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AN OVERVIEW OF MODELLING BULGARIAN WILDLAND FIRE BEHAVIOUR BY APPLICATION OF A MATHEMATICAL GAME METHOD AND WRF-FIRE MODELS*

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Abstract. This paper presents the main achievements of the author's PhD dissertation. The work is dedicated to mathematical and semi-empirical approaches applied to the case of Bulgarian wildland fires. After the introductory explanations, short information from every chapter is extracted to cover the main parts of the obtained results. The methods used are described in brief and main outcomes are listed.

I. General description. Forest and field fires are a growing problem for the countries of EU located in the southern parts of Europe. Statistics

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Key words: Wildland fires, fire propagation modelling, surface fires, mathematical game method, WRF-Fire model.

*This article presents some of the results obtained as part of the Ph.D. thesis "Information systems for simulation of behaviour of field and wildland fires" by Nina Dobrinkova (Institute of Mathematics and Informatics, BAS) succesfully defended in IMI-BAS on 4th April 2012 in Sofia.

concerning the development of forest and field fires in the last 25–30 years are published in reports by the centres in the EU which monitor the forest conditions [1]. Observations in the member states of the EU in the period 1980–2005 showed an increasing number of areas affected by the fires. It is assumed that one of the main causes of fire is the climate change. In this period, Bulgaria was not included in the study because it was not a member of EU, but independent research done on the topic which describes an increase of wildland fires since 1995 on the Bulgarian territory [2, 3]. Worldwide research about wildland fire propagation has begun in the US where NCAR (National Center for Atmospheric Research) is one of the main founders of this type of modelling along with the centre led by Rothermel in Missoula Fire Laboratory in Rocky Mountains [4]. In fact, Rothermel and his team in Missoula are considered as founders of fire modelling research. The first working wildland fire behaviour model was created in 1972 and since then it has been improved several times. Every subsequent model's modifications included consideration of further parameters that could make the simulations obtained by scientists more realistic and accurate.

In the early 80s of the last century, M. Grishin, professor at the University of Tomsk, Russia, has worked on and developed a model [5] which uses data on the types of burning material in the taiga (mostly conifers) and takes into account that the main combustion intensity happens in the crowns of trees.

Approximately at the same time attempts at wildland simulations were made in laboratories in Sydney, Australia. These models did not become as popular as the US ones, because of some computational issues at that time, concerning PC power, data coverage, etc. Nowadays many laboratories are involved in modelling wildland fire behaviour propagation; it is easier to find them in the affected zones, simply because this knowledge saves time and effort when it is working together with the incident commanders on the field.

The development of modern information and communication tools allows application of cutting-edge technologies to solve problems related to the forest and field fires. The use of these tools not only allows early detection of fires but also enables the prediction of the dynamics related to fire spread of the fire line and the extent of the possible damages of the environment and citizens' property.

The main types of wildland fires described in the specialized literature are classified as follows: type 1—surface fires [4,6]; type 2—crown fires [5,7]; type 3—spotting fires as modified crown fires and type 4—fire acceleration, when the terrain has steep slopes.

In this thesis, certain issues related to the modelling of fires of type 1 and dealing with surface fire spread propagation are discussed. The two main approaches described in the dissertation are focused on modelling and calibration of the models of state of the art which can be applied in Bulgarian conditions, in particular having in mind the availability of data and local authorities' will for cooperation.

Main goals and tasks addressed in the thesis. The main goals of the thesis are:

1) Development of software for the practical realization of a mathematical game model that uses relatively simple rules that describe the behaviour of forest fires for areas with grass and shrubs;
2) Adaptation of the semi-empirical model WRF-Fire (for the first time in Bulgaria) using Bulgarian fire data obtained on a GIS orthophoto image topology and combustible materials;
3) Creation of a model architecture for a system that provides predictive results about the fire development over time using different forecasting methods depending on the available data set.

The goals are achieved through the consistent implementation of the following tasks:

1. Analysis of the state of the art of the existing methods and software systems to simulate the behaviour of forest fires and outline their prospects;
2. A study of the properties of the proposed mathematical game model to its realization and application software to simulate the behaviour of forest fires;
3. Treatment of orthophoto images with GIS tools so that meteorological and topographical data can be applied to the area of simulation of wildfire;
4. Development of an algorithm for design of a software system, featuring a user-friendly interface and a choice of method depending on the available data in order to assist decision-making by teams dealing with wildland fires.

II. Short overview of the content. The introduction describes the general concept of the research effort, the state of the art worldwide and in particular the Bulgarian status. The introduction demonstrates the importance of the topic and the great need for development base on scientific approaches.

The introduction also describes the goals, the tasks and the problems which the work addresses. A description of the main approaches and methods applied in the research has been included. Conclusions related to the research results are also listed.

1. Tasks and approaches which describe the development and propagation of wildland fire. The first chapter offers an analysis of the types of wildland fires and the existing methods of modelling surface-type fires. It also includes a brief overview of Sullivan's classification [8–10]. A short description of Rothermel's mathematical model of the spread of surface fire is included. The four types of fires, according to their distribution (recall that we focus on the surface type of fires due to the greater likelihood of their occurrence on Bulgarian territory), are presented as follows:

- The surface type of fires spread in areas with peat/compost, grass, and small bushes. The crucial factors here are the type of combustible materials and the topographical and meteorological conditions. Thus they need to be carefully examined before the applications.
- The crown type of fires occur mainly in terrains with conifer vegetation. Usually crown fires follow initial surface fires as understory burning behavior and then the overstory become crowning.
- The spotting type of fires occur as a consequence of crown fires because of the resin content in the conifer trees. During the burning process of such fires the radiation of the released heat can make the the resin in the conifer burst out up to 15–30 metres of the fire front. These burning bulbs of resin are described as spots and that is how the type is named after the way of spreading of the fire line. The burning bulbs of resin start new small fires which combine with the main fire front when it approaches.
- Fire acceleration can happen in the areas where the terrain is very steep and the slopes have enough vegetation. Thus these fires are mostly influenced by the inclination of the slope (the steeper the slope, the more accelerated the fire) and the vegetation type is not so important. This type of propagation and the fire behaviour is called chimney effect.

Main conclusions.

1) Research in the area of wildland fire modelling has developed intensively after 1990. This is mainly because of the development of computer and

information technology and the availability of better supercomputer machines.

2) Based on the Sillivan's overview [8, 10] and the analysis from the information bulletins published on the page of the International Association of Wildland Fires (IAWF), we can conclude that climate change is one of the main triggers for defining fire danger zones on the world map.

3) Computer-based simulations for modelling fire spread and fire behaviour are more widely used and applied by the responsible authorities and in scientific work. This is because meteorological data can be obtained with the modern techniques at shorter intervals, which significantly improves the scenario development running as computer simulation.

4) There are six main approaches to fire modelling according to Sullivan's classification.

5) Following an analysis of the literature, we divide the approaches as follows: 1) simulation of forest fires depending on whether it applies to the study of physico-chemical reactions during combustion, 2) mathematically defined processes or empirical methods dealing with the spread of fire, often combined with other approaches. We choose the second type as more appropriate for our purposes.

2. A mathematical game-method model: a game-method approach for field fire spread presentation. The second chapter presents a mathematical game-method model. For fieldfire simulations the model uses a special feature for each cell in a grid representing the environment, called the burning coefficient rate, which determines how long each cell can support the combustion process.

The model uses a set of symbols arranged in a two-dimensional grid of cells [11]. The following rules are applied:

– The content of the cells can change under the influence of the fire burning processes in the affected cell;

– Interaction between the contents of neighbouring cells affects these cells.

Cells with content 0 do not burn (this can be a representation of a lake, river, rock or already burned cell).

Every cell contains a certain amount of flammable material. We need to represent characteristics of the fuel material in the cell, such as physical parameters (mass and density), needed for description of the flammable surface.

In fact, every cell is characterized by three components. The first two elements contain the coordinates of the cell. The third component is a factor of combustibility as described in the preceding paragraph. It may be represented by a number corresponding to the density of combustible material for the cell. The resulting configuration of the cells is considered the starting one.

We apply rules as defined above so that we can investigate the statistical accuracy. Therefore we need a sufficiently large number of configurations (30 in our application). We developed a program by using *Turbo Delphi v.6,* called "Field Fire". The final result of the implementation of the algorithm on 30 configurations of size 143 × 143 is shown in Figure 1.

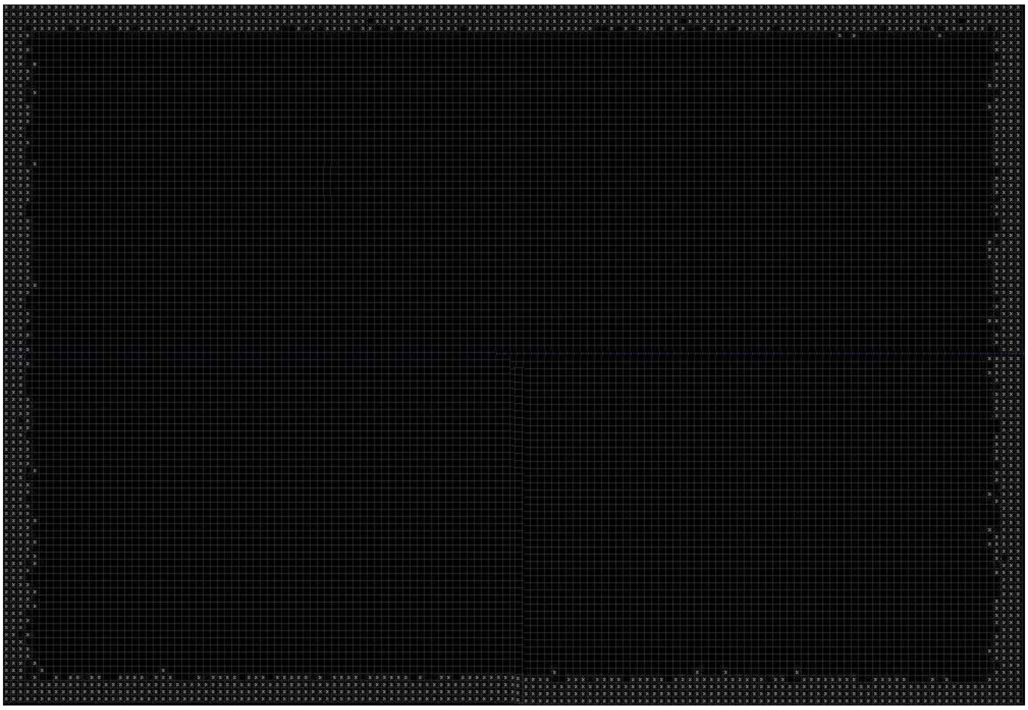

Fig. 1. Differences between burned area marked as total black cells and unburned area with white "x" in the cell.

Here marks the cells which contained different numbers after the comparison between the mean values and the burned coefficient in the final configuration.

The comparison shows that differences appear only in 914 cells (around

4% of the total area of the configuration). The differences occur mainly in the border cells, where we observe the so-called border effect. In this case we can conclude that from a statistical point of view we have reliable results. Therefore the method can be applied for field fires starting from some central point.

Main conclusions.

1) The research gives us a reason to believe that the proposed mathematical game-method model can be used to describe the propagation of fires in flat areas with relatively even distribution of grasses, shrubs or trees. In addition, some results of our program have been added to the "Field Fire" program, following a proposal by Sotirova from Bourgas University.
2) It can be concluded that the model has the necessary qualities for being an important component of a system to monitor the spread of relatively small forest or field fires.
3) An improvement of the program implementing the model could include meteorological parameters (humidity, wind and/or temperature), and consequently the combustion rates can be adjusted.
4) The implementation of the algorithm requires no special computing resources. Because of the non-operational nature of the study, the current user interface does not include options for setting the dimension of the configuration, but this can be easily adjusted if necessary.

3. Testing the WRF-Fire model for Bulgarian conditions. The third chapter presents a new generation model called WRF-Fire [12] created and developed at the University of Denver, USA. The semi-empirical approach for fire spread implies that the fire spreads toward the normal to the front line, which is expressed by a modified Rothermel's formula. The burning area for time t has been presented as area Ω, which is a set of points in the (,) plane. Let:

$$\tilde{S} = \min\{B_0, R_0 + \phi_w + \phi_s\}, \tag{3.1}$$

where B_0 is the fire spread against the wind direction, R_0 is the fire spread in absence of wind, $\phi_w = (\vec{v} \cdot \vec{n})^b$ is the wind correction and $\phi_s = d\nabla z \cdot \vec{n}$ is the terrain correction, $\vec{v}$ is the wind, ∇z is a terrain component of the normal $\vec{n}$ of the fire line, a, b and d are certain constants. In this case the WRF-Fire model describes the maximal fire spread with the formula:

$$S = \begin{cases} 0, & \text{if} \quad \tilde{S} < 0 \\ S_{\max}, & \text{if} \quad \tilde{S} > S_{\max} \\ \tilde{S}, & \text{if} \quad 0 \leq \tilde{S} \leq S_{\max} \end{cases} \tag{3.2}$$

where $S_{\max}$ is the maximal spread of the fire.

After the ignition of the combustible materials its amount of combustible material in point (x, y) decreases exponentially and is given by the formula:

$$F(x, y, t) = F_0(x, y)e^{-(t-t_i(x,y))/W(x,y)}, \tag{3.3}$$

where t is the time, t_i is the ignition time, F_0 is the initial quantity of the burning materials (before their ignition) and $W(x, y)$ does not depend on the time, but on the burning materials.

Heat flow released from the fire is presented in the atmospheric model as a layer above the ground deployed in height [13]. The flow depends on the amount of material burned and can be presented by the formula:

$$\Phi = -A(x, y)\frac{\partial}{\partial t}F(x, y, t). \tag{3.4}$$

This representation is needed because the atmospheric model from WRF does not support limits on heat flow. The coefficients and functions B0, R0, Smax, a, b, d, W and are determined by laboratory experiments.

For each point in the plane the coefficients of combustible materials are given as representatives of one of Anderson's 13 categories [14], valid for US burning materials and applied to Bulgarian conditions. Different altitude values for the wind are also used. WRF-Fire has internal representation for each of the cathegories, which gives options for determining when the simulated area is outside US.

WRF-Fire uses a different modelling of the spread of fire through so called level-set functions [15]. In this approach a function $\psi = \psi(x, y, t)$ is set, which defines subareas of Ω by the rule:

$$\Omega(t) = \{(x, y) \in \Omega : \psi(x, y, t) < 0\}. \tag{3.5}$$

These areas are considered to be burned, and the line of fire is set by the curve:

$$\Gamma(t) = \{(x, y) \in \Omega : \psi(x, y, t) = 0\}. \tag{3.6}$$

The function $\psi(x, y, t)$ satisfies the equation:

$$\frac{\partial \psi}{\partial t} + S(x, y)|\nabla \psi| = 0, \tag{3.7}$$

which can be solved numerically.

The formulas (3.1)–(3.7) are sufficient for the general description of the simulation of the development of fire. At the beginning the atmospheric model interpolates the wind to match the size of the smaller area of the fire. Then a numerical method is applied for evaluating the level set function. The next step applies quadrature formulas for evaluation of the amount of the burning material. Simultaneously the heat flow released to the atmosphere is estimated. The last usually forces changes in the weather and therefore the steps need to be repeated again.

WRF-Fire is tested for first time with real wildland fire in Bulgaria. The fire happened near Leshnikovo village (Harmanli) in August 14–17, 2009. Unfortunately, unlike in the US, not all of the necessary data is available for free in Bulgaria. Thus we develop and present procedures for manual production of some data needed for the land cover and land use by applying GIS tools on available ortophoto pictures for the area of interest. The method uses information about the terrain and the meteorological data (for the corresponding period) as an input file. The most successful simulation was done on the supercomputer at the University of Denver by distant connection. In Table 1 the simulation results are presented according to the number of the cores used.

Table 1. The time required for the simulation presented in seconds depending on the number of processors running the parallel execution of processes

Cores	**6**	**12**	**24**	**36**	**60**	**120**	**240**	**360**	**480**	**720**	**960**	**1200**
Fire line propagation in km.	1.91	1.08	0.50	0.34	0.22	0.13	0.08	0.06	0.06	0.04	0.10	0.04
Region 1	6.76	7.05	2.90	2.06	1.20	0.73	0.45	0.32	0.26	0.23	0.24	0.17
Region 2	0.00	0.00	0.00	0.02	0.02	0.04	0.04	0.06	0.06	0.08	0.07	0.15
Total sec. which is the coeff. for real time	10.59	9.21	3.91	2.75	1.64	0.99	0.61	0.44	0.37	0.31	0.44	0.26

Main conclusions.

1) This chapter shows how a simulation based on real data for Bulgaria can be made from ortophoto images and GIS raster data.
2) The obtained results show relatively good accordance between the actual burned area and the simulated area.
3) The result achieved is an important step towards the creation of a model to predict the distribution of forest and field fires in Bulgaria. Since the simulation of the fire can be faster than the real time development of the fire, it opens up opportunities for reliable predictions and then management of the fire to avoid or minimize the negative impacts.

4. Example of the architecture of a system for prediction and monitoring early warning and fire spread in cases of wildland fire. The fourth chapter describes an example of an architecture in a project system for early warning in cases of wildland fires and the necessary components that it must have in order to be applied in the operational work of the departments of the Ministry of Interior responsible for firefighting and civil defence. For the first time the idea of this architecture was presented by the author in a project proposal called "PERUN", submitted under FP7 in 2007. The implementation of a system for early prediction and monitoring of the development of forest and field fires requires conducting serious research in many areas. The most important ones are listed here:

1. Studying the characteristics of topography, vegetation type, soil and water resources and their characteristics.
2. Research and analysis of existing models and their calibration for Bulgarian conditions as a base. Here the results from the work with the WRF-Fire model shown in Chapter 3 and the results obtained in Chapter 2 can be useful.
3. Developing software, taking into account the additional features that distinguish Bulgaria from other countries where the described and calibrated models are created.
4. Visualization of results showing the climatic characteristics and change in wind turbulence and water evaporation caused by the burning process.

5. Enabling in addition satellite and other images: 1) describing the land use and 2) reacting to occurrence of a wildland fire.

This requires collaboration of researchers from different fields: geographers, climatologists, ecologists, mathematicians, computer scientists, programmers, and last but not least, specialists in fire safety. The architecture example is presented in figure.

The structure is suitable for data coming from satellite sources and data collected by the monitoring areas. Each of the modules processes the incoming data and transmits it to a processing unit. The end result is a visualized image of the simulated terrain where the fire develops.

It is important to note the need for fast parallel computing because this is the only way to achieve reliable and faster simulation of the fire development in real time, which is extremely important for fire safety teams.

Main conclusions.

1) Worldwide there are a number of models for simulation of forest fires, which are tailored to specific local conditions. Not all models may be used for simulations in Bulgaria, since some of the parameters used do not correspond to the Bulgarian characteristics [16, 18]. Some models can be used, but must be revised and adapted to the specific topographic, climatic, land use or land cover issues and conditions and then calibrated for Bulgaria.
2) After the numerical experiments shown in Chapter 3, we can conclude that the WRF-Fire model has all the qualities to be applied for the Bulgarian conditions and used by operational teams of fire safety and rescue. This requires the creation of centralized databases that contain information needed to simulate forest fires, which can be used both for practical purposes and for scientific work in this area.

III. Conclusions.

1. Main scientific and practical contributions. The main scientific and practical contributions in the thesis are:

1. An analysis of pre-existing methods for fire spread and fire behaviour models has been made. An assessment of the possible occurrence of the most common type of fire for Bulgarian conditions – surface fires – has been presented.

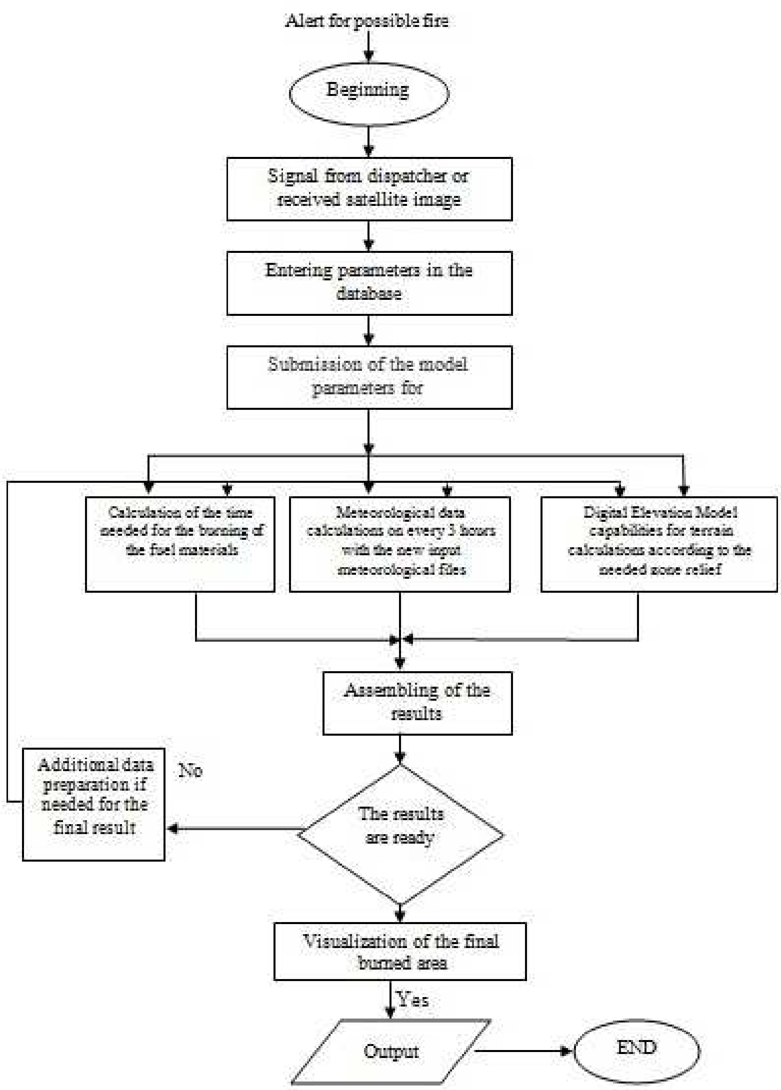

Fig. 2. Diagram of the tasks in the system

2. A game-method model has been proposed for field fires and test software has been developed for the practical evaluation of the method.
3. For the first time in Bulgaria an experimental model (called WRF-Fire) is successfully tested in use for early prediction of the spread of wildland

fires. WRF-Fire has a scientific approach combining functionalities from models such as FARSITE, BEHAVE, BEHAVE Plus and can be applied on supercomputers with parallel calculations practical in scientific tasks.

4. An algorithm has been created for implementing real data when the WRF-Fire model is used. GIS tools are applied for ortophoto processing of the meteorological data, the land use and land cover information for the selected area for simulations and this has been applied in a Linux environment.
5. An example of a possible architecture of an interactive computer-based system for decision support of incident commanders in cases of wildland fire has been created. The system architecture has modules, which makes it easier for computer calculations and optimal on hardware usage. The proposed system can also be used as a self-educating system in firefighters' schools to test special skills.

2. Directions for future research. The results presented in the thesis suggest the following directions for future research:

1. Examining additional models for surface fire spread, along with representatives from the other three types of fires.
2. Completing the considered mathematical game-method model with meteorological data.
3. Creating a Web-based version of the proposed system architecture for decision support in cases of wildland fire behaviour in a way that the responsible authorities can handle the incoming data quickly, easily and faster than the fire spreads.

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