FIRE MODELING IN FOREST FIRE MANAGEMENT

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Abstract:

Models are helpful tools for scientists and engineers. Fire modeling is used to understand and to predict possible fire behavior without getting burned. Fire models are used in different aspects of fire management: a) before fire, for risk factor calculation and this would help fire fighters to focus on area with higher risk and develop better infrastructure, b) before fire for fire fighter training purposes and developing a scenario for training, c) during fire, for planning fire fighting strategies and this would help fire crews position equipment on the ground so that they can minimize damage and stay safe. There is a need to model fire in ground, crown, and surface fuel.

Existing models used for fire modeling are usually classified into: empirical models which are based primary on statistics collected by observation of experimental or historical fires, physical models based on physical principles of fluid dynamic and laws of conservation of energy and mass and semi empirical models based on physical laws, but enhanced with some empirical factors.

The paper will present and explain different forest fires models, giving a short technique for deciding which model is best for particular application, too.

This work on forest fire modeling is a part of more complex integral project of forest fire protection in Split and Dalmatia County. The integral forest fire protection system will be based on information system for integration all activities connected with early fire detection by 24 hours video and micro locations meteorological monitoring, management of forest fire fighting and post-fire recuperation of burned landscape. The module for the forest fire spread modeling is one of its modules.

1. Introduction

Fire is present on earth all since the lightning hit the tree and ignites it, and we can be sure it will be presented here for many more years. It causes natural fear in every living being on earth, only humans are ones who found the way to control it and use it in a way to raise the quality of life on earth. Anyway even humans can't control it in every situation so sometimes it happens that the fire gets out of control and causes large damages.

Why do we use models? People, in general, use models to imitate and to understand the world around us. The process of modeling is very similar to process of human thinking; we create an image of the world which acts in the same way as a real world. Models are useful for planning future acts and to communicate with our environment other people and they are classified into mental, material and symbolic ones. Symbolic models can be either of mathematical, structural or computer type. Scientist use symbolic models for making deduction about something they can't measure based on some measurable parameters.

In a forest fire management system we use computer model of fire to understand how fast would it move and to predict what area would it combust before fire occurs. Results can be used for training, planning of fire protection strategies, or planning of fire fighting, [1],[2],[4].

Model is an approximation of the real world, but necessary good enough approximation. The process of building model is an art, it can't be automated, and it requires certain skills, such as: knowing the lows of physics, economics, sound sense, abstraction and systematization skills and experience of a person or team. Building of a model starts with defining the goal of the model. This includes scope of the model, input parameters, which physical processes will be taken into account, and which physical models will be ignored, which output parameters would we need, and sometimes test scenario with desired outputs. For spatial processes modeling use of Geographical Information system (GIS) is very useful.

2. Basic principles of forest fire spread

Fire propagation can be observed as the progressive modification in time of the status of all fuel cells distributed in space, [4],[5],[8]. Fuel is the matter subject to combustion and, in this case, is limited to vegetal particles either live or dead, and generally it is addressed as forest fuel.

The pass from one to next status is a process which entails the production, transfer and absorption of heat progressively, and each of these processes depend on the environment and fuel conditions of every point. Hence, looking at the basic scheme of forest fire propagation (Figure 1), there exist three basic processes subject to modeling:
- Production of heat by heat sources, mainly due to combustion of unburned material
- Heat transfer from heat sources (fire) to heat sinks
- Absorption of heat by heat sinks (fuel ahead, surrounding atmosphere, soil etc.)

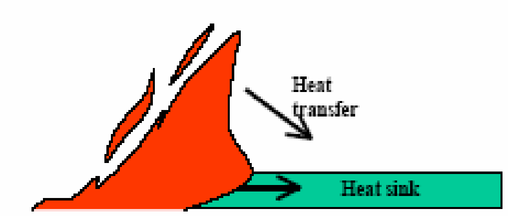

Figure1. Basic scheme of fire propagation

2.1. How fire spreads?

Ones a part of land is burning, combustion of fuel produces heat, which is a form of energy. Heat is transferred to nearby particles, and if conditions are right, the energy is used first for evaporation of particle and then for ignition of it. Spread of fire in landscape depends on *fuel characteristics, meteorological conditions and topography of the land.*

Fuel characteristics:

Forest fuel is the source of heat, heat sink, and in some cases mean of transportation for the heat. It is responsible for ignition, spread and consolidation of crown fire. Forest fuel is made of small particles of different size, live and dead. Forest fuel formations are compound out of different particle sizes of alive and dead vegetal matter, arranged in complexes which include: **duff**, present in ground fires, **litter**, frequently associated to presence of trees, **slash**, as result of natural decay of twigs and branches, **grass**, **shrubs** and **trees** (crowns), governing crown fires.

Parameters of forest fuels:

The weight of fuel that can participate in combustion is called **fuel load**. **Particle size and proportion** has a direct effect on fire behavior and smaller particles have a larger surface for the same volume, and can accept more moisture. **Heat content** is the amount of heat that can be produced as a result of combustion. **Surface to volume ratio** is directly related to particle size. Fuel components with high surface to volume ration are more prone to initiate and propagate the fire, have a quicker response to relative humidity changes, so particles divided finely are the most important ones in defining ignition probability and fire spread rate. The parameter called **packing ratio** expresses the amount of actual fuel present in bulk volume (bulk means the total volume, including air, measured as bulk density). Packed fuels even if they have a large surface to volume ratio, offer less permeability to air and gases transport and acts as a thicker heat sink **Mineral content, waxes and oils** are parameters too.

Meteorological conditions:

Meteorological conditions accounts for more then 90% of forest fire behavior. Fuel dryness is strongly related to its flammability and combustibility, and consequently to fire occurrence and behavior (Viegas et al. 1991), and wind plays a generally recognized key role during the flame front propagation (Rothermel 1972).

Topography of the land:

The presence of topography affects the way a fire is initiated and propagated. Topography affects fire spread by slope steepness. Fire is more likely to spread uphill then downhill. Also the slope and aspect of terrain causes different amounts of insolation of fuel. Fuel affected by sun contents less moisture and is more likely to burn. Most of presented fire models have these factors as input parameters of the model.

3. Wildfire modeling

Numerous fire spread models have been proposed following several methods that can be grouped into

- Empirical (or statistical),
- Semi-empirical (semi-physical or laboratory models),
- Physical (theoretical or analytical).

as shown in Figure 2.

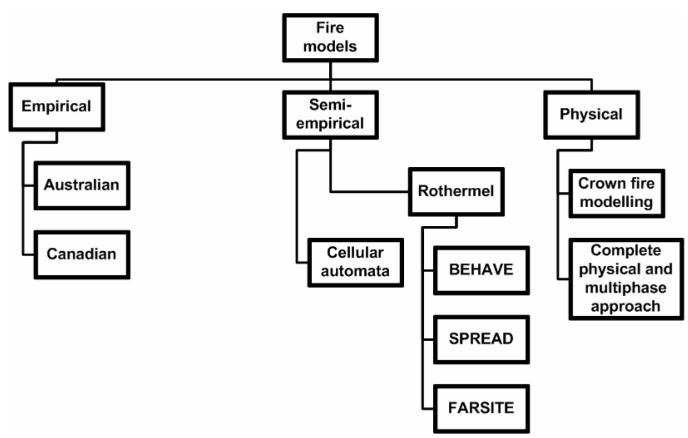

Figure 2. Classification of forest fire models

3.1. Empirical models

Statistical, stochastic, also called empirical models are predicting more probable fire behavior from average conditions and accumulating acknowledges obtained from laboratory and outdoor experimental fire, or historical fires. There are two empirical models widely in use, Australian and Canadian. In Australia, the most widely used model is *McArthur's* model for grassland fires and forest fire. These model make no attempt to include any physical mechanisms for fire spread; it is purely statistical description of test fires of such spread. The model is tested in dry regions of South Eastern Australia. Canadian Forest Service has integrated 25 years of researching experimental and real scenario fires to develop *Canadian Forest Fire Behavior Prediction System* which is now available in book and electronic form. It consists of 89 formulae developed empirically and it is usually presented in tabular form.

We can expect the prediction of the model to be quite accurate if our study area is reasonably represented by one of the choices available.

3.2. Semi-empirical models

Semi-empirical models are based on a global energy balance (Frandensen 1971) and on the assumption that the energy transferred to the unburned fuel is proportional to the energy released by the combustion of the fuel. Several terms of the model must be fitted from laboratory fire experimental results (Rothermel 1972). The simplicity of this approach has allowed developing operational tools.

Rothermel model

The model most widely used in United States is named after R.C. Rothermel who provided the equation (1) for calculating rate of fire spread, ROS and (2) for fire intensity, I_b.

$$ROS = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \in Q_{ig}} \qquad (1)$$

where:
ROS = heading fire steady state spread rate (m min^{-1})
I_R = reaction intensity (kJ min^{-1} m^{-2})
ξ = the propagating flux ratio
ρ_b = ovendry bulk density, kg m^{-3}
ε = effective heating number, dimensionless
Q_{ig} = heat of pre-ignition, kJ kg^{-1}

$$I_b = hw\frac{R}{60} \qquad (2)$$

where:

Ib = fire line intensity and describes the rate of energy release per unit length of the fire front (kWm^{-1})
h = heat yield of the fuel (kJ kg–1), total heat less the energy required for vaporizing moisture)
w = the weight of the fuel per unit area (kg m–2) burned in the flaming front
$R/60$ is fire spread rate converted to units of (m s–1).

Rothermel's model is the basis for many systems in the U.S. including the BEHAVE fire behavior prediction system, the FARSITE fire area simulator, the National Fire Danger Rating System (NFDRS), the National Fire Management Analysis System (NFMAS) for economic planning (Lundgren *et al.* 1995), the RERAP Rare Event Risk Assessment Process (Wiitala and Carlton 1994), and many more. In BEHAVE and *FARSITE* intensity is calculated as (3).

$$I_b = \frac{I_R}{60} \cdot \frac{12.6R}{\sigma} \qquad (3)$$

where σ is the characteristic surface area to volume ratio of the fuel bed (m^{-1}).

The equation is developed governing the energy balance equation and fitting some parameters to laboratory results.

BEHAVE is a system for fire behavior prediction and fuel management presented by P.L. Andrews. It creates tables of fire behavior in conditions given by user. It consists of subroutines for fire behavior prediction, for prescribed fire planning and for fuel modeling. Main withdraw is the representation of results in the form of table, when graphical visualization is more appropriate. BehavePlus is the next generation of Behave, [8]

SPREAD is a computer code intended to simulate surface forest fire behavior in heterogeneous terrain. It computes the burned area shape and evolution, as well as local results on rate of spread, flame length, fire line intensity, reaction intensity, and local times of beginning and end of propagation. SPREAD is based on FIRE1 from BEHAVE, and uses cellular automata to extend the use of FIRE1 to heterogeneous terrain and heterogeneous meteorological conditions. SPREAD was tested in homogenous and heterogeneous conditions and it is a promising tool to analyze surface forest fire propagation. The equations used in SPREAD were implemented as a part of GRASS GIS, the biggest open source GIS system.

CELLULAR AUTOMATA MODEL is the most common approach to simulate fire growth as a discrete process of ignitions across a regularly spaced landscape grid. The cellular automata model of forest fire consists of a 2D rectangular matrix representing landscape. Every cell is considered to have homogenous conditions. Fire spread is represented as transition of fire from one burning cell to eight neighboring cells or nodes on a rectangular grid. Theory of percolation is used for calculating probabilities of transition.

FARSITE is a fire growth simulation model. It uses spatial information on topography and fuels along with weather and wind files. It incorporates the existing models for surface fire, crown fire, spotting, post-frontal combustion, and fire acceleration into a 2-dimensional fire growth model. Farsite uses Rothermel's equation for calculation of local rate of fire spread and Huygens' principle for modeling the shape of fire front. Huygens' principle is named for the 17th century Dutch mathematician Christian Huygens who proposed it for describing the travel of light waves. FARSITE simulates fire growth as a spreading elliptical wave, as shown in Figure 3. The fire is propagated over a finite time step using points that define the fire front as independent sources of small elliptical wavelets. These small ellipses can be thought of as forming an envelope around the original perimeter, the outer edge representing the new fire front.

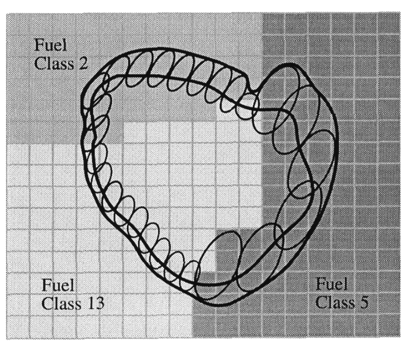

Figure 3. Huygens principle

There is also simplified version of FARSITE called FlamMap available from the same author (Finney). FlamMap does not track fire behavior over time (e.g., spread), but, instead, presents fire behavior under a fixed set of weather conditions, and produces outputs that assume the entire landscape is burning. [1]

3.3.Physical models

Models based on physical principles, have the potential to accurately predict the parameters of interest over a broader range of input variables than empirically based models. Physics based models can also provide the basic information needed for proper description of physical processes (i.e., fluid flow, heat transfer, and chemical kinetics). But physics-based models imply that the developer has an adequate understanding of the underlying physical relations sufficient to achieve the desired objectives, that the underlying physics can be represented mathematically in a manner that permits numerical solution. Improved models are needed for increased accuracy in fire behavior prediction, fire danger rating calculations, and fuel hazard assessment. Models with goal to predict 3-dimensional fire shapes are often referred to as crown fire models.

There is a group of models using approach often referred to as complete physical and multiphase approach. In these models combustible medium is considered to be made of several phases, gaseous an several solid and for each phase, energy and mass balance equation is solved, for gaseous phase Navier-stokes equation, and point balance for each solid phase, [9]

4. Conclusion

In latest years, when global warming and pollution are threatening to our planet, people are approaching to land use in a different way then before. We are trying to save as much green areas as possible. The optimal way of doing that must be planed in advance.

One of the most important parts of land use management is forest fire management, since forests play very important role in food chain and natural equilibrium. Forest fire models allow us to plan fire fighting and fire avoiding strategy in advance.

There is variety of fire model software systems available on the market and decision on which one to use depends on area of application and intended use. On the complexity scale, the models can be classified from simple empirical models to most complex physical models.

Application of empirical models is limited to area for which the model is created. Complete physical models don't have that limitation but they are rarely in use because such detail approach requires input data to be accurate. Calculations in physical models are usually slow and redundant. That is why semi-empirical models, as a middle between two ends are most often chosen for implementation.

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