Computer simulation and predicting dangerous forest fire behaviour

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***Abstract*—**The paper deals with the problem of computer simulation of forest fires and predicting their behaviour to prevent large damages of property and environment and tragic human incidents caused by the fire. The well-known forest fire simulator Farsite was adapted recently for real conditions in Slovak forests and was used for the computer reconstruction of one especially tragic forest fire in the Slovak Paradise National Park (Slovakia) in 2000. The simulation results and the experience achieved during the fire reconstruction allow to predict and analyse potential fire danger and specific fire behaviour in the investigated region. Several recent interesting results on predicting dangerous tendencies of the fire spread under various meteorological, fuel and terrain conditions are presented.

***Keywords*—**Computer simulation, forest fire behaviour, Farsite, fire reconstruction, decision support system.

I. Introduction

FOREST fires belong to highly dangerous destructive natural phenomena causing large damages of property and vegetation, devastating badly a natural scenery, eco-systems and environment of the landscape afflicted by the fire, and often even threatening people`s lives. Advances in computers and information technologies stimulate the development of high-performance computer systems capable to simulate the forest fire growth after the fire detection and to describe its spatial and temporal behaviour. Such systems are able to quantify and often even to display various fire characteristics needed for the fire hazards and effects evaluation (rate of spread, flame length, fire intensity, etc.). They can be used directly for specific purposes of the forest fire management or can be included in more complex decision support systems [1]. However, the current use of the fire behaviour predicting systems and decision support systems in the EU is still generally little [45].

In concrete region, the fire behaviour predicting systems can be used for the fire prevention and planning. They allow to simulate various scenarios of the fire management response to test the effectiveness of tactics and fire suppression strategies under different possible conditions taking into account the specific regional infrastructure, conditions and existing fire-fighting means. They can be used also for past fires reconstruction during the post-suppression stage to better understand the circumstances that lead to human incidents and extraordinary large losses of values and property (see e.g. [38-40, 16]). Finally, they can be used for operational purposes during active fires and for training.

Several advanced software tools capable to perform simulations of real (or potential) extensive forest fires under real (or potential) meteorological, fuel and topographic conditions have been developed. Some of them run on currently available computer equipment and are applicable even for the operational fire-fighting purposes (e.g. systems Behave and Farsite).

There are two dominant principles of the forest fire spread modelling based on field and laboratory experiments, validation and verification. The first principle is represented by so called semi-empirical models. They are based on Rothermel's formulation of the steady-state fire spread. The frontal fire characteristics (rate of spread, flame length, fireline intensity) are dependent on the current environmental conditions such as fuel characteristics and moisture, windspeed and direction, topographic slope and aspect. For the fireline propagation in time, either Huygens' principle or cellular approach are used as simulation techniques for the fire spread in time and space. The systems Farsite [8], Wildfire [41], Firestation [23] and Firemap [3] belong to the well-known forest fire simulators of this type. The space resolution in these programs is usually 10 meters and more. Therefore, the heterogeneity on smaller areas is not considered and parameters related to the space unit are specified as averaged values. Such systems are not strictly limited concerning the simulated space and their calculation time is measured in seconds.

The next principle is represented by so called physical models. The combustion process is described using the conservation laws of mass, species, momentum and energy utilizing the knowledge about computer fluid dynamics. The systems WFDS [6, 25, 42-44], Firetec [22], Firestar [5] and CAFME [27] are examples of such systems. Physical models take into account one or several processes of energy transfer from the burning zone to the unburned fuel and generally lead to differential equations systems requiring sophisticated and time-consuming numerical calculations and advanced high-performance computing environment [28]. They respect the heterogeneity of fuel structure in very small spaces. Despite the space resolution can be in centimeters, the resolution is

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strictly limited by the simulation space where the process is modelled (3D simulations). The calculations are limited to relatively small space having a calculation time measured in hours. A proper parallelization of the calculations is a challenge for future research.

The system Farsite [8] is one of the best semi-empirical forest fire simulators used both for the planning and operational fire-fighting purposes. It is a GIS-based system originally developed by USDA particularly for the use in top fire season forests in the USA. Its applicability for European forests was investigated only recently. Farsite was evaluated in Germany, Switzerland, Italy and Spain [17-18, 2, 26]. The system Farsite incorporates several advanced fire behaviour models including the models for surface fire, crown fire, point-source fire acceleration, spotting, and the fuel moisture calculation model.

In our previous works [9-12, 15] we studied the mathematical foundations of the methods implemented in Farsite to make possible the proper use of the system and its adaptation for intended fire simulation in Slovak forests. The next goal was to reconstruct selected past forest fires in Slovakia. The analysis performed allowed us to better understand models included in the system and their limitations which can affect the simulation.

In this paper some new recent results obtained during the reconstruction of one extraordinarily destructive and tragic forest fire in the Slovak Paradise National Park using Farsite will be described. The results will show abilities of Farsite to predict dangerous tendencies of the fire behaviour and potential regions of increasing fire hazard in specific conditions and circumstances. Some preliminary results related to this fire reconstruction have already been presented [13, 16, 31], but the main results of the fire reconstruction itself are to be published elsewhere. This paper is focussed on presentation of the ability of computer simulation to predict dangerous fire behaviour in the given region.

II. Fire Reconstruction

To perform a good and reliable reconstruction of a past forest fire, it is not sufficient only to have an advanced simulation system. It is necessary to prepare proper real input data to characterize conditions affecting the fire evolution (primarily the data about the topography of given area and its vegetal cover, the actual meteorological situation, etc.). It is also very important to have other sources of special information about the fire behaviour and specific conditions of its propagation including the fire-fighting activities performed to reduce the fire spread. A direct contact with the fire-fighters and specialists on the place is also very helpful. They can afford valuable information about the circumstances of the fire.

The fire selected for the computer reconstruction was a well documented forest fire in the locality Krompla in the Slovak Paradise National Park in October 2000. This fire belongs to the most tragic destructive fires in this region. Damaging about 80 ha of valuable original forest, it caused a big amount of destroyed values and property. Moreover, six inhabitants from the near village Hrabusice lost their lives during the works to reduce the speed of the fire propagation. The fire evolution and actual conditions of the fire can be briefly summarized using the fire documentation [20]:

The fire origin (23.10.2000). In the evening, just before getting dark, smoke was observed. However, the patrol sent to find the fire did not find the source of smoking due to the darkness and difficult unaccessible terrain in the investigated locality.

The first day of the fire (24.10.2000). The fire was confirmed in the locality Krompla (cadastral region of villages Hrabusice and Betlanovce): the first field investigation at 10:00 and the aerial investigation at 12:00 found about 2 ha and 3-6 ha of burned area, respectively. Till the noon, some fire-preventive works (digging around burning area, building fuel-free zones and path cleaning) were being done to reduce the rate of fire spread. The boundary of burning area at 12:00 is plotted in the fire documentation (see Fig. 1). The north-western part of the area was really detected but the south-eastern part was only assumed. Early in the afternoon, a strong south-eastern air circulation from Black Valley to the ridge of Krompla began. It induced increasing fire propagation in a steep slope at the closure of the valley. Moreover, some local crown fires occurred; mainly through crowns of dense branched spruces. During this extremally fast fire spread, six people died at the place plotted in the map (see Fig. 1). Before the tragic incident, some fire suppression works were being performed at the ridge and downhill along borders of burning area. Later, almost all extinguishing works were stopped. Therefore the burned area at 18:00 was not located and it is not plotted in the fire documentation (see Fig. 1).

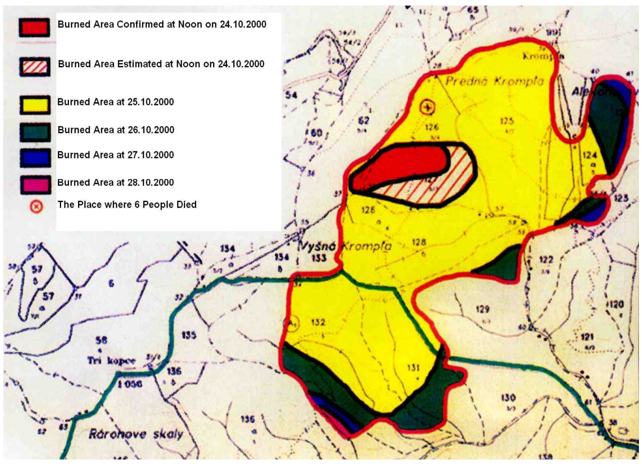


Fig. 1. Fire evolution.

The second day of the fire (25.10.2000). The fire propagated mainly in south-western direction. At noon, it was observed that the area about 15 ha in the Three Hills Landscape Reservation was afflicted with fire. During this day, the eastern boundary of burning area was the main suppression priority. 219 people, 1 helicopter and 2 aircraft sprayers took part in the fire suppression. The effect of the helicopter was evaluated as insufficient because of a low frequency of flights and a distant fuel tankage (in Poprad). The suppression effect of planes was also low due to the forest terrain and lower volume of drained water. The boundary of burning area at 18:00 (about 45 ha) is plotted in the fire documentation (see Fig. 1).

The next days of the fire. During the next days the fire was localized. The first two days of the fire propagation were the most critical period of the fire, therefore the fire reconstruction was focused on this period.

A. Input data and simulation parameters

The input data for the fire reconstruction were elaborated. The GIS data related to the *real topography* (elevation, slope and aspect) and its *canopy cover* were prepared by our collaborators from Technical University at Zvolen (Slovakia). To describe the vegetal cover of given region they used the data extracted from available forestry maps and ortophotomaps and the knowledge about the vegetation of Slovak forests. They also made necessary field investigations at the place and the laboratory evaluation of taken samples of vegetation to specify needed fuel parameters [24, 34-36]. They developed a new original *fuel model* TER valid for the whole area burned by the fire. The parameters of TER are shown in Table 1 where DFL is 1h, 10h and 100h dead fuel loading, LHFL is live herbaceous fuel loading, LWFL is live woody fuel loading, DFSTR is 1h dead fuel surface to volume ratio, LHFSVR is live herbaceous fuel surface to volume ratio, LWFSVR is live woody fuel surface to volume ratio, FBD is fuel bed depth, DFEM is dead fuel extinction moisture, HCDF is heat content of dead fuels, and HCLF is heat content of live fuels.

TABLE I.
PARAMETERS OF THE FUEL MODEL TER.

PARAMETER	UNIT	VALUE
1h DFL	t/ha	5.842
10h DFL	t/ha	3.499
100h DFL	t/ha	0.339
LHFL	t/ha	0.473
LWFL	t/ha	1.57
1h DFSVR	1/cm	77.8
LHFSVR	1/cm	49.0
LWFSVR	1/cm	49.0
FBD	cm	32
DFEM	%	27
HCDF	kJ/kg	18600
HCLF	kJ/kg	18600

The *meteorological data* required were prepared and evaluated by our collaborators from Ecological and Forestry Research Agency (Slovakia) using the data gathered from the meteorological stations in Poprad, Telgart and Kosice [33, 19]. Since these stations were relatively far from the fire, we modified the data according to the information from the fire documentation. The parameters characterizing the meteorological situation are shown in Table 2 where M is month, D is day, H is hour, WS is wind speed above the vegetation [km/h], WD is wind direction given as azimuth [degree] (azimuth of south-eastern wind is 135 degrees, azimuth of south-western wind is 225 degrees), and CC is cloud cover [%].

TABLE II.
PARAMETERS CHARACTERIZING METEOROLOGICAL SITUATION.

M	D	H	WS	WD	CC
10	24	00:00	0	135	50
10	24	12:00	0	135	50
10	24	12:15	30	135	50
10	24	12:45	20	135	50
10	24	17:00	20	135	50
10	24	21:00	20	135	50
10	24	22:00	5	135	50
10	25	00:00	5	135	90
10	25	12:00	5	225	90
10	25	13:30	50	225	90
10	25	14:30	20	225	90
10	25	21:00	20	225	90

TABLE III.
PARAMETERS CHARACTERIZING WEATHER.

M	D	P	H_1	H_2	T_1	T_2	V_1	V_2	E
10	23	0	5	15	-9	17	70	50	695
10	24	0	5	15	-6	18	70	50	695
10	25	0	5	15	5	15	70	50	695
10	26	0	5	15	5	19	52	32	695

Other parameters characterizing the *meteorological situation* are shown in Table 3 where M is month, D is day, P is precipitation [mm], H_1 and H_2 are hours of minimum and maximum daily temperature recorded, T_1 and T_2 are values of minimum and maximum daily temperatures [degree Celsius], V_1 and V_2 are maximum and minimum humidity [%], and E is elevation [meters above sea level].

Due to the low night temperatures and freezy mornings characteristic for the given period of year, both the higher values (10-12 % for died fuel, 170 % for live fuel) and the mediate values (6-8 % for died fuel, 120 % for live fuel) of the *fuel moisture* were tested. It was observed that the higher values better correspond to the fire conditions.

Parameters characterizing *tree crowns* were not determined for the given region therefore the crown fire was not simulated. Similarly, any secondary fires ignited by flying wind-driven burning fragments of the fuel were not considered.

The value of the spread rate reduction parameter (*adjustment factor*) was set to 0.4 performing several comparative simulations with the Farsite system to correspond to the seasonal meteorological conditions and the climate of the region.

III. Forest Fire Simulation

The computer simulation allows to analyse possible potential fire danger in concrete region to predict dangerous tendencies of potential fire behaviour detected by fire simulator. Such an analysis can help to better understand the fire danger in the region and to make more competent decisions during future fire events to prevent losses of people's lives. In this part we summarize the experience achieved during our reconstruction of the fire at Krompla (described above).

One of the most difficult problems related to every past forest fires reconstruction is to determine authentically the *fire origin* (the place where the fire was ignited). The proper identification of the fire shape during the first minutes after its ignition is important also for the purposes of determination of the reason of fire. The shape of burning area during the first minutes and hours of the fire can significantly affect the fire behaviour in later periods of its evolution, especially in variable broken terrain. The correct location of the fire source and the way how the fire was ignited (i.e., wheather it was a point source, ignition line, or a polygon) is significant for the simulation.

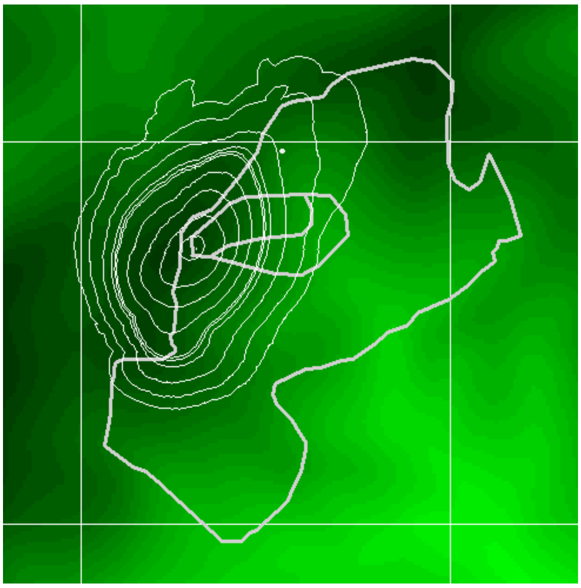
Other problem which appeared to be especially difficult to deal with during the fire reconstruction was to estimate and properly quantify the effect of *human factor* on the fire behaviour. There were not any available sufficiently accurate and reliable data, nor competent estimation of the fire suppression efficiency. For the purposes of the fire reconstruction, the human intervention against the fire was spatialy and temporally approximated by the description of fire-fighting activities in the fire documentation (digging around burning area, cleaning paths, building zones with limited fuel, suppression by ground and aircraft means, etc.). We assumed that the fire-fighting activities during the first hours before and after the fire confirmation focused mainly on preventive actions for the fire speed reduction on wider area. However, according to the fire documentation the fuel-free belts were not very efficient and the works were rather difficult (locally even 60 % slope). Moreover, in the morning on 24.10.2000 it was not easy to identify the size and shape of burning area due to hardly accessible difficult terrain. The fire-engine vehicles sent later even did not reach the burning area at all. On the other hand the fire suppression on the ridge and partly on borders of the fire (suppression in the gradient direction) is mentioned to be efficient and probably affected the fire shape. Due to these reasons we did not assume in this paper any strong effect of suppression activities during the first hours, except of those on the ridge. Note that the rocky parts on the ridge could also retard the fire spread on the ridge.

The next problem appeared was a qualified estimation of the effect of *crown fire* on the fire behaviour. The crown fire is characterized by a fast fire propagation forwards through tree crowns accelerated by falling down burning branches and fragments of the crown, which originate new ignition sources of surface fire. These secondary fires overrun the main fire front and create tree-crown fire streets followed by the lower-speed main surface fire front. A sudden blow-up of the flame and its flash-over into the crown, as well as an unexpected increase of the fire spread dynamics, a noise and a dense smoke caused by reaching live parts of vegetation in crowns are the most significant stress factors contributing to the impaired perception and judgement of the situation and the loss of orientation in the terrain in direct contact with the fire front. According to the fire documentation, the tragic incident happened in a complicated terrain with dense branching spruces, hazels and disseminated maples and beeches. The crown fire appeared after an abrupt change of air circulation in direction from Black Valley onto the ridge in the valley closure. It could contribute to the incident, when the crown fire passed locally very fast into tree crowns and spread fast mainly through crowns of withered dense branching spurces. The crown fire in combination with the characteristic tendencies of the fire behaviour detected by computer reconstruction correspond to the description of the situation leading to the tragic incident in the fire documentation.

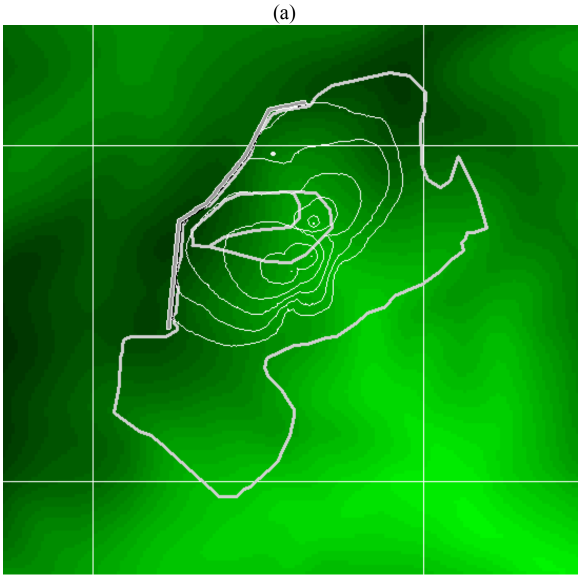
IV. Fire Behaviour Analysis

The first simulations assumed the fire initiation in a point source. The point was denoted by forestry specialists as a probable place of the fire origin (see Fig. 2). The given point lies under the ridge of Krompla near the western boundary of burning area at 12:00 on 24.10.2000. It follows from the picture that the specialists assumed the fire propagation in the morning mainly in eastern direction. This assumption seemed to be contentious because the fire would be propagated mainly downhill which is contradictory to current experience.

Fig. 2a shows a fragment of a 2-days fire simulation started at 9:00 on 24.10.2000 in the point proposed by the forestry specialists with 3-hour perimeters recorded. The simulation indicates that in the first stage of the fire it propagated from the given point in all directions. The 2nd fire perimeter corresponding to the burning area at 12:00 has an oval shape but it does not represent the tendency of fire propagation recorded in the fire documentation (the correct shape is much more easterly oriented). Moreover, the fire affects only a small part of the really observed burning area at that time and almost



(a)



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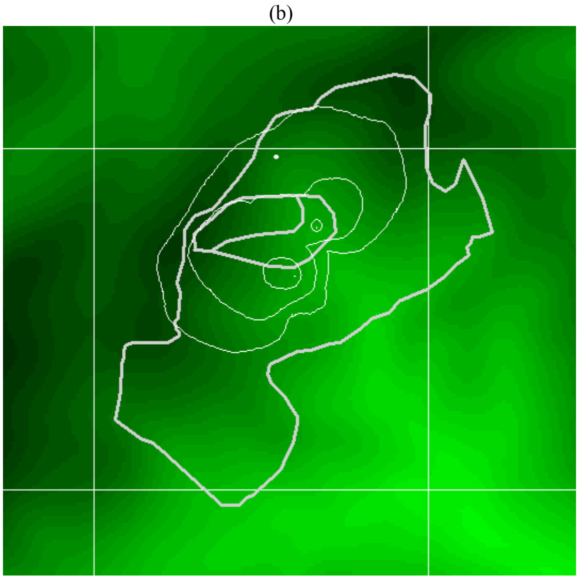

(c)

Fig. 2. Fire behaviour simulations.

complete affected area lies out of the assumed burning area. In addition the fire behaviour markedly differs from the assumed behaviour of the reconstructed fire. The fire relatively early passes through the ridge and propagates on both sides of the ridge in north-eastern, southern and south-eastern direction. However, the reconstructed fire did not pass through the ridge and its northern and partially also its eastern and western part is bordered by the ridge. At 12:00 the simulated fire affects only a small western part of detected and only a small part of the assumed burning area in the fire documentation. The place of the tragic incident, which was reached at around 14:00 on 24.10.2000, is reached by the simulated fire after 15:00 on the next day (see 8th and 9th perimeter). Not until 18:00 on 25.10.2000, the simulated fire does not reach the eastern boundary of the detected burning area at 12:00 on 24.10.2000. Neither the whole fire spread by 18:00 on 25.10.2000 (9th perimeter), nor the main tendencies of the fire behaviour correspond to the fire documentation.

The simulation gave a rather assumed course of fire under given meteorological, fuel and terrain conditions. However, the simulation results do not correspond to the observed fire behaviour. Therefore the simulation indicates that the obtained point is not the probable place of initiation of the reconstructed fire. The described simulation is a good example demonstrating the extraordinary importance of the analysis of fire origin and the way of its ignition in order to obtain a good fire reconstruction.

Further investigations on the reason and the circumstances of the fire origin did not answer the question How the fire began. They discovered a small local fire bellow the ridge appeared a day before the fire confirmation (i.e., sooner) indicating that it was a human-caused fire. Several different interpretations of possible fire ignition appeared. It is assumed that the fire could begin in the point source on the ridge of Krompla near the place given to us by the forestry specialist, or in one or several point sources below the ridge originated by falling some burning pieces from the ridge.

Our further simulation experiments with different kinds and locations of the fire sources (i.e., one or several ignition points, ignition lines and polygons) indicated that it is not sufficient to use a single ignition point to initiate the fire behaving in accordance with the fire documentation (for more details see [14]). By this way we got several possible ways how the fire could origin. Moreover, we achieved a very good experience with the fire behaviour in the investigated region and discover some dangerous tendencies of the fire spread which indicate substantially higher fire danger particularly in the region where the group of people died. In the following we show some examples of such a dangerous fire behaviour.

In Fig. 2b, there is shown a fragment of a fire simulation initiated in three points representing a detailed fire propagation till 15:00 on 24.10.2000 with 1.5-hour perimeters recorded. The points are about 300-350 m far easterly from the point originally denoted as the fire origin. The points are about 100 m far from each other and lie south-easterly and easterly from the detected burning area. They are located near the southern boundary and in the eastern part of the assumed burning area in the fire documentation. The fire at 12:00 on 24.10.2000 affects the whole detected burning area and passes through the eastern and southern borders of the assumed burning area. Around 14:00, it reaches the place where the people died. Fig. 2b shows how the fire spread until 15:00 on 24.10.2000. There are plotted the fire perimeters at 9:00, 10:30, 12:00, 13:30 and 15:00. Showing the fire propagation in more detail, there are better documented inner tendencies of the fire behaviour in given region. Such a simulation allows us to better analyse what can happen in the interior of burning area under similar fire conditions. The first three fire perimeters correspond to the fire behaviour at 12:00 plotted in the fire documentation.

There is shown a dangerous tendency of the fire propagation from the most northerly lying point to the place, where the tragic incident happened. Analysis of this phenomenon indicates that the true reason of formation of the described fire propagation was not only joining both the fires but there was a significant contribution of the fire initialization in the most northwardly located ignition point. Since the fire ignited in a valley between two ridges with a tendency to propagate faster in two dominant directions (north-eastern and western), its fireline has a characteristic shape with a lagging place on its northern part (see perimeter 2 at 10:30). The join of both fires only deepened this tendency of the fire spread in these directions (see the faster lagging on perimeter 3 at 12:00, when the second fire did not contribute to the tendency of the first fire spread in north-eastern direction, and on perimeter 4 at 13:30, when the lagging is already evident). This interpretation of the phenomenon is supported also by the shape of perimeter 5 at 15:00, where the significant weakening of the described phenomenon is visible, probably by weakening of the original main spread tendency of this branch of fire. The fact, that the trajectory of the lagging point on the fire front during the fire evolution lies very close to the critical place, where the people died, indicates that the place could be affected with the fire simultaneously from two directions (from the south-east and the south-west). The simulated fire reached the place at 14:00 which is in accordance with the fire documentation. Although the performed simulation does not simulate any crown fire mentioned in the fire documentation, it indicates the possibility of surrounding the place of incident from two sides.

In Fig. 2c, there is shown a fragment of a fire simulation initiated in two points representing again the fire propagation till 15:00 on 24.10.2000 with 3-hour perimeters recorded. The ingnition points lie again in the distance about 300-350 m far easterly from the point originally denoted as the fire origin. The fire behaviour is similar to the simulation shown in Fig. 2b. Similarly, the simulation indicates that the place where the group of six people died could be affected with the fire simultaneously from two directions. The simulated fire reached the place at 14:00 which is in accordance with the fire documentation. Although the performed simulation does not simulate any crown fire mentioned in the fire documentation, it indicates the possibility of surrounding the place of incident from two sides.

Note that in spite of very encouraging and interesting results obtained by the analysis of the fire behaviour during first stages of its propagation, in general the system Farsite provides relatively limited means for truthworty modelling of the fire origin. This also follows from some properties of the fire spread models implemented in the system because the most of them were developed for the fire spread simulation in the steady-state period of burning. A number of assumptions are critical to modelling the forest fire behaviour. Some of these assumptions are even not strictly met by current modeling methods. However, discussion on the assumptions and limitations of semi-empirical models and their concrete implementation in Farsite is well known in the related literature (for more information see e.g. [8, 32, 12, 4]).

V. CONCLUSION

The works on the computer reconstruction of the forest fire in the locality Krompla located in the Slovak Paradise National Park in October 2000 allow us to analyse the main characteristic tendencies of the fire behaviour in the given region. The simulations performed enable to achieve better experience with the fire spread in different stages of the fire evolution under given conditions and to find new knowledge about the reasons and location of the fire origin, as well as about the way how the fire was initiated. For these purposes, the Farsite forest fire simulator was adapted and used in Slovak forests under specific conditions of the Central Europe. The analysis of the fire behaviour simulated indicates dangerous tendencies of the fire spread at the time when the group of six people engaged in the fire suppression works were entrapped by the fire. The simulations indicate also the increasing fire danger in the critical region. The simulations confirmed that the area where the people died belongs to the most dangerous places in the locality. The simulation results also indicate the usefullness of the computer simulation of past fires for the purposes of fire management, planning and prevention. The results can be used also for better co-ordination of future fire-fighting works in given region and for training purposes.

The knowledge of mathematical foundations of the forest fire spread model implemented in the used simulation tool in variable topographic, meteorological and fuel conditions is significant for better understanding and proper improvement of the model itself, as well as for its correct use and the simulation results interpretation. Due to achieve better results of simulation, the integration of proper models of the influence of wind in variable topography and of tangential forces at fireline on fire spread is a challenge for future research. Particularly the later problem has not been solved yet although fire experiments confirmed that the influence of tangential forses on the fire spread direction and rate is not negligible [37, 39-40, 29]. We studied Richards' elliptical model [32] used in Farsite for surface and crown fire simulation and developed an original procedure for the model derivation which allows to suggest some specific improvements of the model [12]. This method allows also to consider another shapes of local fire spread which were observed in certain conditions during fire experiments.

The development of 3D visualization techniques for real forest fire spread simulation for the purposes of 3D virtual reality of forest fire simulation is the next interesting problem [13, 31, 30, 21]. The insertion of the 3D visualized forest fire simulation to the tree growth simulator SIBYLA [7] developed particularly for Slovak forests is also a challenging problem for future.

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