FOREST FIRE DYNAMIC HAZARD ASSESSMENT AND PRE-OPERATIONAL RESOURCE ALLOCATION

Paolo Fiorucci, Francesco Gaetani, Riccardo Minciardi, and Eva Trasforini

CIMA Centro di Ricerca Interuniversitario in Monitoraggio Ambientale
Università degli Studi di Genova, Italy.
Name.Surname@unige.it

Abstract: In this paper, a dynamic forest fire hazard model is introduced aiming at getting reliable information useful to take pre-operational actions that can reduce the impact of potentially ignited fires over the considered territory. Among such actions, the attention focuses on the pre-operational allocation of aerial means, able to cope with the forest fires. A pre-operational resource allocation problem is introduced, and formalized as a mathematical programming problem. A case study, relevant to the forest fire hazard assessment and aerial resources management at the Italian national scale, is presented and discussed.

Keywords: resource allocation, dynamic modelling, mathematical programming.

1. INTRODUCTION

Forest fires are frequent and widespread in a great number of regions both in the southern and in northern hemisphere. In some of these regions, the number of the events, and the effects that they have on local economy, natural habitat and human activities make wildfires represent the most noteworthy natural risk. This work refers to the (dynamic) pre-operational fire hazard assessment, for which it is assumed that real-time information is available, and that the hazard assessment is carried out with reference to a certain time horizon (say 2-3 days) for which reliable meteorological forecasts are available.

The purpose of dynamic hazard assessment is that of getting reliable information useful to take a number and a variety of pre-operational actions that can reduce the impact of potentially ignited fires over the considered territory, within the considered time horizon. Such actions may include, for instance, re-locating the available resources over the territory, recalling day-off resources to service, alerting local authorities, issuing prohibitions of some dangerous agricultural practices (such as stubble burning), or patrolling the areas affected by the highest hazard. Among such actions, this work will focus on the pre-operational allocation of aerial means over the Italian national territory.

The approach proposed in this paper for the dynamic hazard assessment falls in the considered framework since its goal is that of preventively allocating the fleet of water-bombers in proximity of the areas where a high-risk level is forecasted.

Dynamic hazard assessment allows identifying, within the considered territory, the areas affected by the highest hazard, and the time intervals within the considered time horizon in which this hazard takes place. This paper refers to the Italian national fire danger rating system RISICO (*RISchio Incendi e Coordinamento*; CIMA, 2003) in operation at the Italian Civil Protection headquarters (*Dipartimento della Protezione Civile*, DPC). The architecture of the RISICO system corresponds to the scheme represented in Fig.1, and may be decomposed into two sub-modules, namely a fuel moisture model and a potential fire spread model (Fiorucci *et al.*, 2004).

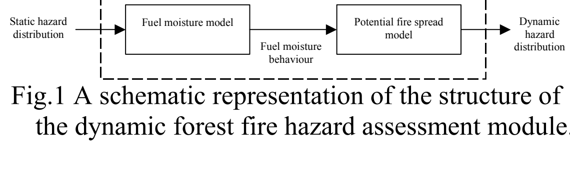

Fig.1 A schematic representation of the structure of the dynamic forest fire hazard assessment module.

The former is capable to represent the behaviour in time and space of the (dead) fuel moisture content [%], whereas the latter defines the behaviour of a (potential) ignited fire in terms of rate of spread [mh^{-1}], and linear intensity [kWm^{-1}].

The information that feeds the two models is depicted in Fig.1 and is of either static or dynamic type. Static information is relevant to topography and land use, whereas dynamic information is obtained mainly from the outputs of a meteorological model. As such forecasts are provided by the model over a certain time horizon, even the forest fire hazard assessment that is obtained by the overall module in Fig.1 refers to such a horizon, and thus it may be represented as a set of functions of time and space, one for each physical variable that is assumed to be significant to assess forest fire hazard. Moreover, a suitable choice for the time discretization interval (3 hours) and the space discretization grid (cell of 0.05° side covering the whole Italian territory, measuring 302 000 km^2) is that of taking the same time-space discretization that characterizes the outcomes of the meteorological model.

The remaining of the paper is organized as follows. In the next Section the pre-operational resource allocation problem is formalized, whereas in Section 3 the application of the proposed approach to a real case study relevant to the 2003 fire season in Italy is presented and discussed. Some concluding remarks will end the paper.

2. THE PRE-OPERATIONAL RESOURCE ALLOCATION PROBLEM FORMALIZATION

As resources are by definition generally scarce, decision makers need to be supported in the evaluation of the possible alternatives that can be chosen, and optimisation techniques are traditionally suited to solve this kind of problems. Among the works that can be found in literature, one can refer, for instance, to the work by Bryson and others (2000) who have proposed a model aiming to develop disaster recovery planning. Their approach allows selecting, among a pre-defined menu of possible sub-plans, the ones that constitute an optimal disaster recovery plan. Such a selection is possible through the solution of a mixed integer mathematical programming problem aiming at maximizing the total value of the recovery capability of the set of sub-plans chosen. Resources, taking into account personnel, hardware and infrastructures, are in this case associated to each specific sub-plan, as well as their utilization costs. Resources are chosen and assigned to the recovery plan only if the correspondent sub-plan is included into the optimal solution of the problem. On the other hand, to be effective, such techniques need to be integrated within an information system that manages the crisis that actually is seldom used (Friedrich *et al.*, 2000).

The information related to the expected daily forest fire hazard is used as the input for a pre-operational resource allocation problem at a national scale. It is assumed that the timelier is the intervention, the more efficient is the action of a resource on a fire.

The evaluated hazard and the associated service demand are represented through the aggregation, both in space and time, of the value of (expected) linear intensity. Namely, the hazard is represented over square cells greater than those of the grid over which the risk is initially evaluated. Moreover, hazard values are averaged over a suitable time horizon. Such an aggregation aims at smoothing the dynamic hazard in order to allow a more effective dislocation of the available means on the considered area of interest. This consideration is even truer when the considered available means are characterized by a good efficiency over a large spatial scale, like aerial resources. Indeed, when a pre-operational location problem has to be solved, the decision of reallocating an aircraft from an airport to another implies high operative costs. Therefore, such (hard) decision has to be taken only when a very high and persistent hazard is forecasted on a geographical area, and not only on the basis of extremes and isolated hazard values.

The area of study (i.e., the Italian territory) is represented as a discretised spatial domain, defined by a grid of K regular cells; within each cell k, the resources' demand is supposed to be homogeneous, and it is represented through the use of parameter D_k.

The resources are not actually positioned in cell k, as they are assigned to the location centres j ($j \in V$, where V is the set of location centres) spread over the territory. Such location centres are assumed to be the airbases able to receive the resources, and able to provide the service of maintenance needed to ensure the effectiveness of the aircraft for the next flights.

The location centres can be treated as nodes of a graph, superimposed to the grid. In this way, the resources have to traverse the links of the graph in order to reach the nodes to which they are assigned. The following decisional variables for the considered problem can be introduced:

Y_j integer decision variable, that represents the number of resources assigned to node j and potentially ready to be used in case of an event occurrence

Further on, some parameters have to be introduced, namely:

σ_k $\in [0,1]$, closeness of cell k to the nearest water supply point; the value 1 indicates that the distance between the location center and the water supply point is null, whereas the value 0 indicates that such a distance is too long for an efficient service;

ρ_{jk} $\in [0,1]$, easiness of reaching cell k by resources located at location center j; here again, the value 1 indicates that no significant distance exists between the cell and the location center, whereas the value 0 indicates that such a distance is too long for an efficient service;

R total amount of available resources.

The cost function aims at minimizing the unsatisfied service demand in each area that can be reached by a resource assigned to a specific location centre. More specifically, a function G_j has been introduced in order to penalize the unsatisfied demand in those cells that can be serviced by resources located in the generic location centre j. In particular, the following form has been chosen for function G_j

$$G_j = \left[\max\left\{ \sum_{k=1}^{K} D_k \sigma_k \rho_{jk} - \delta\, Y_j, 0 \right\} \right]^2 \qquad (1)$$

where δ is a suitable trade-off parameter, introduced in order to make the two terms in the “max” function comparable. Such a parameter depends on the technical characteristics of the considered resources, as it can be viewed as a measure of the capability of the resources to cope with several fires in the same time period. Function (1) is non-linear in the decision variable, but has a quadratic structure, as it seems sensible to penalize at a higher-level unsatisfied demand.

On these bases, the resource assignment problem can be formalized as follows

$$\min Z = \sum_{j \in V} \left[\max\left(\sum_{k=1}^{K} D_k \sigma_k \rho_{jk} - \delta Y_j, 0 \right) \right]^2 \qquad (2)$$

s.t.

$$\sum_{j \in V} Y_j = R \qquad Y_j \in \{0, 1, 2, ..., \Re\} \qquad (3)$$

Such a problem can be simply transformed into a problem with quadratic cost function by introducing fictitious variables M_j ($j \in V$), replacing the original cost function (2) with

$$\min Z = \sum_{j \in V} \left(M_j \right)^2 \qquad (4)$$

and introducing the following further two constraints

$$M_j \geq \sum_{k=1}^{K} D_k \sigma_k \rho_{jk} - \delta Y_j \quad j \in V \qquad (5)$$

$$M_j \geq 0 \quad j \in V \qquad (6)$$

Notice that in the above problem statement no information about the current actual position of the resources is taken into account, and thus the costs relevant to the movement of the resources among the location centres cannot be introduced in the cost function. This goal would be reached by modifying the problem formalization, and by increasing the number of decision variables, as the movement of each single mean should be taken into account. Thus, the computational time required in order to obtain a solution for such a problem would be considerably longer of the one required for the solution of the problem considered in this work. One could also observe that, the choice of neglecting the transfer costs is justified also because the main objective of the considered decisional problem is that of protecting human lives, activities and properties.

3. CASE STUDY

Aiming at evaluating the operational benefits attainable in the resource management by implementing the proposed system, the optimal resource allocation problem introduced in Section 2 has been solved on a near-real case, basing on the information obtained by the 31daily runs of RISICO, and relevant to the time horizon 30th June 2003 – 30th July 2003. The run of the system relevant to day d constitutes the set of data used in order to optimally assign the resources for the day d+1. Thus, in this work the optimal assignment for each day belonging to the whole month of July 2003 has been carried out.

The case study is relevant to the daily dispatching on the active signalled wildfires of the (aerial) resources coordinate by the DPC. For each day of the considered time horizon, the effectiveness of such relocation has been evaluated on the basis of the wildfires actually signalled to the DPC in the same time interval. The data relevant to the wildfires burnt in Italy in July 2003 were obtained from the Forest Service’s Daily Report; this database reports each wildfire burnt in the national territory, which required the intervention of fire fighting resources both of ground and aerial type. Each fire inserted in the database is described by 296 fields dealing with the physical characteristics of the event, and the intervention carried out for its suppression (duration of the intervention, response time, kind and number of means used, kind and number of personnel involved, number of drops, accidents, volume of dropped water,..). From an original database of 2098 records (fires) a sub-set of 609 records has been derived by selecting only the events characterized by a request of intervention addressed to the DPC air command and control.

For the sake of simplicity, in the case study, although a heterogeneous fleet of resources is actually available, (water-bombers, heli-tanker, and a mix of single and light medium twins helicopter) only a homogeneous fleet of 14 CL415 *Canadair* amphibian aircrafts has been considered.

The proposed case of study is relevant to a centralized single resource optimal relocation problem, which requires for its statement the knowledge of some parameters. In the next sub-sections, the information, and the procedures used in order to evaluate such parameters will be described.

3.1 Parameters estimated on the basis of information coming from the linear intensity forecast model

As previously introduced, the original set of data relevant to the estimated linear intensity has been aggregated over a larger regular grid, mainly in order to minimize the computational effort required to solve the pre-operational resource allocation problem. A procedure has been defined aiming at aggregating the original regular cells in a number equal to q^2 original cells. Note that in some cases, i.e., in the border areas of the considered territory, the number of original cells composing a new cell could be minor than q^2. In this case, it has been assigned a value equal to 5 to q.

The procedure, applied over the whole set of cells belonging to the Italian territory, defines a new grid composed by 704 regular cells. In addition, an aggregation in time has been carried out aiming at defining an average value of risk representing the values of each 3 hours interval over the 72 hours time horizon. Let m indicate the generic time interval belonging to the considered time horizon, and let M be the total number of time intervals in such time horizon. Let l indicate the generic original cell (i.e., a generic cell used in the forest fire hazard assessment model), and k the generic aggregated cell. Then, consider the following parameters:

- I_k^m [kWm^{-1}] estimated linear intensity value for cell k in the time interval (m-1, m);
- μ_m $\in[0,1]$ weighting coefficient assigned to the forecast relevant to time interval (m-1, m);
- ε_l^m $\in\{0, 1\}$ binary parameter, assuming value equal to 1 if the linear intensity I related to the cell l in the time interval (m-1, m) is higher than a fixed threshold, and 0 otherwise;
- Nel_k number of original cells actually composing the generic cell k.

On this basis, the service demand D_k associated to each cell k (for the resource relocation problem) is expressed through the following average

$$D_k = \frac{\sum_{l=1}^{Nel_k}\sum_{m=1}^{M}\mu_m\varepsilon_k^m}{Nel_k\sum_{m=1}^{M}\mu_m} \qquad k = 1,\dots,K \quad (7)$$

Thus, for each cell k the service demand is expressed as a function of the number of original cells whose estimated linear intensity is greater than a fixed threshold, selected in order to take into account only those cells where the occurrence of a fire, due to particular risk conditions, should require the service by means of amphibious resources. The value of 1724 kWm^{-1} (Rothermel, 1983) has been chosen as threshold for the estimated linear intensity. The values chosen for the weights in (7) were: μ_m=0.1, m=1,..,8; μ_m=0.6, m=9,..,16; μ_m=0.3, m=17,..,24.

3.2 Parameters estimated on the basis of geographical information

The value of parameters σ_k has been computed basing on the shortest path from each cell k to the coast line, either for sea and lake surfaces, considering as available points of water scooping those included in the official list provided by the DPC. Coefficient σ_k, is evaluated also on the basis of technical considerations relevant to the aircraft's performances (scooping distance, including safe clearance height; fire fighting circuit speed (avg.), and typical drop speed). A value equal to 1 is assigned to σ_k, if a resource can efficiently load water when operating on cell k; on the contrary, a value equal to 0 is assigned to the considered parameter when the distance from the cell to any water supply point is assumed to overcome the operational range of the aircraft. Intermediate values are introduced in order to characterise cells where the resource can operate, but with reduced efficiency (see Fig.2).

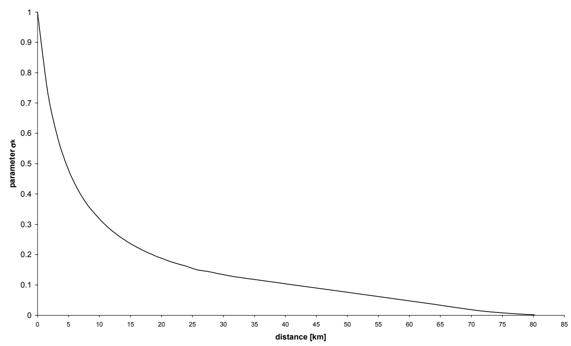

Fig. 2. The values of parameter σ_k: in abscissa the distance between the consider cell k and a water supply point suitable for CL415 aircraft.

Parameters ρ_{jk} have been evaluated on the basis of the Euclidian distance between air base j and cell k, taking into account the performance of the considered resources. Here again, a value equal to 1 is assigned to such a parameter when the intervention on cell k of a resource located in station j is completely effective (i.e., cell k and node j are characterized by the same geographic position), whereas a value near or equal to 0 is assigned to the parameter when the level of service is considered totally inadequate; intermediate values are introduced in order to characterize intermediate level of intervention effectiveness.

4. RESULTS

The procedure adopted for the validation of the proposed system is based on the evaluation of the resource effectiveness that can be obtained through a pre-operational resource location (on the basis of the dynamic hazard forecast) as compared with the performances attainable when resources are located at fixed points, irrespective of the dynamic fire hazard distribution. Such a comparison, of course, assumes that fire hazard forecasts are reliable, and is carried out by evaluating the performances attainable via the dynamic and the static resource location schemes, in connection with the actually occurred fires. However, no attention has been paid to the dynamics of the interventions and to the time elapsed from the request of intervention and the first drop over the fire front.

In order to validate the optimal dynamic allocations results, two *static* allocation schemes (namely *stat1*, and *stat2*) have been considered. Namely, a set of 16 Italian air bases $j \in K$ has been selected, whose technical characteristics have been assumed to be suitable for CL415' daily ordinary service maintenance. The first (simplest) scheme assumes that during the considered time horizon, each airbase receives only one resource except for two minor bases with no resources. The second static scheme, closer to the real case, assumes a large number of aircrafts in Rome DPC airbase and in the Southern air bases. In Table 1 the two considered static allocation relevant to the month of July 2003 are reported in detail.

Table 1. The list of the considered airbases, their coordinates (longitude and latitude), ICAO code, names and the two static schemes considered for the case study.

code	east	nord	ICAO	description	Stat 1	Stat 2
B1	8.293	40.631	AHO	Alghero Fertilia	1	0
B2	9.770	40.590	ALA	Alà dei Sardi	1	2
B3	8.260	44.160	ALL	Albenga	0	1
B4	13.520	43.610	AOI	Falconara	1	0
B5	9.660	45.690	BGY	Bergamo Orio al Serio	0	0
B6	16.768	41.135	BRI	Bari Palese	1	1
B7	9.061	39.254	CAG	Cagliari Elmas	1	1
B8	12.490	41.910	CIA	Roma Ciampino	1	4
B9	15.065	37.468	CTA	Catania Fontanarossa	1	0
B10	8.850	44.414	GOA	Genova Colombo	1	1
B11	8.593	39.894	LIER	Oristano Fenosu	1	0
B12	13.102	38.184	PMO	Palermo Punta Raisi	1	1
B13	15.650	38.130	REG	Reggio di Calabria	1	0
B14	16.145	38.908	SUF	Lametia Terme	1	1
B15	12.520	38.020	TPS	Trapani Birgi	1	1
B16	12.183	45.645	TSF	Treviso	1	1

In order to quantify the aircrafts' performance achievable by implementing the different relocation schemes, a coverage index S_k, has been introduced for each cell k of the considered territory. This parameter takes into account the number of aircrafts, which could intervenes in cell k and their efficiency of intervention in terms of readiness (ρ_{jk}) and maximum number of drops in unit of time (σ_k), and it can be expressed as in the following

$$S_k = \sum_{j \in V} \rho_{jk}\, \sigma_k\, Y_j \quad k = 1, \ldots, K \tag{8}$$

Besides, for each day d of the considered time horizon (July 2003), and for each cell $\hat{k} \in \hat{K}$ where at least one fire has occurred, a further index $c_{\hat{k}}^d \in \left[0, S_{\hat{k}}^d\right]$ has been evaluated, whose value is given by the ratio between the coverage value $S_{\hat{k}}^d$ and the number of fires $n_{\hat{k}}^d$ burnt in that cell

$$c_{\hat{k}}^d = \frac{S_{\hat{k}}^d}{n_{\hat{k}}^d} \quad d=1,..,T;\ \hat{k} \in \hat{K} \tag{9}$$

Finally, an average index C^d, relevant to the considered day d can be obtained as

$$C^d = \frac{1}{N_{\hat{k}}^d} \sum_{\hat{k}=1}^{N_{\hat{k}}^d} \frac{S_{\hat{k}}^d}{n_{\hat{k}}^d} \quad d=1,..,T \tag{10}$$

where $N_{\hat{k}}^d$ is the number of cells $\hat{k}$ with at least one active fire signalled in day d.

The optimization problem defined by cost function (4), and subject to constraints (3), (5), and (6) was solved for the considered time horizon two times, thus giving rise to two different relocation policies (and sequences of decisions) that in the following will be referred to *opt1*, and *opt2*.

The two are different because of a different value of parameter δ. Namely, *opt1* corresponds to δ=3, and *opt2* to δ=7. These values express different evaluations of the capability of an aerial mean to cope with several fires in the same time period (day d); thus, in *opt2* the resources are assumed to be able to sustain a higher workload than in *opt1*. A comparison among the unsatisfied service demand terms in *opt1*, and *opt2* for each day of the considered time horizon shows that *opt2* guarantees the best results, whereas *opt1* is characterized by the worst ones. This consideration is not always true when one considers the index C^d, computed on the basis of equation (10). In fact, this index is influenced also by the actual occurrence of fires in the considered area, and thus it has not *a priori* to assume better values in *opt2* rather than in *opt1*.

In Table 2 the results obtained by applying the proposed approach is presented for each day of the considered time horizon. The second column reports the number of fires actually signalled to DPC, whereas the third column reports the number of cells $N_{\hat{k}}^d$ in which such a fires was burnt (there may be more then one fire in the same cell). The fourth and fifth columns report the value of C^d for each day in case of static allocation scheme *stat1* and *stat2* (see tab.1) respectively. The last two columns provide the value of C^d in case of dynamic pre-operational allocation via *opt1* or *opt2* techniques. Finally, the last raw of Tab.2, provides the average value of the above introduced parameters for the whole considered period of time.

As a general comment to the results obtained, one can observe that the considered index C^d takes into account the coverage S assured by the resources available on day d to those cells where some wildfires have burnt. Since the maximum value attainable by S id equal to the total number of resources available on day d, it is apparent that index C^d gives the average daily value of resources ready to intervene on actually occurred fires.

From Tab. 2 one can observe that the performance index C^d increases substantially in case of pre-operational resource allocation, enhancing their average value of about 0.2 resource/fire in the best case (*stat1* vs. *opt1*). The worst performance of the dynamic resource relocation procedure is the *opt1* one relevant to the 11th of July. This bad functioning can be explained through the occurrence of two negative factors. The former was relevant to the wildfire hazard assessment for this day, which showed a spread and indiscriminate high-risk value with some peak in the Southern regions, whereas the latter was the (unusual and rare for the season) presence of three wildfires (the total number of fires for this day was nine) in prone alpine areas, in a zone far off from any DPC airbases.

Table 2. A comparison among the results obtained by applying two different static allocation and two dynamic pre-operational allocation.

date	fires	cells	stat1	stat2	opt1	opt2
d	$n_k{}^d$	$N_k{}^d$	C^d	C^d	C^d	C^d
20030701	20	18	0.637	0.670	0.850	0.838
20030702	27	22	0.508	0.651	0.652	0.626
20030703	16	15	0.697	0.858	1.023	0.877
20030704	13	11	0.770	1.000	1.262	1.072
20030705	19	17	0.537	0.639	0.739	0.712
20030706	17	14	0.576	0.625	0.659	0.637
20030707	19	15	0.557	0.669	0.617	0.612
20030708	17	14	0.533	0.646	0.585	0.559
20030709	15	15	0.584	0.733	0.722	0.704
20030710	17	16	0.643	0.758	0.673	0.673
20030711	9	8	0.440	0.528	0.419	0.420
20030712	15	12	0.548	0.721	0.681	0.650
20030713	13	12	0.673	0.839	0.831	0.713
20030714	14	11	0.602	0.609	0.745	0.690
20030715	22	20	0.671	0.695	0.831	0.730
20030716	21	19	0.663	0.826	0.864	0.835
20030717	33	24	0.588	0.615	0.819	0.746
20030718	31	27	0.573	0.610	0.844	0.786
20030719	30	23	0.604	0.696	0.954	0.810
20030720	35	31	0.672	0.860	0.883	0.799
20030721	23	20	0.590	0.724	0.656	0.609
20030722	44	37	0.488	0.607	0.556	0.553
20030723	30	28	0.655	0.779	0.894	0.863
20030724	33	26	0.589	0.631	0.949	0.806
20030725	24	21	0.540	0.644	0.743	0.698
20030726	17	15	0.657	0.814	1.028	0.834
20030727	34	32	0.570	0.718	0.694	0.694
20030728	30	26	0.564	0.687	0.743	0.729
20030729	26	25	0.586	0.766	0.761	0.721
20030730	19	15	0.475	0.631	0.584	0.528
20030731	19	16	0.487	0.647	0.693	0.553
avg value	22.645	19.516	0.590	0.706	0.773	0.712

The system performance can be repeated (even if with lower increase in the C^d value) even when considering a worst capability of the considered resources in the multiple interventions on fires in the same time period. In fact, moderate variations in the value of δ parameter bring to results worst then *opt1* and *opt2*, but still better than *stat1* and *stat2*, thus underlining a certain reliability in the obtained results.

5. CONCLUSIONS

In this paper, an approach related to the management of forest fire emergencies has been developed and presented. To this end, a dynamic forest fire hazard model is introduced aiming at getting reliable information useful to take pre-operational actions that can reduce the impact of potentially ignited fires over the considered territory. Among such actions, the attention focuses on the pre-operational allocation of aerial means, able to cope with the forest fires. A pre-operational resource allocation problem is introduced, and formalized as a mathematical programming problem. A case study, relevant to the actual forest fire hazard assessment and aerial resources management at the Italian national scale, is presented and discussed.

6. ACKNOWLEDGEMENT

The activities reported in the paper have been carried out within the framework of Special project n. 4 (2002) Structural and operational design of a decision support system based on a national geographical information system and aiming at forest fire risk management, funded by the Italian Civil Protection Department.

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