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DYNAMIC MODELS FOR PREVENTIVE MANAGEMENT AND REAL TIME CONTROL OF FOREST FIRES

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Abstract: In this paper, a new methodology based on system modelling and optimization is developed to determine forest fire risk, and subsequent resource allocation, over a regional area. A forest fuel moisture model and a propagation model are developed, in order to determine the dynamic risk assessment. The objective of resource allocation is twofold. In the *preventive phase* means and crews are re-allocate on the basis of the forecast risk, in order to successfully fight initially spread fires. In the *real-time phase*, optimal decision techniques must be used in order to determine the optimal composition of means that are sent to signalled fires. *Copyright © 2002 IFAC*

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1 INTRODUCTION

Large and widespread forest and woodlands areas and frequent meteorological conditions propitious to ignition and propagation, make forest fires emergencies a dramatic problem which Italian firemen and forest warden must face. Besides, high probability to have several wildfires simultaneously, limited resources availability and high cost of their allocation make real time forest fire risk management a very complex problem. Then, it is not surprising that every year a great number of wildfires destroy more than 2% of such natural resources.

In Italy, Fire Brigade (CNVF *Corpo Nazionale dei Vigili del Fuoco*), and Forest Service (CFS *Corpo Forestale dello Stato*) manage fire emergencies, while forest fires prevention and forecasting are specific tasks of CFS. CFS/CNVF are hierarchically organized upon different levels, from a national to a local scale. At the national level the COAU (*Centro Operativo Aereo Unificato*) manages the water bombers air fleet, composed by 34 means among helicopters and airplanes. In particular, 18 helicopters are preventively allocated to specific regions, while 16 airplanes are positioned in few main airports and intervene only when a severe active wildfire is signalled somewhere in Italy. CFS/CNVF stations are spread over the territory. Each station is responsible of 300 - 400 hectares of forest or woodland, generally belonging to several municipalities. The main task of forest warden is to evaluate the dangerousness of active fires, and the risk for civil or industrial settlements, and infrastructures. On these bases, they may identify the most suitable way of intervention, taking into account the available forces. Fire prevention, forecast, and management require the co-ordination, at a regional, or a national level, of resources on the territory, especially in the presence of several simultaneous fires.

In this paper, an integrated approach based on system modelling and optimization is presented, in order to support the decision maker in preventive/real time management of forest fire emergencies. A forest fuel moisture model and a propagation model are developed, which are applied on the whole target region in order to make a dynamic risk assessment, in terms of expected fire speed and potential fire intensity.

By using such models, a decision support system (DSS) able to determine "optimal" decision can be set up. In a preventive phase, when no active fire is signalled, the DSS is able to provide the optimal resource allocation, taking into account the expected fire intensity value, transfer times of resources, and the available fire extinction power. That may be achieved by solving an optimization problem whose objective is the minimization of the differences between the expected intensities of the various fires and the fire extinction power supplies assigned to them. The predictive simulation of active fires is obtained by using a dynamical model which allow to represent biomass consumption and fire behaviour in time and space, on the basis of information concerning meteorological and morphological conditions, and fire extinguishing action.

The remaining of the paper is organizes as follows. In the next sections the architecture of the whole system is introduced, including the GIS database, the meteorological Limited Area Model (LAM), the fuel moisture model, and fire propagation models. In the third section, the risk assessment module is presented. In the fourth section, the resource allocation module is discussed, both in a preventive and in real time. Some concluding remarks will end the paper.

2 THE PROPOSED APPROACH

The Decision Support System (DSS) proposed is based on five independent main modules, namely: 1) the fuel moisture model; 2) the propagation model; 3) the risk assessment module; 4) the preventive resource allocation module, 5) the real time resource allocation, which interact with two external modules (GIS, LAM) able to provide the required data needed for the overall system definition. Figure 1 shows the whole system architecture.
The target region is considered as a discretized spatial domain, represented, at each time interval τ_h (h=1,..,n), by a regular grid of M cells. For each grid cell k, a LAM gives, for each time interval τ_h, a vector of weather forecast variables $\bar{x}_k(h)$, while vegetational, orographical, and land-use data are available from GIS databases.

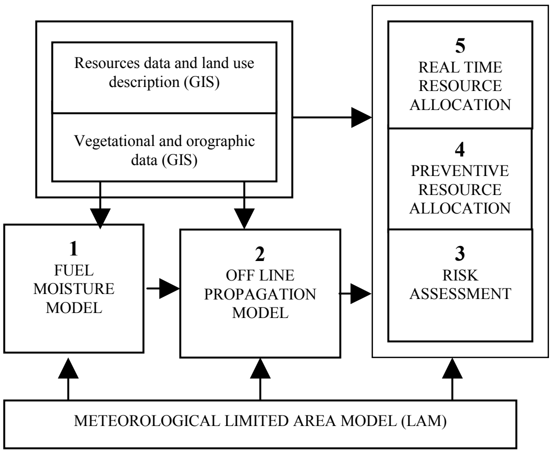

Fig. 1. The system architecture.

2.1 *Dynamic fuel and propagation models*

The fuel classification proposed is based on three main layers containing both dead fine fuel, and live fuel, classified as:
1) layer L_1, constituted by dead fine fuel, including dead grasslands, and dead shrublands;
2) layer L_2, constituted by shrublands including sagebrush and chaparral;
3) layer L_3, constituted by woodlands with tree-dominated areas.

Morphological and physiological characteristics of the species belonging to the three different layers are completely described by a parametric model. It is assumed that morphological parameters cyclically vary over the year, and that it is reasonable to use an average seasonal value for any of such parameters. (Nunez-Regueira *et al.*, 1999).

As regards the physiological characteristics, it is assumed that the information related to average tissue moisture is sufficient to determine both ignition and propagation fuel behaviour. Different tissue moisture models are used for the three different layers. In order to define the fire ignition probability on the first layer (L_1), it is assumed that dead fine fuel moisture level follows the relative atmospheric humidity behaviour through a given functional relationship. Besides, it is assumed that the moisture of layers L_2 and L_3 is characterized by a seasonal dynamics, over which a meteorological dynamics is superimposed. Thus, three random fields, U^i (i=1, 2, 3), representing the moisture levels for the three layers, are considered. Each random field is a collection of random variables u_k^i, i = 1, 2, 3, associated to cells k = 1, …,M.

It is assumed that each of the above random fields is characterized by a joint lognormal probability density distribution, so that marginal distributions are given by:

$$u_k^i = LN\left(\mu_{u_k^i}, \sigma^2_{u_k^i}\right);\ i=1,2,3;\ k=1,\dots,M; \qquad (1)$$

where symbols have an obvious definition. This means that the marginal distribution of the logarithm of variable u_k^i, namely z_k^i, is normal:

$$z_k^i = \ln\left(u_k^i\right) = N\left(\mu_{\ln\left(u_k^i\right)}, \sigma^2_{\ln\left(u_k^i\right)}\right) \qquad (2)$$

Actually, the spatial correlation structure of such random fields is of no use for the following development of the proposed procedure. Thus, in the sequel of the paper, attention will be focused only on marginal distributions of random variables.

It is reasonable to suppose that there is a relation between the parameters (expected value and variance) of the random variable u_k^i (i=1, 2, 3), and the vector of meteorological forecasts $\bar{x}_k$, namely:

$$\mu_{u_k^i} = E\left[u_k^i\right] = \gamma_i\left(\bar{x}_k\right) \qquad (3)$$

$$\sigma^2_{u^i_k} = E\left[\left(u^i_k - \mu_{u^i_k}\right)^2\right] = \vartheta_i(\overline{x}_k) \qquad (4)$$

where functions $\gamma_i(\cdot)$ and $\vartheta_i(\cdot)$ are assumed known and independent from index k. Note that, in the simple model considered here, there is not a dynamic model of the fuel moisture, as the significant parameters of its probability distribution are assumed to be direct functions of the observed or forecast meteorological conditions. More complicate models should include the modelling of such a dynamics (Orieux, 1974).

On the basis of the information relevant to the fuel moisture level, a dynamic propagation model (Fiorucci *et al.*, 2001) allows to obtain the fire front linear intensity I_k [kW/m], for each grid cell.

3 RISK ASSESSMENT

Estimated values of linear intensity, for each grid cell k, allow to estimate fire risk relevant to the target region. Actually, it is assumed that data related to land-use, infrastructures, and urban zones are identified and stored in a GIS database. A number m of different classes of objects c^i (i=1,.., m), are introduced, and are used to represent the various typologies of infrastructures or inhabited areas present in each cell k. In fact, the presence of such objects increases the risk in case of fire occurrence. For this reason, it is convenient to introduce a coefficient $p^i_k \in \{0,1\}$, which expresses the absence/presence of objects of kind i within cell k.

Than, it is possible to assign a risk coefficient to every cell k, as follows

$$R_k = I_k \cdot \sum_{i=1}^{m} c^i \cdot p^i_k \quad k = 1,..,M \qquad (5)$$

where c^i is a weight coefficient relevant to class i.

The knowledge of R_k allows fire fighters officers to broadcast alert messages or to alert the troops located at the stations exposed to major risks.

4 THE RESOURCE ALLOCATION PROBLEM

The objective of resource allocation is twofold. In the *preventive phase*, referring to a suitable defined time interval (e.g. 24 hours), it is necessary, on the basis of the forecast risk R_k, k = 1, ..,M, to reallocate means and crews able to patrol the territory, in order to successfully fight initially spread fires.

In the *real-time phase*, optimal decision techniques must be used in order to determine the optimal composition of means that are sent to signalled fires, considering the whole scenario of active fires, and their forecast behaviour.

4.1 The preventive phase

In this phase, the main purpose of CFS/CNVF is that of maintaining in each station an effective team ready to intervene in case of fire alert.

The daily total amount of fire extinguishing power is given by the sum of the powers of all available means in terms of total water supply deliverable by trucks or aircraft, supposing that all the water carried on the fire front is spread immediately. The total extinguishing power P [kW], available on the considered region, can be estimated on the basis of the latent heat $\widetilde{Q}$ [kJ m^{-3}], and on the nominal rate flow q_r [m^3 s^{-1}] of each vehicle r, under the simplifying hypothesis that all the water directed over the flame is vaporized. Then

$$P = \sum_{r=1}^{R} q_r \cdot \widetilde{Q} \qquad (6)$$

where R is the number of the available means.

The problem to be faced is the optimal partition of the total available extinguishing power among the set of cells (say, Z cells) having R_k >0. Such a problem must be formalized taking into account the objective of minimizing the weighted sum of the differences between the request power and the actual assigned power for each cell of interest. In addition, transportation costs from a station to another must be taking into account, as well as the objective of penalizing the assignment of resources located at a certain station to a cell too distant from that station.

Then, the problem can be formalized as:

$$\begin{aligned} \min \sum_{k\in Z} \left(\sum_{i=1}^{m} c_i p^i_k \right) \max\left(I_k \cdot \Delta - \sum_{s=1}^{S} x_{sk}, 0 \right) + \\ + \sum_{k\in Z} \sum_{s=1}^{S} ct_{sk} x_{sk} + \\ + \sum_{\substack{r=1 \\ r\neq s}}^{S} \sum_{s=1}^{S} ct_{rs} y_{rs} \end{aligned} \qquad (7)$$

s.t.

$$X_s = \widetilde{X}_s + \sum_{\substack{r=1 \\ r\neq s}}^{S} y_{rs} - \sum_{\substack{r=1 \\ r\neq s}}^{S} y_{sr} \qquad (8)$$

$$X_s = \sum_{k\in Z} x_{sk} \qquad (9)$$

$$y_{rs} \geq 0 \quad \forall s\, \forall r \qquad (10)$$

$$y_{sr} \geq 0 \quad \forall s\, \forall r \qquad (11)$$

$$X_s \geq 0 \quad \forall s \qquad (12)$$

where

- Δ is the edge length of each cell;
- x_{sk} is the quantity of extinguishing power located at station s and assign to cell k, $k \in Z$, s=1,…,S;
- ct_{sk} is a measure of the difficulty of reaching cell k form station s, $k \in Z$, s=1,…,S,;
- ct_{rs} is the unitary transportation cost from station r to station s, r=1,…,S, s=1,…,S, $r \neq s$;
- $\widetilde{X}_s$ is the (known) amount of extinguishing power preventively located at station s, s=1,…,S;
- y_{rs} is the amount of extinguishing power whose is sent from station r to station s, r=1,…,S, s=1,…,S, $r \neq s$;
- X_s is the amount of extinguishing power located at station s after the re-location of the extinguishing power, s=1,…,S;

Note that obviously the initial conditions must satisfy

$$\sum_{s=1}^{S} \widetilde{X}_s = P \tag{13}$$

The solution of the above problem, which can be put in standard linear programming form, provide optimal location/assignment of extinguishing resources basing on a continuous modelling of such resources. Then, the solution of such a problem has to be put in an operational form by translating the extinguishing power assignments into actual mean and crew assignments. That could give complicate optimization problems in real case. However, in this paper, this issue is not considered.

4.2 The real time phase

In this phase one or more wildfires are assumed to be burning. The problem will be formalized in connection to a smaller region with respect to the previously considered one, for which transfer times and costs can be assumed to be negligible, even in real time. Let such a region correspond to areas k=1,…,m. In this case, main goal of officers is to assign to each fire a sufficient and effective number of means, taking into account the possible behaviour of fire front in time and space. For this reason, it is necessary to model the fuel consumption dynamics, in time and space, for each burning area, to take into account the influence of the fire extinguishing power, including presently available air means.

For each grid cell k, and each time instant t, the following variables are defined:

- $i_k(t)$	fire linear intensity of active wildfires at time instant t	[kW m^{-1}];
- $\delta_k(t)$	biomass density	[kg m^{-2}];
- $u_k(t)$	biomass moisture	[%];
- $P_k(t)$	active fire extinguishing power	[kW m^{-1}].

An optimization problem can be stated whose objective is the maximization, at the end of a fixed time horizon of length T, of the overall biomass density present in each cell of the target region, namely

$$\sum_{k=1}^{m} \delta_k(T) \tag{14}$$

Wind speed and direction (namely, $w_k(t)$ and $d_k(t)$), for each cell k, are the only meteorological variables needed by the propagation model. However, in the proposed formalization, such quantities will be assumed to be constant over the considered time horizon.

For each grid cell the following initial conditions are known:

δ_k^0	biomass density	[kg m^{-2}]
u_k^0	biomass moisture	[%]

It is assumed that a fire may start in a cell k by direct action due to human or natural cause and, from these, can propagate on a set of neighbourhooding cells V_k (to be suitably defined), by heat transfer. Fire intensity $i_k(t)$ in absence of fire is obviously zero. If a fire is active and signalled in a cell k, the following differential equation can be used to represent the dynamics of linear intensity

$$\frac{d\, i_k(t)}{dt} = a_k \cdot i_k(t) + b_k \cdot i_k^2(t) \quad \text{for } i_k(t) > 0 \tag{15}$$

The above model is proposed, in analogy with models used to represent population dynamics (Begon M., Mortimer M., 1981), to take into account the initial burning phase and the subsequent decay. In such models coefficients a and b are positive and negative, respectively. In our case, such coefficients must be considered dependent on the wind intensity and direction, and on the values of the state variables $\delta_k(t)$ and $u_k(t)$, namely

$$a_k, b_k = f_k^1, f_k^2\left(w_k, d_k, \delta_k(t), u_k(t)\right);\ a_k>0,\ b_k<0;$$

Coefficient a_k is increasing with the biomass density, and decreasing with the biomass moisture. The following simple structure has been assumed

$$a_k = \left(\alpha_k^1 \cdot \delta_k(t) + \alpha_k^2 \cdot u_k(t)\right) \tag{16}$$

where

α_k^1, α_k^2 are parameters related with orographical and meteorological data (wind speed and direction).

Similarly it is assumed that, coefficient b_k, whose value highly influences the fire (auto-) extinguishing phase, can be expressed as

$$b_k = \left(\beta_k^1 \cdot \delta_k(t) + \beta_k^2 \cdot u_k(t)\right) \qquad (17)$$

where β_k^1, β_k^2 are parameters related with orographical and meteorological data too.

Note that the model in (15) is able to represent only the behaviour of an already burning cell and is not able to represent the starting of a fire. For this reason, it is necessary to introduce a further model for ignition. It is assumed that such an ignition, on cell k, can start only as induced by a neighbourhood cell belonging to the set V_k. More specifically, it is supposed that, whenever a certain threshold (which can be assumed as dependent on meteorological variables) of fire intensity is achieved on a cell in V_k, then ignition on cell k starts. In particular, it is assumed the following structure giving the initial value of the linear fire intensity in cell k as a function of the linear intensities in cells in V_k

$$\frac{d\, i_k(t)}{dt} = \sum_{j \in V_k} \max\left\{\varphi_{k,j} \cdot i_j(t) - \varepsilon_{k,j}, 0\right\} \qquad (18)$$

where

- V_k is the set of the indexes neighbourhooding cells of cell k;
- $\varphi_{k,j}$ and $\varepsilon_{k,j}$ are suitable parameters whose values depend on the meteorological variables and on the orography.

As regards the dynamics of biomass consumption, it is assumed that a linear model can describe it, namely:

$$\dot{\delta}_k(t) = -\chi_k \cdot i_k(t) \qquad (19)$$

where χ_k is again a coefficient dependent on meteorological variables and on the orography.

Finally, is assumed that the moisture dynamics is given by:

$$\dot{u}_k(t) = \gamma_k \cdot P_k(t) + \sum_{j \in V_k} \omega_{kj} \cdot i_j(t) \qquad (20)$$

where γ_k is a coefficient related to the distance of water supplies from cell k, and $\omega_{k,j}$ is a suitable parameter whose value depends on the meteorological variables and on the orography.

At this point, to make the problem tractable, it is convenient to introduce a time-discretization, which provides

$$\begin{cases} i_k(t+1) = i_k(t) \cdot \left(1 + a_k \cdot \Delta t + b_k \cdot i_k^2(t) \cdot \Delta t\right) \text{for } i_k(t) > 0 \\ i_k(t+1) = \sum_{j \in V_k} \max\left\{\varphi_{k,j} \cdot i_j(t) - \varepsilon_{k,j}, 0\right\} \quad \text{for } i_k(t) = 0 \end{cases} \qquad (21)$$

$$\delta_k(t+1) = \delta_k(t) - \chi_k \cdot i_k(t) \cdot \Delta t \qquad (22)$$

$$u_k(t+1) = u_k(t) + \gamma_k \cdot P_k(t) \cdot \Delta t + \left(\sum_{j \in V_k} \omega_{kj} \cdot i_j(t)\right) \cdot \Delta t \qquad (23)$$

where t=0,…,T-1; k=1,..,m.

Then, an optimization problem can be stated as follows

$$\max \sum_{k=1}^{m} \delta_k(T) \qquad (24)$$

s.t.

(21), (22), (23), and

$$\sum_{k=1}^{m} P_k(t) \le AP(t);\ t=0,\ \ldots,\ T-1 \qquad (25)$$

that represents a technical constraint related to the maximum quantity of water deliverable in the cell k. AP(t) represents the available extinguishing power over the overall region corresponding to area k=1,…,m. AP(t) is in general a function of time as the extinguishing power can vary over time on the basis of a predetermined schedule.

5 CONCLUSIONS AND FUTURE WORK

In this paper, an approach related to the management of forest fire emergencies has been developed and presented, although in a preliminary form. This approach is based on the application of several models. First, a fuel moisture model, driven by meteorological information, is used to assess, together with an off-line propagation model, the risk level over the considered area.

On this basis, a problem concerning the preventive location/assignment of the available fire extinguish resource can be set up. The solution of such a problem provide optimal preventive location of fire extinguish power at the CFS/CNVF stations and their assignment to high risk areas.

Besides, a real-time resource allocation problem has been formalized, over discrete time, basing on the use of models representing fire linear intensity, fuel consumption, and moisture dynamics.

Further research in this field should be direct to model calibration and validation, and to the development of efficient procedures for the solution of the above problems over large regions. Besides, the modelling of a real-time resource allocation problem whose transfer times and costs of resource cannot be neglected, is necessary. Finally, the proposed techniques are presently under test in connection with case study in the Italy region Liguria.

6 ACKNOWLEDGEMENT

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