A Comparative Review on Wildfire Simulators

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***Abstract*—Phenomena in ecosystems such as forest fires, oil spills, tornados, etc., are complex processes both in time and space. Understanding their dynamics in order to predict their future states is a challenging procedure involving the propagation of several events concerning, e.g., the transfer of energy or material. A common solution used to study such phenomena is the utilization of discrete event models and simulators. Among the phenomena studied by researchers so far, of particular interest and importance, is the forecasting of forest fire propagation since life on earth is greatly dependent on healthy forests. This paper is focused on the investigation of existing simulator models applicable in forecasting forest fire propagation. Twenty-three simulators were found in the literature and are presented here. The comparison discussion concludes with the FARSITE simulator model which is the one that stands out from the rest, and for this reason, it is investigated in depth and evaluated in a test environment.**

***Index Terms*—Event propagation, FARSITE, simulator models, wildfire.**

I. Introduction

UNDERSTANDING and quantifying the process of fire is critical for those seeking to manage fireprone ecosystems. The main parameters, such as fire intensity and rate of spread (ROS) have to be estimated accurately. Fire intensity is important as it determines the scorch height and thereby the amount of the plant canopy consumed, killed or unburnt, and ROS is equally important as it determines the time periods for which plants and animals will be subjected to lethally high temperatures [1]. Further, variables such as fuel moisture, fuel loading, wind velocity, relative humidity, slope, and solar aspect are all recognized as producing important effects on fire. Perry [2] summarizes three physical processes which are integral to fire spread as stated also by Weber [3].

Fons [4] was the first attempting to describe fire spread using a mathematical model. The focus was on the forehead of the fire where the fine fuels carry the fire and where there is ample oxygen to support combustion. Fons reasoned that fire spread in a fuel bed can be visualized as proceeding by a series of successive ignitions and that its rate is controlled primarily by the ignition time and the distance between particles. Considering fire as a series of ignitions helps in reaking down the problem for analysis.

To better understand the fire spread process we have to recall the main heat transfer mechanisms. Based on the second law of thermodynamics, *conduction* heat transfer occurs along a gradient from high to low temperatures. Heat transfer via *convection* between solid objects and fluids occurs as a result of relative motion. Further, *radiation* is the transfer of heat energy through empty space.

In parallel, we have to examine some other parameters that affect the spread phenomenon, such as the fuel density, the flammability of the fuel, the landscape slope and wind. Considering **fuel density**, if the flammable objects (trees, etc.) are sparse, then the fire will be unable to spread over any considerable area. According to Resnick [5], if the fire is allowed to spread into each of its four neighboring squares (north, south, east and west) whenever there is fuel present, the critical density is about 59%. However, if the fire is allowed to spread to anyone of its eight neighbors (including diagonals), then the critical density of an idealized forest is actually only 41%.

Two factors contribute to the **flammability of the fuel**: i) the inherent flammability of each item (trees, dead trees, bushes, plants) and ii) the heat conditions of the day. Since not all items are equally likely to burn, ranking the fuel in terms of flammability is mandatory. Moreover, the temperature together with the humidity and recent weather conditions (lack of rain, etc.) can be grouped together under the classification of *heat conditions*.

Landscape slope may affect fire propagation and fire size. Propagation may be favoured in landscapes that are homogeneous and hindered at places of greater heterogeneity, and where discontinuities occur. Extensive modelling confirmed that fire size was in part related to landscape characteristics of the burned area and of the edges of the fire perimeter.

Two features of the **wind** are important for considering its effect on fire spread: direction and strength. Wildland fire initiation and spread are known to be heavily influenced by wind. The numerical coupling of a fire spread model with an atmospheric model has already been the subject of numerous studies (see [6], [7] and references therein).

Despite the numerous publications in the literature, at present, no single comprehensive model of wildland fire behavior exists so far. This reflects a lack of knowledge regarding the physical and chemical processes as well as the topography and environmental factors and their interactions. Perry [2] comes to fill this gap by studying comparatively the existing models and simulators, pointing out their strengths and weaknesses and proposing appropriate improvements to support their performance.

Diffusion processes (oil spills, fire spread, insect infestation, etc.) are usually represented as partial differential equations (PDEs) that have to be discretized in the form of finite differences or finite elements. Starting with a PDE with derivatives in time and space dimensions, time and space are discretized. There are three basic categories of discrete event modeling: i) *Cellular Automata (CA)*, ii) *DEVS (Discrete EVent System)*, and iii) a hybrid formalism of the two former categories *Cell-DEVS*

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(Cellular-DEVS). All these models are extensively examined and analyzed in the research papers [2], [8]–[14], and in the references therein.

The research of wildfire phenomenon includes not only mathematical approaches, but also implementation of wildfire models and simulators. This paper is focused on the investigation of existing simulator models applicable in forecasting forest fire propagation. The basic parameters of the simulator models that are presented are the mathematical principles used to generate, the input and the output data, the programming language, the last software release and if the project is still running, whether the software is free for evaluation and development or not, and whether they are user friendly or not, based on the details given in the literature for each model by the development researchers as well as by other researchers investigating them. The comparison discussion, in the following sections, concludes that the FARSITE simulator model is the one that stands out from the rest, and for this reason, it is investigated in depth, giving all the details on the way it is developed, presenting its advantages and disadvantages, comparing it with its basic rival, Prometheus, as concluded by the review, and finally, evaluating FARSITE in a test environment. The reason that FARSITE was selected to examine further, is that FARSITE is considered to be the most precise fire propagation simulation model by most of the researchers around the world.

The remainder of this paper is structured as follows. A brief analysis on wildfire modeling is presented in the following section, while in Section III wildfire simulation models are examined. In Section IV the FARSITE simulator is presented in depth and evaluated, and concluding remarks are drawn in Section V.

II. Wildfire Modeling

Wildland fire is the complicated combination of energy released (in the form of heat) in the process of combustion (primarily involving the oxidation of thermal decomposition products of vegetation) and the transport of that energy to surrounding unburnt fuel and the subsequent ignition of that fuel. The former is the domain of *chemistry* and occurs on the scale of molecules, and the latter is the domain of *physics* and occurs on scales ranging from millimeters up to kilometers. It is the interaction of these processes over the wide range of temporal and spatial scales involved in wildland fire that makes the modeling of wildland fire behavior such a difficult task.

Sullivan [15], [16] has attempted to provide a detailed overview of the various approaches of the last two decades (1990–2007) to predict the spread of wildland fire across the landscape. The range of methods that have been undertaken over the years represents a continuous spectrum of possible modeling, ranging from the purely physical, those that are based on fundamental understanding of the physics and chemistry involved in the combustion of biomass fuel and behavior of a wildland fire, through to the purely empirical, those that have been based on phenomenological description or statistical regression of observed fire behavior.

Generally, fire models can be divided into three broad categories: physical and quasi-physical models [15]; empirical and quasi-empirical models [16]; and simulation and mathematical analogue models [9]. A physical model is one that attempts to represent both the physics and chemistry of fire spread, a quasi-physical model attempts to represent only the physics, an empirical model contains no physical understanding at all, generally only statistical in nature, and a quasi-empirical model is one that uses some form of physical framework on which the statistical modeling is based. Many proposals on the two first categories have been proposed. Table I summarizes the basic characteristics of the two first categories. This paper focuses on the last category, i.e., simulation models, which are analyzed in the next sections, since we believe that it is closer to the engineering scope that a manager has to apply to handle efficiently a wildfire event.

The level of detail of data (type and resolution of parameters and variables) required for input into these models is not generally available for landscapes around the world. Additionally, any model suffers from the same difficulties in validation against landscape-scale wildland fires. Many authors of fully physical models are resigned to not being able to predict the behavior of landscape wildland fires in better than real time and suggest that the primary use of such models is the study of fires under conditions, fuels and topographies that are not amenable to field experimentation. In an increasingly litigious social and political environment, this may be the only way to study large landscape-scale fire behavior in the future, but this assumes that the physical model is complete, correct, validated and verified. The basis for fire behavior models of operational use is unlikely to be one of purely physical origin, simply because of the computational requirements to solve the necessary governing equations at the resolutions necessary to ensure model stability. Empiricism has formed the basis for much of the scientific and technological advances in recent centuries and generally provides the benchmark against which theory is tested. It is most likely that for the foreseeable future operational models will continue to be empirical. However, there is a trend towards hybrid models of a more physical nature as the physical and quasi-physical models are further developed and refined.

To overcome the limitations of analytical models, such as the elliptical model, much use has been made of simulation models to predict the growth patterns of wildland fires. Such models make use of computer graphics to produce a visual representation of the growth of a wildland fire event over a landscape. Fire behavior models using multidimensional theoretical wildfire spread models are being developed to predict rates of spread in complex environmental conditions varying spatially and temporally, introduced in the last decades. These models include simulation based on elliptical wildfire models [17], cellular automata [8], fire propagation in arrays [3], Markov chains [18], percolation modeling [19], [20], stochastic contagion techniques [21] and chaotic techniques [22].

In the next section we shall focus on the most important simulation models, trying to provide an in depth analysis and discussion. To our knowledge, there is no such a complete study in the literature so far, while the need for a fast decision making tool is more than necessary during the evolution of a fire event.

III. Wildfire Simulators

Fire spread is a spatial phenomenon that depends on multiple parameters. These parameters include not only weather conditions, but also Geographic Information System (GIS) information, regarding the territory morphology. The investigation of fire spread prediction becomes more difficult if one takes into consideration the fact that the weather prediction science often induces errors, especially when extreme weather phenomena occur. Based on this necessity numerous projects worldwide try for solution.

A running project is **Prometheus** [23], a Canadian national project with its last (open source) software release dated in May 2009. This is a deterministic fire growth simulation tool. It uses spatial fire behavior input data on topography (slope, aspect and elevation) and Fire Behavior Prediction (FBP) fuel types, along with weather stream and FBP fuel type lookup table files. It uses a simple ellipse as the underlying template to shape fire growth. The model simulates fire growth based on Huygens' principle of wave propagation, i.e., the fire front propagation is calculated in a fashion similar to a wave, shifting and moving continuously in time and space. Besides, differential spread equations are used, derived by Dr. Gwynfor Richards at Brandon University. The simulation code is written in Visual C++ and uses the Microsoft COM interface, while it supports 2D and 3D graphical interface. The software is user friendly and allows users to modify fuels and weather data, which are imported as ASCII files.

A tool for bushfire risk management, **Phoenix** [24], is being developed in Australia. This simulation tool relates directly the impact of various management strategies to changes in fire characteristics across the landscape, and the nature of the impact on various values and assets in the landscape. This model is a dynamic fire behavior and characterization model. Unlike many standard fire behavior models, Phoenix runs in an environment where it can respond to changes in conditions of the fire in addition to changes to fuel, weather and topographic conditions as a fire grows and moves across the landscape.

Phoenix operates in a landscape divided into uniform sized square cells. Each cell has many attributes which are either used as inputs or outputs to the simulation. These attributes are stored in a personal geo-database. The size of each cell is specified by the user during the creation of the grid. Grids as small as 5 m have been used for very detailed analysis of a small area, but a grid size of 100 m or 200 m is usually found to be sufficient for most operational purposes. Phoenix incorporates a number of models apart from the basic fire behavior models. Models involved in modifying the inputs or outputs from the fire behavior models deal with the effect of spotfire induced in draughts at the fire front, ember transport and distribution, spotfire ignition, wind-slope interactions, linear disruption to fire behavior, fuel accumulation rates, solar radiation, and fuel moisture models. A second set of models is used to describe the spread of fire across the landscape given the general fire behavior conditions. This is done by considering the conditions at each point on the fire perimeter so that the movement or extinction of that point can be determined from one time period to the next. These models include Huygen's perimeter growth, point self-extinction, surface-to-plan re-projection and fire suppression modeling. The time interval between perimeter spread calculations varies from 1 minute for fast moving fires, to 15 minutes for slow moving fires.

Another computer-based simulation model being developed is **Bushfire** [10], which is a new mathematical approach to modeling fire for Australian conditions. Modeling bushfire spread improves decision-making in critical scenarios. This project promises to develop more reliable bushfire spread simulation and animation technology to underpin and support a wide range of fire management activities, including risk analysis, prescribed burning, wildfire suppression and incident control training. A computer-based environment permits rapid and repeatable execution of bushfire simulations under a wide range of conditions, assisting with real-time decisions and "*what if*" scenarios. Simulations are based on the latest understanding of fire behavior captured within a computer model. Simulations inform predictions of fire behavior and the effectiveness of containment strategies. They also increase understanding of the nonlinear scaling found in extreme fire behavior. Outcomes include visual display and useable interface.

Green *et al.* [25] produced a landscape modeling system called **IGNITE**, that utilized the fire spread mechanics of Green [26]. This system (developed at the Australian National University in Canberra) is a raster-based fire spread model that uses the fire spread models of McArthur [27] and an elliptical ignition template to predict the forward ROS in the form of *time to ignition* for each cell around a burning cell. IGNITE very easily deals with heterogeneous fuels and allows the simulation of fire suppression actions through changes in the combustion characteristics of the fuel layers.

The **FIRE!** simulation model of Green *et al.* [28] uses a vector or wave-type model, as opposed to a cellular model in which fire spread is simulated as a contagious process between cells. The FIRE! model is GIS based and uses the FARSITE fire spread model (discussed below). The vector approach propagates the fire front in a fashion similar to a wave, shifting and moving continuously in time and space. Vector models solve for the position of the fire front at specified times. While rasters are still used to represent the underlying landscape and to record fire characteristics during the simulation, the fire perimeters are processed and stored as continuous vectors.

The **CD**++ environment [29] allows implementing DEVS and Cell-DEVS models. The high level language of CD++ reduces the algorithmic complexity for the modeler while allowing complex cellular timing behaviors. In order to improve the error rate while keeping the number of messages small, the developers have dynamically changed the size of the quantum according to a ratio in order to reduce the error introduced by quantization. The quantum size increases or decreases by the ratio according to the level of activity of the cell. The level of activity is measured by seeing how much the cell changes. If the value of the cell passes a threshold, the quantum is increased by the ratio. On the other hand, if the cell's value does not pass the threshold, the quantum is decreased by the ratio.

Li and Magill [11] have developed **Extended Swarm**, a general purpose network simulator to simulate fires using the Rothermel's mathematical model [30]. In their work, they describe a model for simulating bushfire spread using the CA approach taking into account a number of important environmental factors such as bush density, land height, flammability, and wind condition. The model simulates an artificial environment on a 2-D grid where bushes are initially randomly generated at various locations. Fire is represented at a microscopic level as groups of flames interacting with their environment. Fire can then be ignited from a certain spot or one side of the artificial world, then spread across the world according to some *interaction rules*. However, this model is quite simplistic since it does not consider radiation or convection as well as spotting.

FireMaster [31] is a Java applet, which represents the first phase of the disaster simulation using the internet. The simulator uses the method of Knight and Coleman [32] as a fire propagation engine. GIS data is retrieved from a central server, allowing each user to run their own simulation of fire spread on any Java-capable browser. The system is designed using object-oriented software engineering principles; the architecture of the system is designed to be modified and extended. The system is divided into three main levels. 1) The Data Level, where all data needed by the operations to be performed is loaded into the system from a central server. Results of spatial operations are also stored here. 2) The Operational Level, where each spatial operation exists as an object, requiring spatial data to run on and producing new data or modifying existing data. 3) the User Level, where the user interface, by which the user can invoke operations, choose the dataset to be operated on, and view the results on a spatial display. Operations are carried out on each client, rather than the server. This means that a large number of users can use the server at once, by using the client's hardware rather than the server's. Another problem dealt with is interacting with already-existing GIS information. This has required recoding in Java to access this data.

FireStation [33] implements Rothermel's fire spread model [30] in a raster-based GIS platform. The software utilizes both single- and double-ellipse fire shape templates, depending on wind speed, to dictate the spread across cells. The 3-D wind field across the landscape is based on local point observations extrapolated using either a linear conservation of mass approach, or a full 3-D solution of the Navier–Stokes equations. Slope is treated as an equivalent wind. The software implements a semi-empirical model for fire ROS, 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 is developed under a graphical interface, aiming at a better ease of use and output readability so as to facilitate its application under operational conditions.

PYROCART [34] implement Rothermel's fire spread model [30] and GIS information. This simulation model utilizes the fire shape model of Green *et al.* [25], which is a function of wind speed. The principal aims of the research were to test the applicability of overseas fire behavior models to New Zealand ecosystems, and to assess the applicability of GIS to fire spread prediction. The overall predictive accuracy of the model is estimated to be 80%, as claimed by the developers, a measure of performance based on the percentage of cells predicted to be burnt compared with those that were unburnt or not predicted to burn.

Fuel type and slope appear to be the dominant influences on fire spread. No trends in prediction accuracy by wind speed or direction were apparent. The predicted burnt area and the real burnt area had a similar overall shape. It was found, however, that at high wind speeds the model tended to over-predict rates of fire spread in some directions. The PYROCART model shows potential as a land management tool, especially for the testing of hypotheses concerning land management strategies. However, due to the complex input data and parameterization techniques it requires, it is less suitable for in situ fire management.

Kalabokidis *et al.* [35] introduced **DYNAFIRE** using similar methods to spatially resolve Rothermel's spread model [30] in BEHAVE [36] by linking it to raster-based GIS platforms. Kalabokidis *et al.* developed a simulation technique that derived a "friction" layer within the GIS for six base spread rates for which the friction value increased as spread rate decreased. This was combined with six wind speed classes to produce a map of potential fire extent contours and fireline intensity strata across a range of slope and aspect classes.

Karafyllidis and Thanailakis [12] developed a raster-based simulation also based on Rothermel [30] for hypothetical landscapes, named **Thrace**. Here, the state of each raster cell is the ratio of the area burned of the cell to the total area of the cell. The passage of the fire front is determined by the sum of the states of each cell's neighbors at each time step until the cell is completely burnt. This approach requires, as input parameter for each cell, the ROS of a fire in that cell based on the fuel alone. Berjak and Hearne [37] improved the model by incorporating the effects of slope and wind on the scalar field of cell ROS using a slope effect model and an empirical flame angle/wind speed function. This model was then applied to spatially heterogeneous Savanna fuels of South Africa and found to be in good agreement with observed fire spread.

Prolif, by Plourde *et al.* [38], extends the application of Huygens's wavelet propagation principle as utilized by Knight and Coleman [32]. However, rather than relying on the template ellipse as the format for the next interval propagation, the authors utilize an innovative closed contour method based on a complex Fourier series function. Rather than considering the perimeter as a series of linked points that are individually propagated, the perimeter is considered as a closed continuous curve that is propagated in its entirety. This propagation model appears to handle heterogeneous fuel but the timestep is given as 0.05 seconds, resulting in very fine scale spread but with the trade-off of heavy computational requirements.

Geofogo [39], [40] is a cell-based fire spread simulator developed in Lisbon, Portugal. It uses the DEVS formalism to model the fire. Each cell in the landscape is in one of three states; unburnt, burning or burnt. When a cell ignites, the Rothermel fire behavior model [30] is used to calculate the propagation delay, i.e., the length of time required for the fire to burn to each of the neighboring cells. If there is a change in weather while a cell is burning, the propagation delay is re-calculated. When the propagation delay for a given direction elapses, the neighbor in that direction is ignited if not already burning. When all propagation delays elapse, the cell state changes to burnt. Although the authors have not published results for a uniform fuel in no wind, the DEVS method should not be subject to distortion of the fire shape due to the grid because of the continuity of time which is equivalent to having an infinite number of states for each cell.

The method is validated by comparison with real fires and good agreement is obtained. Geofogo was validated using very detailed weather data (temperature, humidity, wind speed, and direction). Though, it is not clear how data are extrapolated from the weather stations to other points on the grid, so it is difficult to determine how wind is allowed to vary over the grid or if a uniform wind direction is used.

FIREMAP [41] is a simulation system designed to estimate wildfire characteristics in spatially nonuniform environments and simulate the growth of fire in discrete time steps. This simulation system integrates Rothermel's behavior prediction model [30] with a raster-based GIS. The outputs can be displayed as digital maps. This simulation model assumes that the resolution of the rasters is such that all attributes within each cell are uniform. Fire characteristics such as ROS, intensity, direction of maximum spread and flame length are calculated for each cell and each weather condition to produce a database of output maps of fire behavior. Simulation is then undertaken by calculating each cell's *friction* or time taken for a fire front to consume a cell.

SpaSim [13] is a software for running spatial simulations that consolidates in one application the resources needed to define, simulate, visualize and analyze spatial models based on CA. The software includes modules to 1) define spatial models in terms of CA, where the models may have multiple layers and different neighborhoods can be defined in each layer; 2) simulate the models during a specified period of time and save the results of simulation, using one of the two space-temporal data structures provided; 3) visualize the different layers of the automata in a given time or any other raster layer exported into the system, 4) perform spatial and spatio-temporal queries of simulation results; 5) export the CA model to java source code so that extensions or modifications not allowed directly in SpaSim can be performed by the user. The specification of the CA is done in terms of the definition of the grid or model space, neighborhood and rules. Two types of analysis operations are provided: spatial and spatiotemporal. Spatial analysis operations include reclassification, scalar operations and overlay. The spatiotemporal analysis operations allow answering questions that frequently arise when looking at output of a simulation.

HFire (Highly Optimized Tolerance Fire Spread Model) [42] is a raster-based spatially explicit model of surface fire spread through Southern California chaparral written in the C programming language. HFire can be used to predict the speed and direction of a fire spreading across the landscape in real-time. HFire can also be used for stochastic multiyear simulations of fire regime. The model is a product of research funded by NASA through the Southern California Wildfire Hazard Centre. A global sensitivity analysis (GSA) was conducted on HFire, a spatially explicit raster model developed for modeling fire spread in chaparral fuels, based on the Rothermel's spread equations [30]. The GSA provided a quantitative measure of the importance of each of the model inputs on the predicted fire size. This software is free for evaluation and also free for developers.

SiroFire [43] is another computer-based fire spread simulator. The Australian Commonwealth Scientific and Research Organization (CSIRO) bushfire spread simulator SiroFire is a real-time PC-based decision support system with the capacity to predict the behavior and spread of up to ten fires over the landscape. It is based upon the McArthur Fire Danger Rating Systems for grassland and forest but also includes the CSIRO Grassland Fire Spread Prediction System and the Rothermel's model for grass and forest litter fuels. A GIS-derived map and digital elevation model provide information about fuel types and topography while information about fuel condition and weather is provided by the user. Launched in 1994, SiroFire used information such as temperature, relative humidity, wind speed and direction, fuel load and conditions, grass curing, slope, and the selected fire spread model to predict the spread of a wildfire and plot the perimeter on a map of the area of interest. GIS information is used to graphically present the spread of the fire over the map display.

Further, **RERAP** (Rare Event Risk Assessment Process) [44], [45] is a program used to estimate the risk that a fire will reach a particular point of concern before a fire-ending event occurs. It incorporates weather, fuels, topography, and Rothermel's surface spread [30] and crown fire [46] models with two waiting-time distributions (one for the fire-ending event and the other for critical spread events) to produce probabilities along a straight-line transect. RERAP helps calculate the information needed to manage prescribed fires and wildland fires. It allows a user to dynamically calculate the risk of undesired fire movement, including how to identify high and low risk opportunities for wildland fire use and general prescription control strategies and how to estimate fire movement and spread events based on historical weather information and professional knowledge. The RERAP program consists of three modules: 1) the Term Module, which allows a user to calculate the Weibull waiting-time probability distribution for fire-stopping events; 2) the Spread Module, which allows a user to estimate the ROS toward a designated location; and 3) the Risk Module, which combines information from term event information and fire spread events and allows a user to specify and combine fire-stopping and fire movement waiting-time probability distributions to estimate the likelihood of a fire impacting a designated location before a fire-stopping weather event.

FlamMap [47] is another spatial fire behavior mapping and analysis software that computes potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.) over a landscape for constant weather and fuel moisture conditions. FlamMap makes independent fire behavior calculations (for example, fireline intensity, and flame length) for each location of the raster landscape (cell), independent of one another. That is, there is no predictor of fire movement across the landscape, and weather and wind information are held constant. FlamMap output lends itself well to landscape comparisons (i.e., pre- and post-treatment effectiveness) and to identifying hazardous fuel and topographic combinations, thus aiding in prioritization and assessment. It incorporates the following fire behavior models; Rothermel's [30] surface fire model, Van Wagner's [48] crown fire initiation model, Rothermel's [46] crown fire spread model, and Nelson's [49] dead fuel moisture model. FlamMap is widely used by the USDI (United States Department of Interior) National Park Service, USDA (United States Department of Agriculture) Forest Service, and other federal and state land management agencies in support of fire management activities. The current version of FlamMap (v3.0) was released in March 2006.

Moreover, **FFP** (FireFamily Plus) [44] is a fire climatology and occurrence software that combines the functionality of the pcFIRDAT [50], pcSEASON [50], FIRES [51], and CLIMATOLOGY [52] computer-based programs into a single package with a graphical user interface. It allows the user to summarize and analyze weather observations, associate weather with local fire occurrence data, and compute fire danger indices based on the National Fire Danger Rating System (NFDRS) and the Canadian Forest Fire Danger Rating System (CFFDRS). Fire occurrence data can also be analyzed and cross-referenced with weather data to help determine critical levels of fire danger for staffing and other fire management activities. The last software release was dated in December 2008.

Firementor [53] consists of a consumable sensor network, which broadcasts real-time information on the temperature and changes in a forest. Each sensor has a thermometer, a microcomputer and a wireless communications unit. The sensors are camouflaged within the tree canopy, and the operated network is an ad-hoc network. The idea of self-organized networks is applied in this system. In case of a fire eruption, sensors can be destroyed having first dispatched a message which is routed via other sensors to reach the local control node of the network. Then, the network is automatically reorganized covering the gap left by the damaged sensor, in order to deliver all messages to the central/base node. The sensors are installed and record their exact position using GPS technology.

When a fire breaks, it is directly felt by the system, which is useful for large areas where the topography does not permit supervision by humans. Moreover, if a fire breaks out in two or more points, it can be concluded with certainty that this is arson. The Firementor system does not only detect a fire, but it also predicts the evolution of fire, in order to indicate the best location and routing of response units. It also allows assessment of the risks inherent in a possible evacuation of the area in case of panic. The system can also lead vehicles (fire brigade, ambulances etc.) and firefighting aircraft, taking into account the limitations and risks arising from the spread of fire. The Firementor software uses meta-heuristic algorithms, to drive vehicles through an optimal route. The developed software supports the definition of scenarios and produces reports in HTML format for future use. The system processes all spatial information in XML format, thus allowing for open and transparent spatial data management which guarantees its easy deployment everywhere.

The essential input digital data in Firementor are 1) three-dimensional digital map of the region, 2) high-resolution satellite images, 3) information about building blocks and population of the region, 4) digital road maps, 5) fuel maps, and 6) real-time meteorological data (temperature, humidity, wind speed and direction). The system was tested in New Penteli, Athens, Greece, where the researchers experimented by altering the data and created series of scenarios for possible signs of an outbreak of fire and other potential development.

Last, but not least, comes **FARSITE** (Fire Area Simulator). FARSITE [54]–[56] is a model for spatially and temporally simulating the spread and behavior of fires under conditions of heterogeneous terrain, fuels, and weather. It must be underlined that, FARSITE has been selected by many federal land management agencies as the best model for predicting fire growth. Besides, according to Sullivan's review paper [9], the two models found to best simulate the historical fires were vector-based implementations, FARSITE and Prometheus. For these reasons, FARSITE simulator is going to be presented in depth and evaluated in the next section. Also, a comparison table between the two models standing out from the rest, FARSITE and Prometheus, is given in the next section, pointing out the strengths of each simulator.

IV. FARSITE: In-Depth Analysis and Evaluation

As mentioned in the last section, FARSITE is considered to be the most precise fire propagation simulation model by many researchers and even governments around the world. Based on this, in this section we present in depth and evaluate the simulator model.

The modeling approach uses an implementation of Huygens' principle of wave propagation for simulating the growth of a fire front. FARSITE requires the support of a GIS system, to generate, manage, and provide spatial data themes containing fuels vegetation, and topography.

The FARSITE software was initially developed for management support of prescribed natural fires (PNFs), now called *fire use*. The model was intended for both planning and operational phases. Among the many potential uses for fire growth simulations, the most relevant to FARSITE are short and long term projections of active and potential fire use fires. The Microsoft Windows interface offers flexibility for office or field prediction of fire growth. Fire growth and behavior scenarios can be developed relatively quickly using short term weather forecasts or long term weather projections (ideally based on historic records). Finally, different kinds of fire behavior can be considered.

FARSITE simulator is based on the BEHAVE [36] fire behavior prediction system, which itself is based on the spread model of Rothermel [30]. The FARSITE model incorporates five sub-models of fire behavior: surface fire [30], crown fire spread [46], [48], fire acceleration, fuel moisture, and spotting from torching trees. All fire behavior calculations apply to the perimeter of a fire. If the perimeter of the fire is specified as a line or polygon, the model calculations are performed at the vertices and serve to locally propagate that edge as elliptical wavelets according to Huygen's principle [17], [56]. The elliptical wave shape is determined locally at each vertex by the additive combination of wind speed and slope. Spatial data on fuels and topography required for these calculations are obtained from gridded maps from GIS information. Weather is obtained from data streams that discern time-dependent changes in wind speed, wind direction, temperature, humidity and cloud cover.

Here, the fire front is propagated as a continuously expanding fire polygon at specified time-steps [17]. It is essentially the inverse of the cellular method. The fire polygon is defined by a series of 2-D vertices. The number of vertices increases as the fire grows over time, implying expansion of the polygon. This expansion is determined by computing the ROS and direction from each vertex and multiplying by the duration of the time-step. Spread direction and rate normal to the fire front is determined from the direction and the maximum ROS by an elliptical transformation. The reliance on an assumed fire shape, in this case an ellipse, is necessary because the ROS of only the heading portion of a fire is predicted by the present fire spread model [30]. Fire spread in all other directions is inferred from the forward ROS using the mathematical properties of the ellipse. It is most common to assume that the ignition point or fire origin is coincident with the rear focus of the ellipse. Although not necessarily correct, this does provide an implicit backing fire ROS. Alternatively, the location of the fire origin along the major axis of the ellipse could be computed from an independently calculated backing ROS, i.e., the constant no-wind-no-slope ROS.

Realistic predictions of fire growth ultimately depend on the consistency and accuracy of the input data layers needed to execute spatially explicit fire behavior models. FARSITE requires eight data layers for surface and crown fire simulations. These data layers must be both precise and consistent for all lands and ecosystems across the analysis area. More importantly, the layers must be congruent with all other GIS layers. Comprehensive development of these input data layers requires a high level of expertise in GIS methods, fire and fuel dynamics, field ecology, and advanced computer technology.

So the FARSITE model, which is available for free to anyone both for use and for further development (open source), requires fuels layers that are quite costly and difficult to build. Unfortunately, most fire and land managers do not have the fuels maps, or even base maps from which they could create the fuels maps, needed to run the FARSITE model for their area. Most existing vegetation layers and databases do not quantify fuels information to the level of detail or resolution needed by FARSITE. Moreover, some attempts to create FARSITE layers from existing maps have failed because of inexperience with fuels and vegetation modeling and mapping in the context of fire behavior.

As mentioned in the previous section, FARSITE and Prometheus models tend to stand out from the other models. Table II summarizes the basic specification-information for these two simulator models. The main outputs of the comparison table are 1) Prometheus is still a running project, 2) FARSITE's mathematical background is relatively complete and more detailed, 3) FARSITE supports input data based on GIS information, 4) the input and the output data of both simulators are very detailed and multiparametric, making them more reliable and accurate compared to all other models, 5) FARSITE has gained the confidence of many governments. FARSITE has one more basic advantage against all other simulators; it is able to handle multiple fire fronts and ignitions, whereas, this fire situation is difficult or even impossible to model using most fire simulation systems. These severe scenarios involve rapid transitions in fire behavior, abrupt thresholds in fire activity, and strong feedbacks between fire behavior and environmental conditions. Therefore, most models are poorly suited to explain or predict the fire behavior in these extreme situations.

On the other hand, any fire predictive model generates estimates of fire spread and behavior that is subject to some inaccuracy, in both the burned area extension and the values of the fire behavior parameters (ROS, fireline intensity, etc.). As is the case with any field experiment, it is very difficult to measure all required quantities to the degree of precision and accuracy required by the models. In the case of wildland fires, this difficulty is increased. Boundary conditions are rarely known and other quantities are almost never measured at the site of the fire itself. Mapping of the spread of wildland fires is haphazard and highly subjective. One of the main sources of the FARSITE simulator inaccuracies is linked to difficulties in the acquisition of reliable input data, with the required spatial and temporal resolution. Sometimes the model is not applicable to some sites or specific situations, due to the lack of an adequate model calibration phase. The complexity of the phenomena involved drives to preliminary assumptions and limitations. As in many of the simulators, the fire growth simulations of FARSITE generally get worse with time and spread distance, because there is a cumulative effect of errors. The simulation of the fire growth increases its accuracy when accurate data at high spatial and temporal resolution are used. Besides, high frequency variability in wind direction and intensity is a common cause of non steady behavior of fires; in these conditions many simulators produce results not consistent with observed fire propagation. As already pointed out, the Rothermel's model is able to reproduce only a surface fire, spreading along a uniform, homogenous, and contiguous to the ground. The fire behavior outputs reflect a surface burning front, moving in an entirely uniform (horizontally and vertically) fuel complex, within 2 m of the ground. Clearly, this is a major simplification of the actual surface vegetation, particularly when the landscape is covered by shrub lands, as can be observed in Mediterranean areas. Obviously, model results would be expected to suffer where strong interactions of wind and terrain are present. Furthermore, calculations that depend on fuel temperature and moisture may not be accurate where shadows are cast by topography, precipitation varies elevationally or spatially, or water availability is significantly altered (e.g., higher fuel moistures near streams).

At this point, the FARSITE software is evaluated. The essential information has to be loaded to the simulator in order to experiment on the growth of the fire. This information involves landscape, such as fuel model, slope aspect, elevation, canopy cover, tree height, crown base height, crown bulk density, duff loading and coarse woody. Also, information about weather conditions, wind conditions, initial fuel moisture, fuel model conversion, custom fuel models and fire acceleration are necessary, as well as some other parameters that can be used, which are optional to run a simple simulation, although they become important in real situations where every detail counts. The software is user friendly and allows users to modify input parameters either manually, or import them as ASCII files.

At first, the landscape information is loaded, and right after the project is configured by loading weather, wind, moisture and custom fuel model parameters. Vector files, corresponding to roads/highways, streams, barriers (e.g., firewalls) can also be included as can everything that can prevent the spread of the fire. All the above information is drawn on a map, like the one given on Fig. 1.

The simulation starts and several graphs, tables and maps, regarding fire area, fire perimeter, fire characteristic chart, post

TABLE I
BASIC CHARACTERISTICS OF PHYSICAL AND EMPIRICAL WILDFIRE MODELS

	Physical	Quasi-physical	Empirical	Quasi-empirical
Application	- Used for simulation purposes or to explore a particular physical process or aspect. - Applied to large-scale *landscape* domains, or to small-scale *laboratory* domains.	- Used in a laboratory-scale domain.	- Estimates the likely spread in the direction of the wind for suppression planning purposes. - Conducted in the form of simple calculations for plotting on a wall map.	- Particularly suited to faster than real time computation with low requirements for data.
Main feature	- Based on theory (both physical and chemical processes of the phenomenon). - Differential equations with numerical solutions used to describe the spread process. - Complex nature.	- Based on physics theory. - Lack of combustion chemistry and reliance on the heat release transfer. - Parameters determined by laboratory experiments. - Plane of prediction, and vertical plane rather than horizontal plane.	- Based on observation and experiment and not on physics/chemistry theory. - Pragmatic nature. - Determination of the key characteristics used to describe the behavior of the fire.	- Data gathered from experimental observation, statistically analyzed using a physical framework for the functional relationships between dependent and independent variables.
Output	- Basically the ROS. - Energy released from the fuel. - Radiation transfer to surrounding unburnt fuel and to the atmosphere. - 2-dimensional or 3-dimensional models of fire spread.	- ROS. - Fireline intensity. - Flame geometry. - Radiation transfer to surrounding unburnt fuel and to the atmosphere. - 1-dimensional models.	- ROS. - Rate of increase of the perimeter. - Fire damage area. - Height, angle and depth of the flames. - 1-dimensional models.	- ROS. - Convective heat output to rate of buoyancy production. - Ratio of combustion time to time characteristic of flame dynamics. - Fuel moisture content. - Geometry of the fire perimeter.
Advantages	- Analytical in nature. - Detailed fuel descriptions to better represent wildland fuels. - Ability for computer based tests of the model.	- Rely upon a higher level model compared to physical models.	- Relatively straightforward implementation. - Direct relation to the behavior of real fires.	- Alleviating the influence of the size of the dataset and personal choice.
Disadvantages	- Restricted in scope with respect to their computational domain. - Low spatial dimensionality.	- Not suitable for landscape simulation or operational context.	- Highly dependent on the conditions obtained by the source data. - Requires major approximations.	- Highly dependent on the conditions obtained by the source data. - Requires major approximations.

frontal combustion, fire numbers, environmental maps and combustion maps are generated. During the simulation, one can observe the fire perimeter as it moves, as well as all the above graphs, tables and maps. These are illustrated in Figs. 2 and 3. The tabular data can be exported to files, while graphs can be exported to bitmap files. Besides, queries can be performed for a specific spot on the map. The results of an example of such a query are illustrated in Fig. 4, indicating detailed landscape information, as well as fire data information. Finally, the simulation ends, and the map of the final damage of the landscape is shown in Fig. 5.

Concluding, it should be mentioned that all graphs and tables presented in Figs. 2 and 3 alter as the simulation runs. Furthermore, Fig. 4 shows some details regarding specific coordinates of the landscape. Here it should be paid attention especially on the perimeter of the fire (the fire front). Finally, from Fig. 5 it can be observed, among other things, that in the southern part of the landscape the fire spread is stopped by the presence of the barrier (this could be a highway or a firewall as mentioned above, since it is a straight line) that exist there.

Unfortunately, the FARSITE simulation model is not going to be upgraded anymore by the developers of the tool. The last version was released in May, 2008. Our intention is to make improvements to the source code of the model, and to make it applicable to our neighbor suburban forest, in Thessaloniki, Greece, at first.

In the future, FARSITE source code can be moderated to make the software able to import real-time weather conditions information, regarding temperature, wind, moisture, etc., while this weather information can change in time as the simulation runs. Also, in FARSITE, as well as in most of the simulators, the ignition of a fire is set manually. In the future, the exact place of the ignition of a fire can be pointed by an alarm given by a sensor, operating in a wireless sensor network (WSN). The idea of self-organized networks is applied in this system, while the operated network is an ad-hoc network. Such a system can broadcast real-time information on the temperature and changes in a forest, indicating an alarm when significant changes occur, implying a fire ignition. This system would be most useful, because of its real-time notification, and especially for large areas where the topography does not permit supervision by humans.

V. CONCLUSION

In this paper, a review on wildfire simulation models has been presented. Before that, a brief analysis of wildfire modeling has also been made. Twenty-three simulators were found in the literature and are presented here. The basic parameters involved in the comparison of the simulators were mainly focused on

TABLE II
SUMMARY OF SIMULATOR MODELS DESCRIPTION

	Prometheus	**FARSITE**
Last software release	May 2009	May 2008
Program language and OS	- Visual C++ - MS Windows	- C++ - MS Windows
Fee	Free (open source)	Free (open source)
Importing files	ASCII	ASCII
Mathematical models used	- Huygens' principle. - Gwynfor's differential spread equations.	- Huygens' principle. - BEHAVE fire behavior prediction system. - Rothermel's surface spread model. - Rothermel's crown fire spread model. - Van Wagner's crown fire initiation model. - Nelson's dead fuel moisture model.
Input data	Inputs divided into 5 general categories: fuels, weather, topography, foliar moisture content, and type and duration of prediction.	- GIS support. - 8 data layers for surface and crown fire simulations.
Output data	4 primary and 11 secondary outputs. Primary outputs are generally based on a fire intensity equation, and secondary outputs are calculated using a simple elliptical fire growth model.	Outputs are compatible with PC and Workstation graphics and GIS software for later analysis and display. The basic are ROS, flame length, time of arrival, fireline intensity, heat/area reaction intensity, crown fire activity and spread direction.
Graphical interface output	2D and 3D	2D and 3D
Used by	Sub-system of the Canadian CFFDRS	Many federal land management agencies

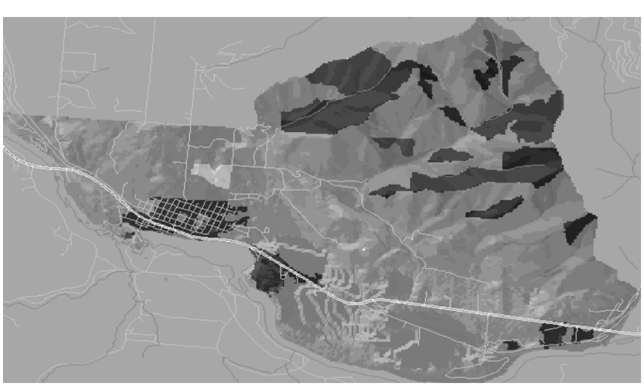

Fig. 1. Example of a landscape.

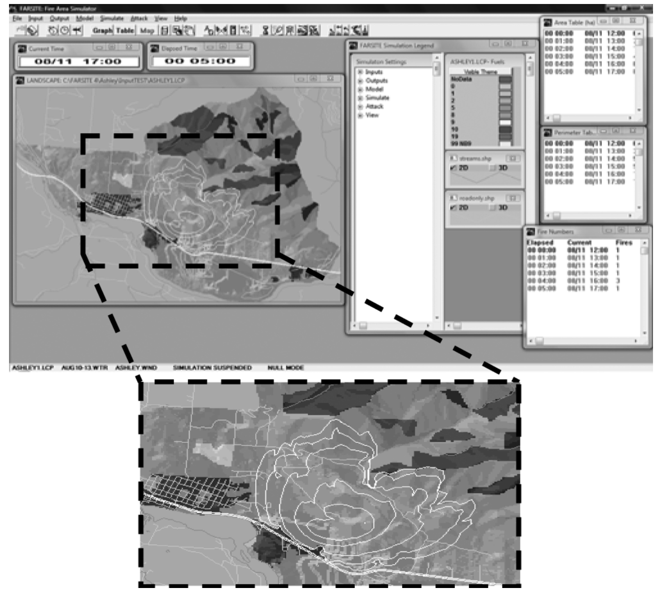

Fig. 2. FARSITE simulation as it runs—table results.

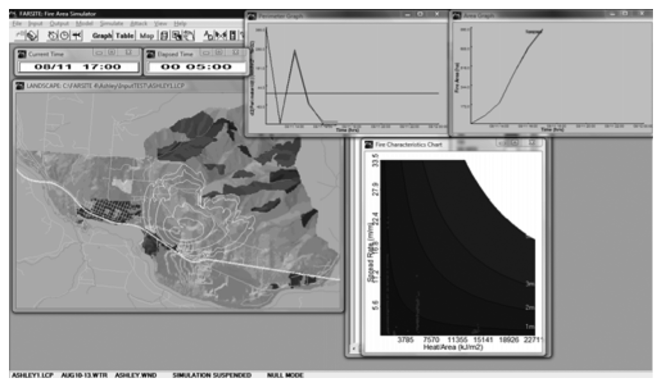

Fig. 3. FARSITE simulation as it runs—graph results.

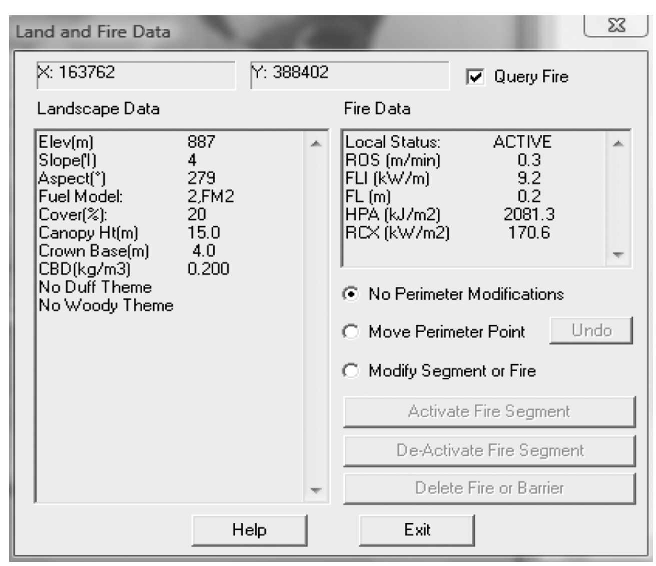

Fig. 4. Land and fire data query of specific coordinates.

the mathematical principles used, the input and the output data, the programming language, the last software release and if the project is still running, and whether the software is free for evaluation and development or not.

At last, the FARSITE simulator was investigated in depth and evaluated in a test environment. The reason that FARSITE was selected to examine further, is that FARSITE is considered to be the most precise fire propagation simulation model by many

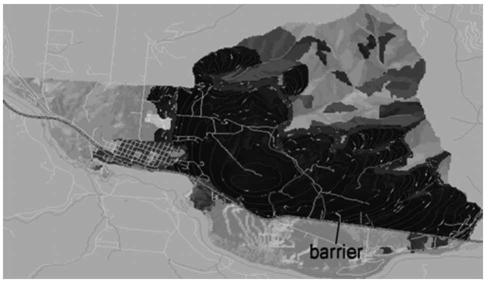

Fig. 5. End of simulation—illustration of the final damage of the landscape.

researchers around the world. Besides, FARSITE has been selected by many federal land management agencies as the best model for predicting fire growth.

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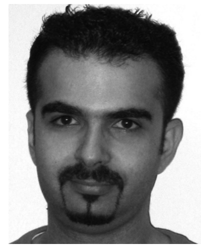

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