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An Operational Scheme For Dynamic Resource Management In Case Of Natural Disaster Events

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Abstract: The management of the resources engaged in emergencies due to the occurrence of very intense natural events requires the acquisition and processing of a huge number of heterogeneous data. Such data, both of deterministic and random nature, generally refer to different spatial and temporal scales. Considering the three main frameworks in which a natural risk scenario can be classified (i.e., preventive, emergency, and post-emergency phases), risk assessment has to be followed by a decision-oriented phase, whose objective is the selection of the optimal actions to undertake, on the basis of the available information. In the paper, the conceptual scheme and the system architecture of a hierarchical decisional model relevant to a natural risk emergency scenario are considered and discussed in detail. Such a scheme relies on system modelling and optimisation techniques, and is based on different decisions layers. At the top of the hierarchy, a decision centre makes use of aggregated information, generated by specific models, in order to relocate resources to the local centres. The lower centres must cope with the (forecasted or actually reported) emergency events with their own resources, basing their strategy both on the local information sets, and on the aggregated data provided by the highest decisional centre.

1. INTRODUCTION

The exploitation of the territory for the location of new infrastructures, and the rapid and extensive expansion of inhabited areas exposes a growing number of people and their economic livelihoods to the effects of natural disasters. In fact, the demand of new spaces is often satisfied to the detriment of natural areas, even when safety in case of natural events is generally very poor.

For this reason, the occurrence of extreme meteorological or geophysical events can produce huge and amplified effects (damages and victims) on the exposed elements. In the last years, there has been an impressive increment of damages and casualties, especially in the Countries where the territorial planning has not followed the economical and demographical growth.

Considering the sole year 2005, there have been 360 natural disasters; that is, compared to 305 in 2004, an 18% rise. Figures indicate that the number of floods has increased by 57 % in 2005 (107 in 2004 vs. 168 in 2005), and droughts by about 47 % (15 in 2004 vs. 22 in 2005). In total 157 million people, 7 million more than in 2004, required immediate assistance, were evacuated, injured or lost their livelihoods. Despite this, loss of life was significantly lower than in 2004, during which 244,500 people died as a result of natural hazards. Disasters in 2005 cost a total of 159×10^9 USD in damage, although out of this figure, 125 x

10^9 USD were for losses caused by Hurricane Katrina in the US. (UN ISRI, 2006).

In this connection, specific information including observations, forecasts, reliable projections, and scenaria collected or developed on multiple spatial scales have the potential to address international, national, and regional decision-support objectives. However, for the information to be useful, its applicability and reliability for different applications must be evaluated.

In addition to the spatial scale, natural disasters can be analysed in relation with the period of time that precedes, corresponds and follows the occurrence of extreme values of some meteorological or geophysical variables. For each time interval, an acquisition phase has to be considered, aiming at performing a hazard assessment, followed by a decision-oriented phase, whose objective is the selection of the best actions to undertake.

On these bases, natural risk assessment and mitigation can take place starting within three different conceptual frameworks. In the first one, which can be denoted as static risk assessment, the distribution of the risk over the territory is carried out only basing on off-line information relevant to the territorial characteristics and the historical observation of the considered phenomenon. The purpose of such an assessment could be planning the sizing and the location of the different kinds of resources and logistic necessary to manage the risk over a wide territory. Another objective of such an analysis could be obtaining indications about land use and territorial planning, over a small-medium regional area.

Within the second framework, which will be denoted as dynamic risk assessment, it is assumed that real-time information is available, and that the risk assessment is carried out with reference to a certain time horizon (say 12-48 hours) for which reliable forecasts (meteorological or geophysical) are available. Along with forecast information, the real-time information used for dynamic assessment may come from different sources: present weather conditions, ground-measured data, data coming from satellite or airborne sensors. Besides, with a slight abuse of terminology, in the following the term "real-time information" will be intended to include also the meteorological forecasts (nowcasts) for the (short) time horizon over which the risk is assessed. The main advantage of dynamic risk assessment is that of identifying, within the considered territory, the areas affected by the highest risk values, and the time intervals within the considered time horizon in which this risk takes place. The purpose of dynamic risk 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 risk scenaria over the considered territory, within the considered time horizon. Such actions may include, for instance, relocating the available resources over the territory, recalling day-off resources to service, alerting local authorities, issuing prohibitions of some dangerous practices, or patrolling the areas affected by the highest risk. Within dynamic risk assessment framework falls also the case in which some event is active, and the problem that has to be solved is to select the best actions to mitigate its effects. On this basis, an operational decision procedure can be applied, in order to support the decision makers in taking decisions about the actions to undertake in order to contrast effectively the event and possibly to avoid any losses or damages, taking into account the information corresponding to the distribution of risk over the considered territory.

A third level can be added to the above outlined conceptual scheme, referring to information processing and decision making after the occurrence of an event. Actually, the actions relevant to such a level are of a considerable importance in the risk management, but on the whole, their discussion is beyond the scope of the present paper. In Figure 1 the conceptual scheme that has been outlined above is reported.

Since the rationale of the present work is to define an operational scheme for dynamic resource management in case of natural disaster events, in the following no attention will be paid to the static risk assessment and the planning phase. Nevertheless, it is worth observing that the planning phase stands at the basis of whatever dynamic strategy for resource management, and represents the first and fundamental effort to be accomplished in order to protect people and territory from natural risks effects. In the remaining of the paper the structure of the decision processes relevant to the pre-operational (preventive) and real-time resource management will be considered in detail. A general scheme for the decentralization of the decision functions based on a hierarchical decision framework in which central and local centres cooperate in order to achieve the optimal results will be introduced. In particular, in Section 2.1, and Section 2.2, an optimal approach relevant to the management of the resources used in case of forest fire risk, for preventive and real time phase respectively, will be presented and discussed in detail.
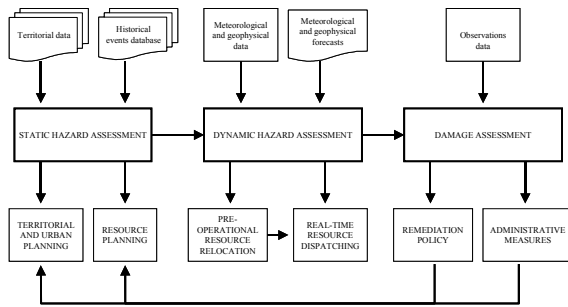
Figure 1. A schematic representation of the various functions and of the information flows in an overall natural risk management scheme.

2. SYSTEM ARCHITECTURE

Resource management in a natural risk scenario represents a hard challenge for Civil Defence decision makers. In fact, in very short period of time, they are required to implement reliable strategies on the basis of incomplete or biased information, relocating scarce and costly resources, which have to be assigned to unsafe operational theatres. In addition, the incertitude characterizing geophysical and meteorological (stochastic) phenomena, doesn't allow making sharp and ultimate prediction on the dynamics of the considered event, forcing decision makers to take into account all the possible scenarios due to change in some variables.

From the system designer's perspective, the multi-faceted nature of dynamic hazard assessment poses severe constraints on the underlying software and hardware architecture. Consider the very strict timing requirements, which concerns all phases of the process, decision making is the most obvious example, since it usually involves very time consuming algorithms whose output must be produced in time to be of some use, thus requiring to be analysed in the theoretical framework of anytime and iterative computing. Data acquisition through geographically distributed sensor networks made of intelligent and low-powered nodes (e.g., by solar cells) is another example, since each node must dealing with the obvious limits on the computational power available for local processing, which is necessary to send information on a communication channel with a low bandwidth and/or corrupted by noise.

Other issues could be named to "give the flavour" of the architectural complexity of the system: reliable communication for collecting sensor data and sending control actions to local operators, high usability of human-machine interface both on supervision stations and on Personal Digital Assistant (PDA) that local operators are possibly equipped with, fast and intelligent information retrieval from Knowledge Bases (e.g., Semantic Webs, Geographic Informative Systems), etc. Notice that almost all Computer Science research topics would deserve to appear in this list, which is consequently doomed to be incomplete.

A reasonable approach to design effective large-scale control structures is that of considering a network based on different decisions layers. At the lower one, which corresponds to a regional or sub-regional area, lye one or more Local Command Centres (LCC). LCC network require the support of computer science technology, TLC devices, dedicated software for modelling and knowledge sharing tools, in order to monitoring, acquire, elaborate, and share information useful for the definition of present and future risk assessment in the considered (regional) area.

At the higher layer, a Central Command Centre (CCC), access to the whole information sets, and coordinates the various LCC, providing more aggregated information, on-demand, or by some self-rule, in case of expected or active events. As a general rule, the control variables (number and kind of resources) provided by CCC to the lower layer (LCC) are used as reference values for the decisional problems to be solved for each LCC. In this way, the lower control layer is obviously implemented in a distributed fashion.

Referring to the higher-layer control problems, it is reasonable to consider such problems within a discrete-time setting. In passing, note that the time discretization interval of the higher-layer problems should be considerably larger than the time discretization interval used for the lower-layer control problems. Also as regards the space scale, it is reasonable to consider different models for the lower-layer and the higher-layer decision problems, respectively.

In this context, "Grid" computing systems seem to be the best candidate to implement multi-layered decision networks while meeting all the architectural constraints that have been introduced so far (in terms of timings, communications, interfaces, etc.). In general, Grid computing refers to a kind of wide-area distributed system aimed at coordinating resource sharing and problem solving in dynamic, multi-distributed programs (Foster, and Kesselman, 1998). When mapping multi-layered decision networks for dynamic hazard assessment onto the open grid service architecture (OGSA), a similar hierarchical organization is found: at the higher layer, the Resource

Management System (RMS), which matches service requests with Resource Managers (RM) able to serve them; below, many geographically distributed RMs, and, eventually, nodes which directly manage available resources.

It is interesting to notice that, in this general framework, no constraints are put on the hardware or software characteristics of the lower level nodes: they can be high-speed supervision workstation running time-consuming data mining procedures, as well as 1 mm³ "Smart Dust"[1] intelligent sensors for distributed data gathering, or even a distributed Knowledge Base organized under the form of a Semantic Grid (Zhuge *et al.*, 2005). In this sense, the OGSA paradigm defines only how resources should be accessed and managed, thus being the best choice to support concurrent and geographically distributed activities, which are very different in their nature.

Finally, notice that RMS has only the purpose to match requests with available services, and a central coordination between the RM sites does not exist. As anticipated, this is fully justified by our approach to the decision process, in which higher-layer decision problems are decomposed into a set of local decision problems. This approach is obviously heuristic; however, in the following, each of such problems is formalized and solved through mathematical programming tools.

In the following paragraph an example of the proposed scheme applied to forest fire emergencies will be discussed for the preventive phase, whereas some procedural notes will be introduced for the real time case.

2.1 The Preventive Phase

The occurrence of natural disaster events is in almost the totality of the cases related with very intense (extreme) values of some meteorological o geophysical variables. In this connection, the forecast of the dynamics of such variables can be used as input for some physical or empirical model capable to predict their effects for given area and time horizon.

The aim of modelling tools is twofold. If no event is active, they can be used to assess a preventive management of the resources, positioning men and means where the probability of occurrence of an event is the highest for the next 24-48 hours. On

the counterpart, when an event is active and already signalled, the capacity of simulating the behaviour of the event over a near future period of time (3-6 hours) can be extremely helpful for the management planning, and the organization and control of resources.

The case of wildfires is particularly suited for the adoption of some preventive resource management. In fact, the resources dynamics can be considered as faster than the dynamics of the expected event and, in some cases, capable to modify or reduce its impact on the exposed elements. In this case, the resource management can be scheduled on daily basis, using the forecasted risk values relevant to the next 24-48 hours. A grid of $k=1,..,K$ cells can be used to represent the considered area; whereas the evaluated risk and the associated service demand can be represented through the aggregation, both in space and time, of the value of the (expected) linear intensity I_k [kWm^{-1}], i.e., the potential power of the fire front determined by means of a suitable numerical model (Rothermel, 1972). Such a model determines the value of $I_k(h)$ for each time interval $h=0,..,H-1$ of a given (future) time horizon. A suitable representation of the model is

$$I_k(h) = M(\underline{x_k}(h),\ \underline{\theta_k}(0),\ \underline{\eta_k})\ h=0,..,H\text{-}1,\ k=1,..,K\ (1)$$

Where $\underline{x_k}(h)$ is the vector of the meteorological forecasts, $\underline{\theta_k}(0)$ is the vector of the state variables observed at time instant $h=0$, and $\underline{\eta_k}$ is a vector of parameters (topography, land use, kind of vegetation). Note that the values of $\underline{\theta_k}(0)$ are provided to CCC/LCC by the available RMs network.

In addition, it is assumed that within each cell k, the resources' demand is homogeneous and represented through the use of a parameter $D_k=f(I_k(h))\ h=0,..,H-1$. Indeed, for the worth of simplicity, resources are assumed to be constituted only by mobile vehicles (trucks, engines, water-bombers,..) and, therefore, each resource is assumed to belong to some location centres j ($j\in V$, where V is the set of location centres), which are spread over the considered area. Such location centres can be considered as nodes of a graph, superimposed to the grid. In this way, resources have to traverse the links of the graph in order to reach the nodes (corresponding to a certain cell k) to which they are assigned.

Thus, the (integer) decision variables of the problem are the Y_j, which represent the number of resources assigned to node j and "ready to go" in case of an event occurrence.

A cost function aiming at minimizing the unsatisfied service demand in each cell k that can be reached by a resource assigned to a specific

location centre is introduced. More specifically, the function G_j penalizes the unsatisfied demand in those cells that can be serviced by resources located in the generic location centre j; the following form has been chosen for function G_j

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

Objective (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.
Finally, the (preventive) resource assignment problem can be formalized as follows

$$min Z = \sum_{j \in V} G_j \qquad (3)$$

s.t.

$$\sum_{j \in V} Y_j = R \qquad Y_j \in \{0,1,2,...,\Re\} \quad (4)$$

where R is the total amount of available resources. Note in passing that, in problem (2)÷(4) the current position of a generic resource $m=1,..,R$ are not explicitly defined and, therefore, transfer costs among the different j centres are neglected. Aiming at considering such costs, the binary decision variables q_{mj} are introduced, being q_{mj} equal to 1 if resource m is assigned to location centre j, and 0 otherwise. Besides, parameters c_{mj} are introduced, taking into account the transfer costs of resource m from its current position to node j. Therefore, the cost function may be rewritten as the sum of two terms, the first one related to the unsatisfied service demand, and the second one related to the transfer costs

$$Z = \sum_{j \in V} G_j + \alpha \sum_{j \in V} \sum_{m \in R} c_{mj} \, q_{mj} \qquad (5)$$

where α is a suitable weighting parameter, and s.t.

$$\sum_{j \in V} q_{mj} = 1 \qquad m=1...,R \qquad (6)$$

$$Y_j = \sum_{m=1}^{R} q_{mj} \qquad (7)$$

Obviously, preventive phase assumes different significances in connection with the scale of application. At a central level, CCC disposes of a relative limited number of resources (i.e., water-bombers), therefore their (national) relocation has to be based on the information set relevant to the expected daily national forest fire risk for the next 24-48 hours elaborated by suitable model at a macroscopic scale (i.e., cell k with area $A_k \geq 25$ km^2). In this case, risk values can be aggregated over a suitable time horizon aiming at smoothing the dynamic hazard in order to allow a more effective relocation of the available resources. Indeed, when a preventive location problem has to be solved, the decision of relocating a resource 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. On the counterpart, when the preventive relocation problem is carried out by LCC, problem (5)÷(7) has to be solved over a finer grid (typically $A_k \leq$ 0.01 km^2), taking into account an heterogeneous set of kinds of resources, denoted by transfer time not negligible. In fact, LCC typically coordinates short-range vehicles, whose transfer times depend on the characteristics of the resource and on the topography of the considered area. Thus, preventive phase at local scale can be finalized on the displacement of the available resource, originally located in some location centres w, over the whole set of cells requiring the higher service demand. In the LCC case the service demand $\hat{D}_z$, $z=1,..,Z$, takes into account both the forecasted linear intensity I_z obtained using a microscopic model for wildfire risk assessment, and the (potential) reduction on I_z due to the resources, which can intervene on $z=1,..,Z$ relocated by CCC. The aim of such displacement is not relevant only to the intervention on active fire but has also the fundamental function of patrolling and monitoring the high-risk zones.
On this basis, equation (2) can be rewritten as

$$\hat{G}_z = max\left(\left(\hat{D}_z - \sum_{w \in W} \sum_{i=1}^{n_w} \frac{\kappa_i \, m_i}{1 + \beta \, t_{wz}} \right), 0 \right) \qquad (8)$$

where $\hat{D}_z$ is the service demand in cell z, n_w is the number of resources m located at centre w, t_{wz} is the transfer time from location centre w to cell z, β and κ_i are suitable weighting parameters.
The LCC resource relocation problem can now be stated as

$$min \hat{Z} = \sum_{z=1}^{Z} \hat{G}_z \qquad (9)$$

s.t.

$$M_w = \sum_{i=1}^{n_w} m_i \quad w \in W \qquad (10)$$

2.2 The Real-Time Phase

This phase represents a major task in decision making, because of the number of uncertain variables related to the dynamics of the system, and the requirement of rapid decision times to cope efficiently with the active emergencies.

Real-time phase main goal is to provide LCC/CCC with feasible and effective solutions for the scheduling-dispatching of the available resources on active signalled wildland fires. In this case, the objective is twofold; at higher level, decision makers need to schedule the (relative scarce) aerial resources according to a given objective, which typically represents a trade-off between the efficiency of the intervention (number of resources and transfer times) and the costs of intervention. From a local level perspective, LCC has to (optimal) share its resources among the different points of demand, taking into account the time required for the intervention, and the logistics of the operational theatre.

In this case, the role of RM network within the decision process is dominant, since the larger is the available information set, the easier is the processing-assimilation procedure needed for the characterization of the operational theatre.

To this end, one can suppose to define an approach based on the maximization of a cost function similar to (8), but completed by terms that take into account the dynamics and the efficiency of the available resources, as well as by considering a concentrated (punctual) demand (the active wildfires) instead of a distributed demand.

Of course, in this case, a dynamic model of the active wildfire should be applied, and retained as a constraint in the optimisation problem. The decision variables of such a problem should include, along with the variables related to the dispatching of the resources, those expressing the control actions on the system (i.e., the extinguishing power of each resource). The use of very powerful (time-consuming) fire propagation software tools appears as mandatory for reliable and significant prediction on future time horizon. The dataset provided by RM network, along with the information elaborated in the preventive phase are used as input for propagation models both at LCC, and CCC scale.

6. CONCLUSIONS

In the paper, an operational scheme for dynamic resource management in case of natural disaster events has been presented and discussed. Such scheme can be efficiently applied in order to support decision makers in the resource management during preventive phase and in real time phase.

An example of how such scheme can be applied has been presented with reference to wildland fires emergency management. Several practical as well as conceptual problems remain to be investigated to assess the validity end the practical relevance of the proposed approach. Experimental evaluation with reference to a real case study is presently carried out.

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