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A DSS for the evaluation of the consequences of natural hazards on a complex territorial system

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Abstract: In this paper, a decision support system (DSS) able to assist urban planners in natural hazard mitigation in preventive phase is proposed. In order to define the structure of this DSS, a methodology based on influence graphs is defined, in which nodes represent entities that are important for their social, environmental and social functions on the territory, and links represent the influence between the entities.

The level of functionality of each entity is influenced by both its physical integrity and the functionality of the related entities. As not all the entities influence the considered one in the same way, different levels of influence are taken into account. Several rules to automatically identify the level of relationship between different entities are defined.

The proposed methodology has been applied to the territory of Imperia, in the north-western coast of Italy, with special regard to wildfires risk. Several entities have been selected, over the considered territory, according to their relevance. The hazard distribution over the considered area, due to wildfire risk has been estimated. On this basis, an overall procedure capable to assist the decision maker in the analysis of the territorial risk can be established.

Keywords: Decision Support System, Natural Hazard, Risk Assessment.

1. INTRODUCTION

Natural hazards occurrence can deeply influence the physical territory, as it is able to create both permanent and temporary modifications on infrastructures or other settlements spread over the interested area. Thus, an effective forecast of natural events occurrence may be necessary, in order to determine the expected magnitude and in order to beforehand carry out actions able to mitigate the effects on the territory by suitably defining emergency plans. The objective of a reliable forecast cannot be always achieved because of the peculiar characteristics of the phenomena under concern, whose forecast is sometimes impossible (as for seismic events), or strictly related to the data accuracy of the target area (as for flood events).

This critical situation is even more hard to manage whenever the territory is analysed as a set of singular elements. In fact, in general the elements of a given territory are functionally interconnected. The existence of such relationships compromises the degree of functionality of many elements on the territory, even if only a limited set of such elements is directly damaged. Then, the territory has to be considered as a complex system, in which the vulnerability (i.e., the capacity to cope with an external stress) is a function of both physical and functional components.

The behaviour of territorial systems can be viewed as similar to that of environmental systems, as both classes of systems are heavily characterized by complexity and uncertainty. Following the influence diagram theory applied to environmental system [Varis, 1997], some of the authors modelled a complex territorial system by means of influence diagrams, representing and evaluating the physical and functional integrity of each element belonging to the territorial system by a network representation.

Influence diagrams allow modelling territorial system and representing the complex relationships among the different elements. However, the procedure implemented in [Chirico, *et al*., 2001] to analyse the urban system is characterised by a high sensitivity to the subjective experience of the technicians involved in the procedure. Furthermore it does not allow considering the mutual influences, as no cycles can be included in an influence diagram.

Thus, in this paper influence diagrams are utilised only to represent the conceptual links among the different elements, and a qualitative relationship structure is defined and applied for each couple of element, between which a relationship exists. In this paper, an approach based on GIS (Geographical Information Systems), is followed, in order to identify, represent, and define, by means of objective attribute, the role of each element, and the mutual relationships between the set of elements.

The aim of presented approach is to evaluate the loss of functionality developing a procedure for the whole territorial system, as a consequence of a natural hazard occurrence. On the basis of such procedure, it is possible to define a decision support system (DSS), able to support urban planners in natural hazard mitigation.

In the next section of this paper, the proposed model for the territorial system is introduced, as well as the classes of territorial elements that have been considered are described. In the third section, an approach for natural risk evaluation, taking into account both physical and functional issues, is presented. In the fourth section a simple case study, related to the municipality of Imperia (located in the north-western coast of Italy) is presented. Some conclusions will end the paper.

2. THE TERRITORIAL SYSTEM

2.1 The considered territorial elements.

A correct knowledge of the effects of natural disaster occurrence on a territorial system is an essential requisite to implement a DSS, having the purpose to support decision makers in their activity aiming at the safeguard of human beings, and at the protection of properties and economical - social activities.

Although this is an important need for a regional authority, only recent specific scientific works present mathematical formalizations. A recent example is the work by H. Tamura *et al.* [2000], who proposed an approach based on a “value function under risk”, to mitigate natural disaster effects.

In this paper, the territory has been considered as a complex system, in which also the functional relationships have been considered. This approach has been applied in this paper mainly as regards elements, which are essential in emergency management. Nevertheless, it can be applied in the same way to other class of elements in the territorial system.

Focusing on the emergency management, three main classes of physical elements have been considered, each of which is characterized by few main attributes.

Residential centres are considered the principal target of a natural hazard event, and represent the demand to be satisfied by rescue supply in case of emergency. Some attributes have to be introduced in order to characterize these territorial elements, i.e., the number of inhabitants, the area, and their geographical coordinates. The operative centres represent another class, where the decisions about rescue operations, and resource allocation are taken; in order to mitigate the effects of the hazardous event on the territory. Medical structures, which can be utilized to recover victims caused by natural hazards, represent the last considered class.

Besides the geographical coordinates, some other attributes have to be related to the latter two classes of territorial elements, which express their capability to provide services. Namely, such attributes are the number of available beds for the medical structures, and the amount of in service resources for the operative centres.

Obviously, if a GIS is utilized in order to collect data, all the attributes describing the territorial elements can be easily and automatically obtained.

2.2 The proposed modelling of the territorial system

For each considered element q_k, belonging to class $i=C(q_k)$, two variables are defined: the level of physical integrity y_k, and the level of functional integrity x_k, $k=1,\ldots,n$, where n is the number of different elements.

The first one defines the physical integrity of q_k, as, for example, the integrity of a structure after an earthquake. The second one, $x_{k,}$ describes the condition of functional integrity of q_k, which does not always coincide with the level of physical integrity, and it is strictly related to the functional integrity of other objects belonging to the target area. For instance, a hospital can have stood up perfectly to an earthquake, but it can be not operational when the unique road to reach it is not practicable.

Both the above-defined variables take values in the range [0, 1], where the maximum value indicates the complete physical or functional integrity, whereas the null value indicates the total failure of the object, or its uselessness.

3 THE RISK ASSESSMENT

Risk can be defined on the basis of the probability to have a certain loss of a physical or, in general, functional integrity as a consequence of a natural hazard occurrence.

To formalize the above statement it is necessary to introduce different variables, for each territorial element q_k, namely:

- the hazard H_k;
- the physical vulnerability V_k;
- the functional vulnerability W_k;
- the cost S_k.

Hazard, H_k, is defined as the *magnitudo* or intensity, in time, associated to a natural event. The uncertainty associated to the event occurrence, in terms of time and intensity, makes hazard assessment and forecast a very complex problem.

In general, for a given time instant, and a given object, hazard can be modelled as a random variable. Each different class of objects belonging to the target area is defined by a set of attributes concerning both physical characteristics and use. Thus, the vulnerability V_k is introduced, aiming to measure the response of each object q_k, in terms of physical integrity or direct loss of functionality as a consequence of an external stress H_k. The physical vulnerability, V_k, can be evaluated on the basis of a function, which express the influence of the considered stress H_k on q_k.

Then, it is possible to define the physical integrity, y_k, by introducing a suitable function $f(\cdot,\cdot)$, namely:

$$y_k = f(H_k, V_k)$$

It is assumed that a suitable cost or value S_k is given for each object q_k. Their cost depends on its class $i=C(q_k)$, and corresponds to determine the amount of money necessary to repair or rebuild the interested object. Obviously, such a cost is a function of y_k, namely it is written $S_k(y_k)$.

It is assumed that the (residual) physical integrity of each object q_k influences its functional integrity through a suitable function $g_k(\cdot)$, namely

$$W_k = g_k(y_k)$$

where W_k represents the residual functional integrity after the physical damage suffered directed by element q_k.

Then in order to take into account the mutual influence of all elements in the territory, it is assumed that the functional integrity of the generic element q_k. The level of joint functional integrity, for each object k, can be expressed as follows:

$$x_k = F_k\left(W_k, w_{k,h}, x_h;\ h = 1,\dots,n;\ h \neq k\right) \qquad (1)$$
$$k = 1,\dots,n$$

where $w_{k,h}$ is a variable that expresses the relationship between the generic object q_k and the generic object q_h. Such a variable is in general a function of the attribute of elements q_k and q_h.

Note that equations (1) are expressed in an implicit form, i.e. their solution requires in general the use of numerical tools for the solution of systems of non linear equations.

4. A CASE STUDY

4.1 The target area

The approach introduced in the previous sections has been applied on a test area located in a northwestern region of Italy placed along the border with France. Specifically, the methodology has been applied to evaluate the damage due to wildfire risk over the area belonging to the district of Imperia. Forest fires are widespread and frequent in this region and represent the most common natural hazard occurring all year round.

This region is characterized by meteorological condition propitious to the fire ignition for many days of the year, with minimal winter temperatures higher than continental European one, and scarce rainfall in summer. Furthermore, the vegetation, on the whole region, is characterized by an elevated mean value of Higher Heating Value [Fiorucci, *et al.*, 2001b].

The increase of sprawl and the growth of urbanization directly interfaced with natural forested area, make extremely dangerous the occurrence of a fire, which can represent a severe risk for the inhabitants and their activities.

Several territorial objects have been identified. Specifically, the following elements have been identified: 45 residential centres, characterised by their coordinates, area, and number of inhabitants, 15 operative centres characterised by their coordinates and number of available resources; 4 medical structures characterised by coordinates and number of available beds.

The Euclidean distance between each couple of territorial objects has been evaluated by the use of a GIS.

Wildfire hazard is defined by the expected fire front linear intensity [kW m^{-1}], given by a suitable procedure based on a fuel model and a propagation model [Fiorucci *et.al.*, 2001a].

4.2 The relationships among the territorial objects

Referring to equation (1), the relationship among different objects on a territory is expressed by variables w_{kh}. Then, it is necessary to express such variable as functions of the objective attributes of the considered elements. In this way, the proposed procedure can work, at least in principle, without the need of a planning expert to assess the relevance of the relationship between the considered elements.

The relationship occurring between a residential centre q_k and a medical structure q_h can, for instance, be modelled as:

$$w_{k,h} = \alpha_{k,h} \cdot \frac{in_k}{bp_h} \cdot e^{-\beta_{k,h} d_{k,h}} \qquad (2)$$

where in_k is the number of inhabitants of q_k, bp_h is the number of available beds in q_h, and $d_{k,h}$ is the Euclidean distance between the two elements. $\alpha_{k,h}$ and $\beta_{k,h}$ are suitable parameters. Analogous expressions can be used for each similar couple of objects, for what it is reasonable to assume that the value of functions $w_{k,h}$ arises when the ratio between demand and supply of services grows, and when the Euclidean distance decreases.

Again referring to equation (1), a proper definition of function F_k is generally quite difficult, as it requires a deep knowledge of the relationships among the different entities. In this paper it has been assumed that the conditioning links between the entities have generally a necessity means In other words, this equals to assume that the complete functionality of elements conditioning object q_k is necessary for its complete functionality. The function "min" can thus be reasonably used to express this type of dependence, in that it is equivalent to the logical operator "AND". Then, a possible structure for equation (1) can be represented by:

$$x_k = min\left(W_k, G(w_{k,h}), x_h; h = 1,...,n\right)$$

for k=1,.., n; $k \neq h$ (3)

where function $G(\cdot,\cdot)$ is defined as

$$G(w_{k,h}, x_h) = \left(1 - 0.1 \cdot w_{k,h}\right) \cdot \frac{1 - e^{-w_{k,h} x_h^2}}{1 - e^{-w_{k,h}}} + 0.1 \cdot w_{k,h} \qquad (4)$$

Equation (3) represents a system of 64 equations to be solved, where the decisional variables are $x_k; \quad k = 1,...,n$.

This system has been solved using a software package, developed by the use of C++. An initial value for quantities x_k is considered, namely $x_k(0)$, which is evaluated on the basis of its risk index H_k, physical vulnerability V_k, and functional vulnerability W_k. Equations (2), (3) and (4) are then applied until the procedure reach an equilibrium.

4.3 Results

The proposed method has allowed the attainment of encouraging results and to gain exhaustive and reliable information about the functionality of the overall territorial system. Obviously, the procedure is sensitive to the choice of the parameters that have to be introduced in equation like (2). However, the significance of the approach is presented, especially as regards the objective of identifying the heaviest sources of criticality, disregarding the exact quantification of the overall loss functionality on the whole territory.

Focusing on the territorial objects belonging to the residential centres class, it can be noted that the functionality lost due to the mutual interconnections of the considered objects is very spread on the territorial system.

The parameter Δx_k is defined as the difference between the value of $x_k(0)$ and the value assumed by x_k when the analysis procedure attains the equilibrium point, expressed as a percentage of the initial value. It is worth to observe that for 71% of considered territorial objects this parameter assumes a positive value. Table 1 shows the percentage of residential centres whose loss in functionality Δx_k is higher than 0%, 10%, 30%, 50%, and 70%.

Table 1. Percentage of territorial elements belonging to the class of residential centres whose loss in functionality Δx_k is higher than a fixed threshold.

$\Delta x > 0$	71 %
$\Delta x > 10$ %	60 %
$\Delta x > 30$ %	44 %
$\Delta x > 50$ %	16 %
$\Delta x > 70$ %	0 %
Δx: mean value	24 %
Δx: maximum value	67 %

Figure 1 shows the target area and the considered residential centres: a darker colour corresponds to a lower functionality. The residential centre of Airole, in the north-western area of the district, shows a loss in functionality Δx_k equal to 67%, that is the highest value in the whole area.

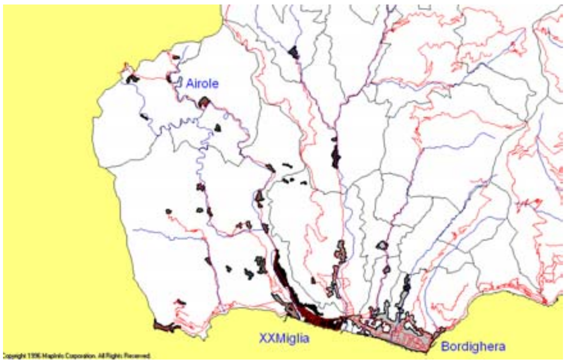

Figure 1. Target area, located in the north-western coast of Italy: the darker objects correspond to residential centres with a lower residual functionality.

5. CONCLUSIONS

A model of territorial systems for management of natural hazards has been presented.

The main characteristic of this approach is to allow the user analysing the territorial system only on the basis of geographical data, as it does not need the help of territorial planning experts.

Even if the functions describing the relationships among the territorial objects could be defined in a more refined way, the proposed approach can be taken into account as a first approach to allow decision makers to evaluate possible interventions on a territory to prevent heavy functionality losses due to environmental natural hazards.

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