel heating and subsequent ignition.

 $\vec{\phi}_{w}$ - wind factor.

 $\vec{\phi}_{s}$ - slope factor.

 ρ_b - bulk density, *i.e.*, mass of fuel per unit volume [kg/m³]

 ε - effective heating number, *i.e.*, ratio between the bulk density and the mass of fuel involved in the ignition process.

Q_i - heat of pre-ignition, *i.e.*, heat required to bring a unit weight of fuel to ignition [J/kg].

All the quantities in eq. (1) are computed using fuel and environmental characteristics, as follows:

$$I_{r} = \Gamma' W_{n} h \eta_{m} \eta_{s} \qquad [W/m^{2}] \qquad (2)$$

$$\Gamma' = \Gamma'_{\max} \left(\frac{\beta}{\beta_{op}}\right)^{A} \exp\left(\frac{A(1-\beta)}{\beta_{op}}\right) \qquad [s^{-1}] \qquad (3)$$

$$\Gamma'_{\text{max}} = \frac{0.168\sigma^{1.5}}{\left(2941.6 + 0.01\sigma^{1.5}\right)} \qquad [s^{-1}] \qquad (4)$$

$$\beta_{\rm op} = 8.858\sigma^{-0.8189} \tag{5}$$

$$A = \frac{1}{4.24\sigma^{0.1} - 7.27} \tag{6}$$

$$\eta_{\rm m} = 1 - 2.59 \frac{M_{\rm f}}{M_{\rm x}} + 5.11 \left(\frac{M_{\rm f}}{M_{\rm x}}\right)^2 - 3.52 \left(\frac{M_{\rm f}}{M_{\rm x}}\right)^3 \tag{7}$$

$$\eta_{s} = 0.174 S_{e}^{-0.19}$$
(8)

$$\pi = (192 + 0.2595\sigma)^{-1} \exp\left[(0.79 + 0.68\sigma^{0.5}) (\beta + 0.1) \right]$$
(9)

$$\phi_{\rm w} = C U_{\rm m}^{\rm B} \left(\frac{\beta}{\beta_{\rm op}} \right)^{-\rm E} \tag{10}$$

$$C = 7.47 \exp\left(-0.069\sigma^{55}\right) \tag{11}$$

$$B = 0.01336\sigma^{0.54}$$
(12)

$$E = 0.715 \exp\left(-1.09 \times 10^{-4} \,\sigma\right) \tag{13}$$

$$\phi_{\rm s} = 5.275 \beta^{-0.0225} (tg\phi)^2 \tag{14}$$

$$W_n = \frac{W_0}{1 + S_t}$$
 [kg/m²] (15)

$$\rho_{b} = \frac{W_{0}}{\delta}$$
 [kg/m³] (16)

$$\varepsilon = \exp\left(-\frac{453}{\sigma}\right) \tag{17}$$

$$\beta = \frac{\rho_b}{\rho_p} \tag{18}$$

$$Q_{ig} = 581092 + 2594 \times 10^3 M_f$$
 [J/kg] (19)

Eq. (2) computes the reaction intensity, which quantifies the energy release rate per fire unit area. The fraction of this energy transmitted to the fuel in zero wind and slope conditions is the propagation factor π . The reaction intensity is computed as a function of the net fuel load (W_n , kg/m²), the reaction velocity (Γ' , s⁻¹) and fuel particles heat content (h, J/kg). Reaction velocity is the inverse of the time a fuel particle would take for complete combustion, with zero moisture and no mineral content. The effects of moisture and mineral content are introduced through the parameters η_m and η_s , respectively.

Most of fuel properties are supplied for different fuel size classes and dead-live classification. Since different size classes are allowed, most properties are averaged between size classes using the surface area to volume ratio as the weighting factor, as suggested by Rothermel (1972). Dead and live components are treated separately, each being used to compute its own reaction intensity. The final value for the reaction intensity is obtained as the sum of the corresponding values for dead and live fuels. Thus, in summary, the input parameters for the fire propagation model are:

Fuel load W₀ [kg/m³]
Fuel depth, δ [m]
Surface/volume ratio, σ [m⁻¹]
Fuel heat content, h [J/kg]
Fuel moisture content, M_f

Midflame height wind speed, U_m [m/s]

Terrain slope, $tg(\phi)$

2.2 - Fire shape

Rothermel's model gives as output the rate of spread along the maximum spread direction, but does not provide any information about fire size and shape. Nevertheless, simulation of fire growth needs a mathematical description of fire shape. The present system employs two different models: the one proposed by Anderson (1983) and the model by Alexander (1985). Both these models take as input the wind speed at mid flame height. The effect of topography is modelled through the addition of a fictitious wind speed that would produce the same effect upon fire rate of spread as the actual slope. This equivalent wind speed is obtained from eq. (10):

$$U_{eq} = \left[\frac{\phi_{s} \left(\beta / \beta_{op}\right)^{E}}{C}\right]^{\frac{1}{B}}$$
(20)

The "effective" wind speed is obtained through the vectorial summation of the wind speed and the equivalent wind speed:

$$\vec{U}_{tot} = \vec{U}_m + \vec{U}_{eq}$$
(21)

Both fire shape models consider that fuel characteristics do not affect the fire shape. The model proposed by Anderson (1983) defines fire shape as a double ellipse:



where U_{tot} is the given in m/s.

The dimensions of the double ellipse are relative to the length along the maximum spread direction, d. Several proposals are available for the length to breadth ratio of the single ellipse shape, as a function of the wind speed. Alexander (1985) makes a comprehensive review of the different proposals, some of which were developed for particular fuel conditions, spread regimes and/or wind speed range. The proposal of Alexander represents a good compromise to the available data. The geometrical parameters of the ellipse and wind speed are related as presented below. As compared to the single ellipse formulation, the double ellipse tends to predict lower flank fire spread rates, leading thus to a smaller burned area. The double-ellipse model is employed when the wind speed at midflame height is below 0.2 m/s, as the doubleellipse formulation doesn't cope with a zero-wind situation.



where U_{tot} is the given in m/s.

2.3 - Fire growth simulation

The local model for fire rate of spread, together with the global models for fire shape (single- and double-ellipse) defines the "physical" behavior of the fire. In terms of implementation, fire simulation may be carried out either as a vector-based process, applying the Huygens' principle (c.f. Richards 1990), or using a raster approximation. In the present case, the later option was adopted. The topography is divided into cells, over which fuel properties are assumed as constant. Fire growth simulation thus becomes a process of contagion between burning and non-burning cells, a process which is carried out in the following way: at a generic time instant, the time the fire takes to propagate from each burning cell to its (non-burning) neighbors is computed with the models previously described. The neighbors are thus assigned numbers which represent the shortest time instant at which 'ignition' would take place as a result of contagion from the already burning cells. The non-burning cell with the shortest time assigned thus becomes a burning cell. This process, which is based on the Dijkstra's dynamic programming algorithm, leads to a time progression which may not be constant, i.e., time may

step non-uniformly, following the contagion process (Kourtz and O'Regan, 1971).

The choice of the cells defined as neighbors plays an important role in terms of discretization errors. Figures (1) and (2) exemplify the case where 16 neighbors are defined and the difference between the ideal ellipse shape and the fire shape obtained from the contagion process. The shape obtained when the cell size tends to zero corresponds to a polygon whose vertices are located at the points of intersection of the propagation direction and the ideal ellipse. One may conclude that the raster approach tends to underpredict the fire area. This under-prediction decreases as the number of neighbor cells increases. The counterpart of increasing the number of neighbor cells is the negative effect of considering a contagion between cells more distant apart, which may lead to higher errors in the case that the terrain characteristics are not uniform in space.

Since the input parameters may vary from cell to cell (this includes fuel properties, wind and slope), the calculation of the rate of spread for the contagion process should be based on some kind of averaging procedure applied to each pair of cells. Although at first sight an arithmetic mean would appear attractive, this method would clearly produce misleading results if the tested cell would be incombustible. This was resolved in the present work by obtaining the 'conjugate' rate of spread through the application of an harmonic mean to the characteristic rate of spread associated to each cell, as follows:

$$R = \frac{2R_1R_2}{R_1 + R_2}$$
(22)

where R_1 and R_2 are the characteristic rate of spread associated to each cell and R is the resulting rate of spread. This process assures that the incombustible cell will not be ignited.



Fig. 1 - Arrangement for 16 neighbors, for contagion calculation.



Fig. 2 - Comparison between the 'ideal' and the calculated fire shape.

2.4 - The Fire Weather Index

Fire behavior predictions given by FireStation are aimed at support decision-making on forest and fire management activities at a local scale. Nevertheless, the system also incorporates a fire danger rating system applicable at a broader scale, namely at regional and national level. The fire danger rating system incorporates the Canadian Fire Weather Index (FWI) (Van Wagner and Picket 1985; Van Wagner 1987), which integrates weather and fuel parameters affecting fire potential. The system allows to (1) have a broad assessment of large-scale fire potential through the evaluation of the daily and spatial variation of the fire danger index and (2) estimate the moisture content of dead and live fine fuels through empirical relationships.

The FWI takes into account the cumulative effect of site-specific daily weather conditions that are related to forest fire occurrence and spread. The inputs are:

- noon air temperature [°C]
- noon air relative humidity [%]
- rain fall in the open [mm]
- noon wind velocity $\left[\text{m/s}\right]$

The output of the FWI System consists of three sub-indexes representing fuel moisture and three indexes that give information on various aspects of potential fire behavior. The system is based on field data and physical reasoning. The description of the mathematical structure of the system is beyond the scope of this paper and will not be presented here. A brief description of the sub-indexes and indexes is given below (Stocks *et al.* 1989):

- Fine Fuel Moisture Code (FFMC): is a numerical rating of the moisture content of fine litter. It is an indicator of the easiness of ignition and fire spread rate.

- Duff Moisture Code (DMC): is a numerical rating of the moisture content loosely compacted forest floor organic layers of moderate depth. It is an indicator of duff and medium size fuels consumption.

- Drought Code (DC): this sub-index is an indicator of deep and compacted forest floor organic layers. It is also related to the moisture content of live under story vegetation (*cf.* Viegas *et al.* 1998). It is an indicator of mop-up difficulty and deep organic layer fuel consumption

- Initial Spread Index (ISI): this index combines the FFMC and wind intensity to give a rating of fire spread velocity.

- Build-Up Index (BUI): this index combines the DMC and DC to estimate the total amount of fuel available for combustion.

- Fire Weather Index (FWI): this index is the final component of the system and combines the ISI and BUI to give a numerical rating of the potential frontal fire intensity. This information is used on the determination and allocation of fire suppression resources needed at a given place and at given moment.

2.5 – Wind field simulation

Wind is probably the single most important input parameter for fire-spread calculation. For the case of forest fires, one is primarily interested in the knowledge of the wind speed and direction at a distance to the ground equivalent to approximately midflame height. At this vertical level, wind is influenced both by topography and by vegetation. Large-scale effects (e.g. Coriolis forces) may be neglected, since their role at such small scales is negligible.

Wind field, as a fluid dynamics situation, is governed both by the continuity equation (mass conservation) and the Navier-Stokes equations, which describe the momentum conservation:

Continuity:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0$$
(23)

Momentum conservation:

$$\frac{\partial}{\partial x_{i}} \left(\rho u_{i} u_{j} \right) = -\frac{\partial P}{\partial x_{i}} + \frac{\partial}{\partial x_{i}} \left[\Gamma \left(2 \frac{\partial u_{i}}{\partial x_{i}} - \frac{2}{3} \operatorname{div} \vec{V} \right) \right] + \frac{\partial}{\partial x_{j}} \left[\Gamma \left(\frac{\partial u_{i}}{\partial x_{j}} + \frac{\partial u_{j}}{\partial x_{i}} \right) \right] - \frac{2}{3} \frac{\partial (\rho k)}{\partial x_{i}}$$
(24)

For practical applications such as an operational fire prediction tool for real time fire fighting planning, it is important to have computational times that allow a real time prediction. This means that such a potentially lengthy calculation procedure such as the solution of the complete set of Navier-Stokes equations is not possible under such conditions. On the other side, if one intends to test different fire scenarios for planning purposes, time is not such an important matter and longer calculations do not pose a problem. Bearing this in mind, FireStation implements two different wind models: NUATMOS, a linear model and CANYON, a Navier-Stokes solver. These models will be described next.

2.5.1 – The model NUATMOS

If one needs expedite calculations of wind over complex topography, the original set of equations (23, 24) and their solution must be somehow simplified. One possible approach is to consider analytical models, such as the one proposed by Taylor et al. (1985). This types of models is, nevertheless, limited to idealized terrain features and, thus, encounter little application for practical situations. Mass-consistent models (or kinematic models) represent another type of approach, where the continuity equation is solved numerically on a 3D grid. These models do not satisfy the momentum conservation requirements, and possess, consequently, some limitations: buoyancy and separation phenomena cannot be simulated and their range of applicability is limited to relatively smooth topography. In spite of these limitations, the solutions given by these models are in most cases quite realistic, with the inherent advantage that the code is very low time consuming and very stable from the numerical point of view.

FireStation implements NUATMOS, a model developed by Ross *et al.* (1988). NUATMOS takes as input the values of wind speed and direction measured at discrete points in space. As a first step towards the solution, an initial velocity field is computed by simply interpolating and extrapolating velocity values into all grid points of the area under study. This initial velocity field is then adjusted following a method of variational analysis. The minimization function employed attempts to reach a divergence free flow field, so as to satisfy the mass conservation principle. This adjustment is subjected to the restriction that the final wind field should be as close as possible to the initially interpolated wind field.

The precision of the predictions given by this model will be increased by using a larger number of wind observations in the area of interest. Another parameter that should be taken into account is the atmospheric stability. This is a measure of the damping or enhancement of the vertical component of air motion, as a result of the variation of temperature with height. In fact, the wind pattern over complex topography may be considerably affected by this parameter, with stability enhancing the influence of topography on the wind field. Although, from the physical point of view, momentum equations should be solved to take into account stability, within NUATMOS this behavior is simulated by adjusting the maximum allowed value for the vertical component of the velocity, with respect to the horizontal components.

2.5.2 – The model CANYON

CANYON is a 3D Navier-Stokes solver written for a 3D generalized coordinate system (Lopes *et al.*, 1995). It employs a control volume approach for the integration of the transport equations. The SIMPLEC algorithm (van Doormaal and Raightby, 1984) is employed as a means for the segregated solution of the primitive Cartesian velocity components (u, v, w) and pressure. Turbulence effects on the mean flow field are modelled with recourse to the standard k- ε turbulence model (Launder and Spalding, 1974), whose equations are presented below.

$$\frac{\partial}{\partial x_{i}} \left(\rho u_{i} k \right) = \frac{\partial}{\partial x_{i}} \left[\left(\mu + \frac{\mu_{t}}{\sigma_{k}} \right) \frac{\partial k}{\partial x_{i}} \right] + P_{1} + G - \rho \epsilon \quad (25)$$

$$\frac{\partial}{\partial x_{i}}(\rho u_{i}\varepsilon) = \frac{\partial}{\partial x_{i}} \left[\left(\mu + \frac{\mu_{t}}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon}{\partial x_{i}} \right] + \frac{\varepsilon}{k} \left(C_{1}(P_{1} + C_{3}G) - C_{2}\rho \varepsilon \right)$$
(26)

$$P_{1} = -\overline{\rho u_{i}^{'} u_{j}^{'}} \frac{\partial u_{i}}{\partial x_{j}}$$
(27a)

$$G = -\beta g \frac{\mu_t}{\sigma_t} \frac{\partial T}{\partial z}$$
(27b)

$$\mu_{t} = C_{\mu} \frac{\rho k^{2}}{\epsilon}$$
(27c)

$$C_{\mu} = 0.033; C_1 = 1.45; C_2 = 1.9; C_3 = \tanh \left| \frac{w}{u} \right|;$$
 (27d)
 $\sigma_k = 1; \sigma_s = 1.3$

The effects of terrain roughness (or vegetation effects) are modeled by assigning a variation of velocity near the ground according to the logarithmic law:

$$\frac{u(z)}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z}{z_0} \right)$$
(28)

where κ is the von Karman constant (0.41), z_0 is the roughness parameter (proportional to the physical vegetation height) and u_* is the friction velocity, which is computed as a function of the shear stress τ_w :

$$u_* = \sqrt{\frac{\tau_w}{\rho}}$$
(29)

The momentum transfer near the ground (shear stress) is thus computed as follows:

$$\tau_{\rm w} = \rho \left[\frac{0.41 u_1}{\ln \left(29.7 z_1 / h_r \right)} \right]$$
(30)

where the subscript 1 indicates the value computed at the closest node to the ground and h_r is the physical average height of the vegetation.

Although CANYON may take into account thermal effects (Lopes *et al.* 1995), these are not usually taken into account when wind is used as input for the fire propagation model. The justification lies in the fact that the fire spread equations take as input the unperturbed wind velocity at midflame height. This issue is, nevertheless, still in open discussion and it is a fact that larger fires affect wind field in such a manner that thermal effects should, in any form, be taken into account in wind field calculations.

2.5.3 – Calculation of wind speed at midflame height

The calculation of the wind speed at midflame height is performed using the method proposed by Albini and Baughman (1979). This consists in performing an integration of the logarithmic law between the vegetation top and the flame height, and assigning this mean velocity as input for the fire spread model:

$$\frac{u_{av}}{u_{1}} = \frac{1 + 0.36(h_{r} / h_{f})}{\ln\left(\frac{z_{1} + 0.36h_{r}}{0.13h_{r}}\right)} \left[\ln\left(\frac{h_{f} / h_{r} + 0.36}{0.13} - 1\right)\right]$$
(31)

where h_f is the flame height and u_{av} is the average value for wind speed at midflame height.

3 – FireStation and its Interface

3.1 - General Organization

The FireStation system for decision support is made up of three modules that are interdependent relatively to the flow of information. The hierarchical organization is the following:

- 1. Wind Speed Module
- 2. Fire Danger Rating Module.
- 3. Fire Spread Module

Although the first two modules are independent, their output being valuable information for itself, they also serve as a source of input data for the fire propagation module.

The general organization of the different functional features of FireStation may be better perceived through the flowchart presented next. These are the titles of the different options available in the pull-down menus accessible from the FireStation main menu. Functionalities available inside in the Dialog Boxes are not shown



3.2 - User Interface

In this section, the main Dialog-Boxes of FireStation are presented.

A shortcut to some FireStation functions is available to the user on the Tool Box represented at right. It allows the user to quickly access some features such as the display of the wind field, representation of the meteorological stations, display of the topography, vegetation mapping, simulation of ignition locations, etc. Additionally, the user may take profit of different visualization features of Microstation for rotating views, making zooms and store information in different view levels.



3.2.1 - Wind Speed Calculation

Wind speed calculations are performed in a threedimensional grid. FireStation is able to automatically generate the required grid based on the terrain description given in a standard GIS format. Fig. 3 depicts the Dialog Box used for generating grids for NUATMOS and CANYON models.

For both wind models, input for the meteorological stations is performed in the Dialog Box of Fig. 4. The transient data section allows the user to define a set of meteorological readings spaced in time. With this data, wind field calculation may be updated as fire simulation progresses in time, according to the new information available.

| ZDTM 🗵 | 1 |
|---|---|
| Files | |
| height (m) 3199 dzinit (m) 10.0 nnodes 24 | |
| Aux Data | |
| hmin: 0 | |
| hmax: 1199 | |
| Recom.h 3199 | |
| Recom.nn: 24 | |
| ni: 105 | |
| ni: 77 | |
| grid (m): 100 | |

Fig. 3 - Dialog Box for grid generation.

Both wind models run as external DOS applications that are called from inside Microstation. The model NUATMOS, due to its simplified character, runs in a quite short period of time. For a grid of 50x50 nodes with 15 vertical levels, a solution is obtained with 30 sec. of run time, in a PC Pentium II 350 Mhz. A similar run for the model CANYON takes 5 min. of run time. The graphical representation of the wind field is made with vectors which size is proportional to the wind speed. Coloring schemes and proportionality factors are controlled by the user.



Fig. 4 - Dialog Box for definition of wind data.

3.2.2 – Fire Weather Index

A set of meteorological stations is defined for the calculation of the different components of the FWI System. In this set of stations, in addition to the wind speed, information on air temperature, humidity, and rainfall amount is also needed. The Dialog Box where this information is specified may be observed in Fig. 5. This Dialog Box also displays, for each station, the different parameters computed by the Canadian System. The spatial distribution of the different indexes may then be mapped on the physical space. The value in each location is obtained from the value calculated at each station, applying a weighted average based on the inverse of the distance.



Fig. 5 - Dialog Box for the calculation of the FWI indexes.

3.2.3 – Fire Spread Calculation

The main input for this module is a file containing the x,y,z coordinates of the terrain, defined in a uniformly spaced grid. Additionally, this file stores, for each node, a number identifying the corresponding fuel type. Optionally, this information may be imported from GIS (Geographical Information System) common formats, generated by Arc/View or Idrisi software. Vegetation mapping may be defined inside Microstation as well, using specific tools for that purpose (cf. Fig 6). The characteristics of each fuel type, which are input parameters for the fire rate of spread calculation, are defined in the Dialog Box represented in Fig. 7. Optionally, the fuels moisture may be defined in this Dialog Box, in percentage for each fuel type and different particle dimensions. Particles dimensions are specified in terms of the time the fuel takes to reach 63% of the final equilibrium moisture, when subjected to new ambient moisture (1 h, 10 h and 100h). As previously referred, alternatively, the Canadian System (FWI) may be used for obtaining the spatial distribution of fuel moisture.



Fig. 6 – Dialog Box for the vegetation mapping.

| 8Fuels - Definition | × | | | | | |
|--|---------------------------|--|--|--|--|--|
| Name PPIN-3 | | | | | | |
| - Fuel Load [kg/m2] Dead | Extinction Moisture [%] % | | | | | |
| | Fuel Height (m) | | | | | |
| | | | | | | |
| Heat Content [kJ/kg] Dead | Surface/Volume [1/cm] | | | | | |
| Live 22261 | Live 55 4 - | | | | | |
| ft. lenght [m] 4.000 Color 14 Fuel Moisture [%] 1 h 10 10 h 12 100 h 14 Live 70 Cancel | | | | | | |

Fig. 7 - Dialog Box for the input of fuel properties.



The specification of the fire ignition is done with recourse to the Tool Box represented at left. Ignition may be defined as a single point, a line or a closed area. Other information concerning fire ignition and spread is displayed in the

Dialog Box depicted in Fig. 8. Here, geo-referenced information is available, such as UTM coordinates, local slope and altitude, and burned area in [ha].

| 😤 Fire Simulation 🛛 🛛 🛛 | | | | | | | |
|------------------------------|--------------------------|---------------|--|--|--|--|--|
| File Graphs | Defs | | | | | | |
| Colors Several Fire Growth | | | | | | | |
| dt(min) 30 | Time | Time 0h:18m | | | | | |
| | Area [ł | Area [ha]: 75 | | | | | |
| 🔲 Wind | | | | | | | |
| 🔲 Actual. | Utmx: 553918 | z [m]: 250 | | | | | |
| | Utmy: 4454226 | Slope 0 | | | | | |
| Reset | Reset Review Colors Time | | | | | | |
| Close | Mem. | Кеу | | | | | |

Fig. 8 - Dialog Box for the fire spread simulation.

Among other features, the user may define firebreak lines, which represent regions were the fire couldn't propagate. This is a valuable tool for fire fighting and prevention planning purposes, since this allows the user to plan the best strategy for fire suppression or prevention purposes. scale, fire management planning at local scale, operational fire fighting strategic planning and training, and national level fire-fighting resource allocation. Within the scope of the description of the system for the present work, four different examples of application of the system were selected for demonstration:

(1) wind field simulation

(2) wildfire simulation with comparison with real data

(3) support of fuel management decision based on critical fire weather scenarios

(4) large area fire danger based planning.

4.1 – Wind field simulation

The results shown are purely illustrative of how the wind field is affected by the topography and how the differences between both models are reflected in the results obtained.

The region of concern is located in central Portugal, in the Lousã mountain range.

Figures 9 and 10 show the wind vectors computed at an height of 10 m above the ground, for a grid size of 150 m. The topography is depicted using colors which depend on the local altitude. The perspective views help the reader visualize the topography. A careful examination of these figures shows how the wind vectors obtained from the model CANYON are more influenced by the topography, especially in the lee side of the hills, as compared to the NUATMOS results. In some locations, recirculation regions were predicted by CANYON. Nevertheless, it may be observed that the NUATMOS results are, from the physical point of view, quite realistic. A quantitative assessment of the models performance is out of the scope of the present publication and will be addressed in a future work.



Fig. 9 - Wind field obtained with the model NUATMOS.

4 – Application of FireStation

The output of the FireStation software has a broad range of possible applications from site specific fire effects on soil and plants, hydrology at a drainage



Fig. 10 - Wind field obtained with the model CANYON.

4.2 – Wildfire Situation

For the evaluation of the fire behavior predictions of FireStation under a wild fire situation, the output was compared with a well-documented wildfire. The Seia Wildfire was ignited by arson at 11:25 of 28 August 1996 near Seia, Central Portugal. The fire burned with an active flame front for six hours. The fire growth and behavior for the six hours was reconstructed and documented through a combination of onsite fire behavior documentation and interviews with fire fighters. Weather data (wind, temperature and relative humidity) were collected at a nearby weather station (4 km away). Live fuel moisture samples were collected on site at the time of the fire. Dead fuel moisture values were estimated through models (Rothermel et al. 1986). A fuel map of the area was made through aerial-photo interpretation and post-fire ground thruthing.



Fig. 11 - Screenshot of FireStation software after fire growth simulation. The main view depicts the fuel map with the simulated fire intensity and fire contours under no suppression situation for Seia wildfire. The vectors represent the wind field, the length being proportional to the windspeed. Figure 11 represents a screenshot of the software with predicted 30 min. fire contours and frontal fire intensity for a 3 hour burning period (not considering suppression actions). This information, together with the wind vectors for the final hour are represented over the fuel map. This information would allow the identification of hazardous areas for fire fighting, fire time of arrival at different locations, potential damage to urban structures and forest stands. The analysis of the simulation results would support decision making on strategic planning of fire fighting operations taking into account the safety of fire fighters and population, and optimal areas for effective fire control operations.

Figure 12 shows the final actual perimeter of Seia wildfire and the predicted 30 min. interval fire contours after six hours of fire spread. In this case the simulation took into account suppression actions by aerial and ground fire-fighting resources. Although no exact statistical analysis was made for comparison of the predicted versus the actual situation, the comparison of the predicted and actual final fire perimeter shows acceptable agreement. It should be noted that under an actual fire situation, the fire behavior analyst would have difficulty to gather such high quality input data as the one used in this example. Much of the input data would need to be estimated through models, which could decrease the agreement between predicted and actual fire behavior.



Fig. 12 - Final perimeter for Seia wildfire (brown line) and predicted fire contours (black lines) and suppression areas (blue line).

4.3 – Fuel management

Fuel management is a fundamental component of any proactive fire management program, in which forest fuels are modified to mitigate fire hazard at a broad scale. The use of fire growth simulators such as FireStation is of great utility for the planning of fuel management activities. Traditionally, the spatial definition of areas to be subjected to fuel treatments is based on empirical knowledge of the area by land managers, and the priorities identified by those managers. The use of a system such as FireStation allows the identification of areas to be treated based on a predefined set of rules (e.g. area and land planning constrains, silvicultural needs, fuel treatment method) and potential fire behavior under critical fire weather conditions.

Using the same study area as for the wildfire analysis case, priority areas for fuel treatment can be identified after running a series of potential fires burning under extreme fire weather conditions (high intensity wind speeds and low fuel moisture contents) and with random ignition points.

Figure 13 shows the fire intensity and fire perimeter 1.5 hours after ignition with 30 minutes fire contours. From the simulation, it is seem that the fire would threaten the urban areas shortly after ignition with the consequent risk of structure loss due to the high fire frontal intensity near the houses. The fast rates of spread would possibly signify that the fire would reach the structures before any fire fighting resources had the time to reach the area. Based on the simulation results, several areas were selected for fuel management.



Fig. 13 - Simulation for Seia wildfire case study area under worst case fire weather conditions scenario. Black lines are fire contours at 30 min. intervals. Purple areas in map are urban areas and vectors depict wind direction and intensity.



Fig. 14 - Simulation for Seia wildfire case study area after fuel treatment for the worst case in terms of fire weather conditions. Brown areas are areas of fuel conversion. Black lines are fire contours at 30 min intervals. Purple areas in map are urban areas and vectors depict wind direction and intensity

Figure 14 shows the fire growth simulation for the treated landscape under the same fire weather scenario and ignition point. The simulation results show the utility of the system on planning fuel management treatments. The strategic layout of the fuel conversion areas reduced the areas under extreme fire intensity (red color in Figure 13 and 14), and increased the areas burning under low intensity flame fronts which would allow effective fire suppression.

4.4 – Large area fire danger rating

FireStation software can also be used for largescale fire danger rating through the calculation of FWI indexes (Van Wagner 1987) and their mapping on the landscape. The analysis of the temporal variation of the spatial distribution of the indexes allows the identification of temporal and spatial patterns of variation on fire danger at regional and national levels.

The file export capabilities of the system, namely ASCII and Arc/View format, allows the information to be disseminated through a internet server and be available for quick viewing and query by local fire managers. Figure 15 gives an output image of the FWI index spatial distribution over Portugal for July 3, 2000. The main weather stations of the Portuguese Institute of Meteorology are displayed on the map. The red dot identifies the weather stations used in the present calculation. The various colors indicate different fire severity potential. The analysis of the FWI distribution would support decision-making concerning restrictions to forest and agricultural related fire activities in areas of high to extreme fire danger and transfer of fire-fighting resources from low/moderate to high/extreme fire danger areas.



Fig. 15 - Spatial distribution of fire danger over Portugal. Dots indicate weather stations. Fire danger scale is: Light blue – low; Blue – moderate; Green – high; Red – extreme.

5 – Conclusions

FireStation was developed as a decision support application for various fire management related issues. In the present work, FireStation was evaluated through the analysis of its outputs for specific tasks: (1) wildfire simulation; (2) support of fuel management decision, and (3) large area fire danger based planning. Although the system capabilities were not subjected to a thorough analysis, the cases examined showed the utility of the system in supporting decision making in those situations. The system made realistic simulations of the wildfire growth that could be used in planning fire suppression operations. The use of FireStation in supporting fuel management decisions allowed the definition of critical areas subjected to potential extreme fire behavior, and in that way the optimization of resource/treatment allocation in a given area. The use of the system for the analysis of fire danger indexes at a broad spatial scale was illustrated and discussed although no formal evaluation of the interpolation algorithm was made.

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