Resilient City and Seismic Risk: A Spatial Multicriteria Approach

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Abstract. Nowadays, the most common approach to seismic risk mitigation is characterized only by strategies reducing building vulnerability, through structural interventions, and it does not consider the possibility to intervene at urban scale, reducing urban seismic vulnerability. This paper deals with the concept of urban seismic vulnerability, and introduces resilience, as the capacity of a system to adapt itself to new, generally negative, conditions, in order to re-establish normal conditions. Each city can express resilience, and the identification of its elements is the goal of our research. A spatial multi-criteria approach is here proposed.

Keywords: Resilient cities, Seismic Risk, Seismic Vulnerability, Urban Vulnerability, Spatial Multicriteria Analysis.

1 Introduction: Seismic Risk and Resilient Cities

Considering cities as complex systems, according to Salzano [1], we can recognize *urbs*, *civitas* and *polis*, respectively representing aspects related to physical environment, to the society living there and to governmental activities through which spaces are organized. These three main components – *urbs*, *civitas* and *polis* – interact each other in a continuous way, making complex governance and making it more complex when risks must be managed.

The first question which arises is what to do to face emergency conditions. Further questions concern how to manage crisis in order to limit damages caused by natural and other disasters and how to go over crisis and to guarantee the re-establishment of ordinary conditions.

At present, we are conscious that warding off occurrence of natural disasters is not always possible, even if we know that we can intervene in several ways; for instance, in Italy prevention could be more efficient, in particular if we consider hydro-geological disasters, which often could be avoided by a careful maintenance of hydrographic network. Anyway, considering the possibility of such disasters, we must work in order to face them, and to react, with as least as possible loss.

Considering natural events, risk assessment takes into account several components: generally, it is defined as a function of hazard, exposure and vulnerability [2]. Hazard

B. Murgante et al. (Eds.): ICCSA 2011, Part I, LNCS 6782, pp. 410 – 422, 2011.

concerns natural characteristics of a natural phenomenon; for instance, if we consider seismic risk, hazard depends on historical seismic characteristics, ground geological characteristics, geotectonic and seismic-genetic structure characteristics, which do not depend on human intervention, so that we are not able to control them.

Exposure, instead, concerns the human presence in a certain area. So, we could affirm that if hazard conditions are worrying (i.e. hazard is high), then we should not establish human settlements. Generally, this kind of decision depends on planning and urban tools. Sometimes, after a disaster, a law can intervene to forbid human settlements in a certain area: for instance, in Italy, Law 405 of 1907 ratified the displacement of many urban centres elsewhere in reason of dangerous landslides. This kind of decision, nevertheless, is hard to accept: historical centres, built over centuries, probably ignoring hazard conditions, because of limited knowledge, and now well-established, also in terms of urban shape and community identity, are hard to uproot and re-build in another place, even if this presents safer characteristics.

The only possibility is therefore to intervene on vulnerability of elements that are exposed to hazard. Generally, vulnerability is defined as the tendency of a certain element to be subjected to damages or corruptions, depending on its own physical and functional [3] characteristics. Generally, vulnerability is referred to the elements composing a settlement; in the case of seismic risk, for instance, vulnerability mainly refers to seismic vulnerability of buildings, and it is evaluated considering their structural characteristics. Such structural aspects, therefore, determine building behaviour in case of a seismic event.

In literature, however, the concept of urban seismic vulnerability has already been used (see for instance [4]): it has been recognized that global activity in a town can be compared to activity of a network system, where each edge, working at local level, contributes at global level. From this point of view, it becomes evident that physical damages are not only components of global damage. Moreover, it has been observed that earthquake effects are not limited to physical damages, but they have some ripples on economic, social and political activities, and they have a strong role onto city capacity to react.

That being so, risk prevention must be characterized by a new approach, that should go over building structural adjustment, and that recognizes single components working as a whole system: these components, that are not only physical ones (such as buildings and streets), but that refer to social, economic and political functions, strongly contribute to urban seismic vulnerability. New approaches must define tools able to mitigate such urban seismic vulnerability; therefore, it should forecast, before a seismic event, what kind of response the single components might show.

In other words, we affirm that an approach aiming at mitigating urban seismic vulnerability, must maximize system resilience, as the capacity of a certain system to adapt to new , generally negative conditions, to re-establish normality [5].

The paper is organized as follows: in the next paragraph, resilience concept and its relation with vulnerability will be deepened, and the idea of resilient city will be described, with some considerations about its relationship with both urban and emergency planning tools.

In the third paragraph, we will provide some theoretical considerations about spatial multicriteria approach, that is adopted in order to identify resilient city. The fourth paragraph contains a description of the study case, the identification of a resilient city in Marsicovetere, Southern Italy and finally, some opening questions and future directions of research.

2 What Is a Resilient City?

2.1 What Is Resilience?

In the last paragraph a resilience definition is provided, and an equivalence relation between urban seismic mitigation and resilience maximization is proposed. In this paragraph we want to deepen this relation, starting from the several facets showed by resilience concept and from several interpretations that nourish the debate.

As known, resilience concept has been developed in origin in the field of ecology. Holling [6] defines resilience as a property of a system that measures its ability to absorb changes of state variables, driving variables and parameters and still persist, and relates its concept to that of stability, intended as the ability of a system to return to an equilibrium state after temporary disturbance. In the last years, resilience became a usual term in the field of risk management. Pelling [7], for instance, affirms that resilience to natural hazards is the ability of an actor to cope with or to adapt to hazard stress. It is a product of the degree of planned preparation undertaken in the light of potential hazard, and spontaneous or premeditated adjustments made in response to felt hazard, including relief and reuse. Concept of seismic resilience considers also the social dimension: according to [8], community seismic resilience is defined as the ability of social units to mitigate hazards, to contain the effects of disasters when they occur, and to carry their recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes. This can be achieved both working on structural aspects and emergency response and strategies, involving institutions and organizations, and in particular those related to essential functions for community well-being, as acute-care hospitals.

Therefore, The International Strategy for Disaster Reduction, Hyogo Framework for Action 2005-2015, is called “Building the resilience of nations and communities to disasters”, where resilience is defined as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure, and is determined by the degree to which the social system is capable of organizing itself to increase its capacity of learning from past disasters for better future protection and to improve risk reduction measures [9].

These last considerations highlight that as resilience is considered a strategy to mitigate risks, communities recognize to be capable of coping a stress situation, where they must manage demands, challenges and changes, with available resources and competences [10]. Considering that a society flexible and able to shift rapidly, is also able to exploit any positive opportunity that might arise in an uncertain future [11], flexibility must be strongly enhanced.

Obviously, this is not a unique aspect to be considered. Considering natural disasters, several strategies could lead to enhance resilience in terms of augmented capacity of absorption and recovering from changes [11]. In particular, properties of resilience can be considered in order to identify strategies [8]: robustness, intended as the ability of elements to resist to a certain stress without suffering degradation or loss of functionality; redundancy, intended as the substitutability of elements in order to satisfy some requirements no more satisfied by a degraded element; resourcefulness, particularly concerning social systems, intended as the capacity of identifying problems and finding solutions depending on priorities and available resources; ability, defined as the capacity to meet priorities and to achieve goals as quickly as possible. Even if such properties seem to be abstract, they can find a concrete application. For instance, decentralization of decision making (i.e. creating several decision making centres in a town) or strategies about mobility, generally refer to redundancy, and so on.

2.2 What Is the Resilient City?

Paton et al. [10] define a resilient city as a sustainable network of physical systems and human communities, where the first ones include all kind of structures and infrastructures, "acting as the body of the city, its bones, arteries, and muscles", and the second ones represent the social and institutional components of the city, including all kind of associations and organizations and "acting as the brain of the city, directing its activities, responding to its needs, and learning from its experience". The metaphor makes clear that during and after a stress, both systems are determinant: if body collapses, the entire system collapses; if brain breaks down, the entire system breaks down.

Therefore, the most important aspect concerns how to define and apply strategies. In order to answer to the question, we started from the observation of the city; we recognized that, if we model city as a network system, it is characterized by a main trunk and some secondary branches, whose elements are hierarchically less important than the trunk ones. In terms of response to an earthquake, therefore, trunk elements must have a faster response, because they are charged of main activities of city, and moreover they represent place identity.

Adopting such an approach, it is required to define what elements of a city can represent the minimum set able to guarantee functionality.

2.3 How to Identify a Resilient City?

The minimum set of elements can be identified with reference to the four phases that Civil Protection indicates as the phases of disaster management. Considering forecasting and prevention (referred to peacetime) and emergency and post-emergency phases (in the aftermath), minimum set can be sketched as the nesting of four sub-sets, as in the following scheme:

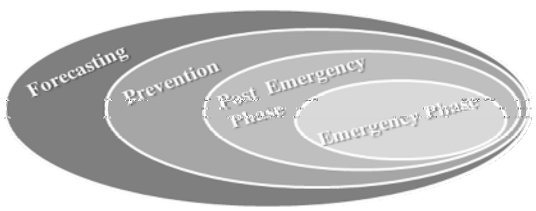

Fig. 1. Elements composing resilient city, sub-divided in four sub-sets referred to disaster management phases. Our elaboration

In peacetime, in particular during forecasting phase, once the expected seismic scenario is defined, it is needed to identify elements:

- requesting prevention, which do not satisfy acceptable vulnerability levels;
- needed in emergency phases, referred to the expected seismic scenario;
- needed to overpass the emergency phase, referred to the expected seismic scenario, and to re-establish normality.

Prevention phase will be characterized by all the actions aiming to bring elements composing sub-sets in acceptable vulnerability conditions.

All such elements are referred to the several aspects of city organization, such as accessibility, lifelines, etc.. In Figure 2, main systems of resilient city are showed, and their main components are synthetically listed. Their identification depends on functional, morphological and dimensional characteristics of the considered urban system [21]. A brief description of systems composing resilient city is presented below.

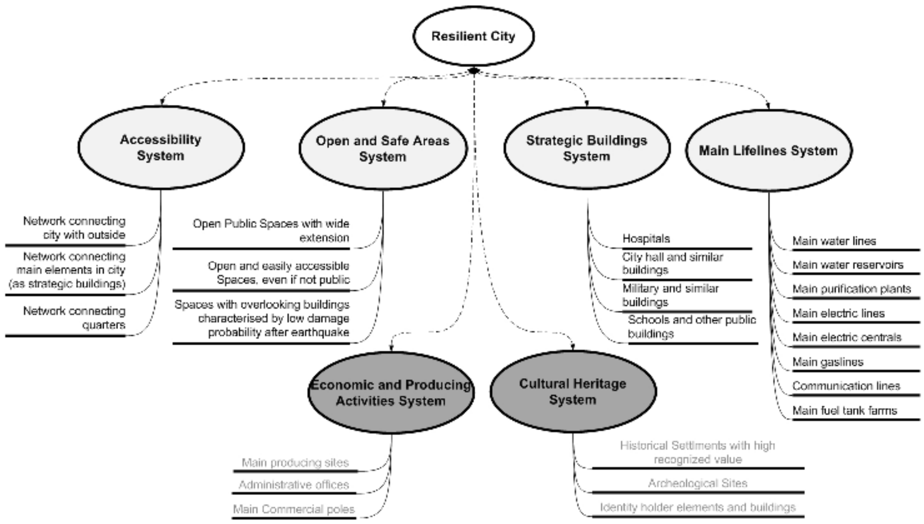

Fig. 2. Systems composing resilient city. Our elaboration.

- Accessibility system: in order to guarantee a minimum of normal cities functionalities, one aspect is related to accessibility: first, identification of main roads, useful as way of escape and allowing access to strategic buildings, as hospitals, and to shelter areas, then, roads connecting quarters and finally internal roads.
- Open and Safe areas Systems: at the same time, open spaces where gathering people, offering a recover, disposing a field hospital and so on, must have been identified, with strong guarantee of their safety.

- Strategic Building Systems: emergency activities need some buildings where decisions can be made, but firstly need hospitals, military buildings, in order to help hit people.
- Main Lifelines Systems: all these activities assume that main services work (water, gas, electricity distribution and communication must be efficient).
- Economic and producing activities and cultural heritage are presented in the figure, but represented in grey, in order to highlight their relative importance, depending on specific characteristic of the considered town.

2.4 Who Decides about Resilient City?

Recognition of resilient city is not so useful if it is not connected to a set of strategies aiming to reduce vulnerability and maintaining characteristics of resilience of the considered elements. At present, who has this responsibility? What is the relation among resilient city, government and planning tools? Is resilient city something with no-ordinary conditions, so that it is related only to emergency and disaster management or has it an ordinary component, and does it need to be introduced into ordinary management tools?

Considering the Italian situation, we notice that:

- Seismic Risk management is almost totally entrust to Civil Protection;
- each municipality should adopt an Emergency Plan, aiming at defining a possible risk scenario and the subsequent actions to manage the emergency;
- emergency plan does not consider the possibility of intervening to mitigate risk before seismic event occurrence;
- laws concerning spatial planning generally do not consider seismic risk as a crucial element influencing development strategies and policies. Considering, for instance, Basilicata region, law N.23/1999, even if the main part of region is classified as high hazard area, there are not specific directions in order to reduce risk.

So, we can affirm that at now resilient city does not yet represent a tool useful in risk mitigation. Civil Protection activities are quite different, and they seem very far from a prevention approach; at the same time, spatial planning tools do not consider seismic risk.

A reason of this situation can be found, probably, in the confusion related to the resilience concept. It is widely used, but it does not seem an operative concept, so that administrations are not able to acknowledge and take it into their instruments.

A possible solution can be an operative approach aiming at resilient city definition, as that one of spatial multicriteria approach, proposed in the next paragraphs.

3 Spatial Multicriteria Analysis

In order to identify resilient city, and define strategies to improve resilience and mitigate urban seismic vulnerability, in this paper we propose a spatial multicriteria approach to identify what parts of territory must resist to a seismic event and must rapidly re-establish their functions to guarantee a return to normal.

Considering multicriteria analysis as "a decision-aid and a mathematical tool allowing the comparison of different alternatives or scenarios according to many criteria, often conflicting, in order to guide the decision maker toward a judicious choice" [12], when alternatives and criteria have an explicit spatial dimension [13], models become "spatial" [14] and can benefit from using Geographic Information Systems; GIS, indeed, provides a powerful set of tools for manipulation and analysis of spatial information [15].

In this context of Spatial MCA, criteria are represented as map layers, and generally they are indicated by the term criterion maps. In particular, a criterion map represents the spatial distribution of an attribute that measures the degree to which its associated objective is achieved [16].

Considering that generally nature or human beings imposed some limitations that do not permit certain actions to be taken [17], in Spatial MCA it is necessary to model also constraint maps, representing restrictions and modelled as territory portions to subtract from criterion maps: constraints play as a hole in territorial extension, as showed in figure 3.

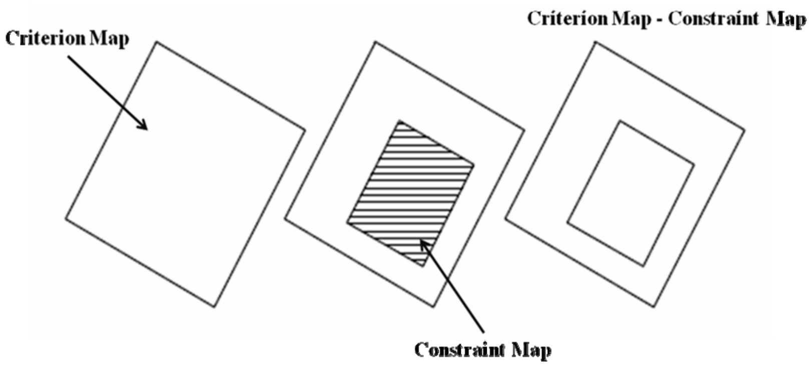

Fig. 3. Criterion maps and constraint maps

3.1 Spatial Multicriteria Analysis Model

Flowchart in figure 4 shows the process of modelling spatial multicriteria analysis.

The main phases are those of Intelligence, Design, Choice and Implementation; each one is characterized by several operations, deepen described below.

In order to compare criterion maps each others, various scales on which attributes are measured must be transformed to comparable units: this is a standardization process, showed in figure 4.

Considering deterministic maps (as in the study case, below described), transformation of input data can be made through several methods; here, linear scale transformation has been adopted, through maximum score procedure.

Linear scale transformation consists of a transformation of raw data into standardized criterion score, applying for each object (that can be a point, a line, a polygon if criterion map has vector data model, or grid cells if it has raster format) a

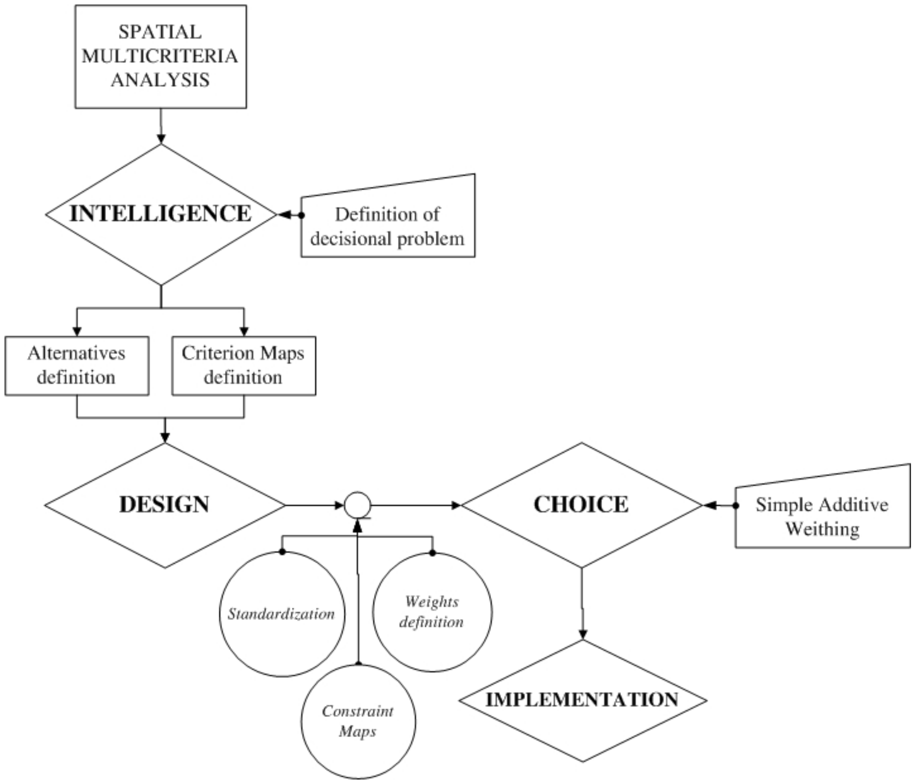

Fig. 4. Our modelling of Spatial Multicriteria Analysis

simple formula. In particular, the Maximum Score Procedure, that consists in a proportional transformation, is obtained through formula showed in (1),

$$x_{i,j}' = \frac{x_{i,j}}{x_j^{\max}} \tag{1}$$

where $x_{i,j}$ is the raw score for the i^{th} object considering the j^{th} attribute, $x_{i,j}'$ is the standardized score and x_j^{max} is the maximum score for the j^{th} attribute on all objects; this formula is adopted when the criterion map represents a benefit, and it is to be maximized; in the case of minimization, when a criterion map represents a cost, formula (2) is adopted:

$$x_{i,j}' = 1 - \frac{x_{i,j}}{x_j^{\max}} \tag{2}$$

As a result, a criterion map ranges from 0 to 1. This procedure, anyway, does not guarantee that the lowest standardized value is zero, sometimes making the interpretation of criterion difficult.

Multi-criteria analysis allows to take into account several stakeholders playing a role into decisional process and which sometimes play a real role into decision. During the modelling phase, stakeholder value systems are to be considered, and introduced into analysis evaluating the relative importance of criterions for each stakeholder. This means identifying criterion weights (weights definition in figure 3), and it is the most subjective aspect of MCA, even if several methods help the analyst in weight identification. In the study case, a pair wise comparison method has been adopted, referring to the analytic hierarchy process by Saaty [18], and developed in subsequent steps, as showed in figure 5.

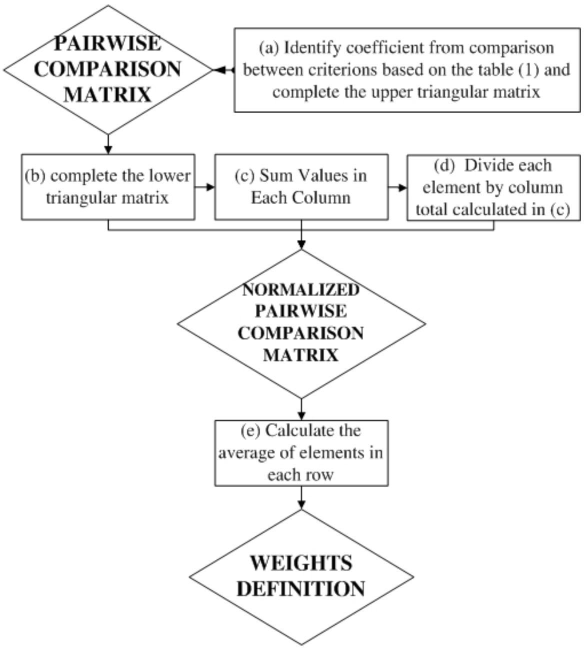

Fig. 5. Pair wise comparison method procedure, our scheme

After weight definition, next step in multicriteria analysis is the definition of decision rule, the procedure allowing ordering alternatives [19], in order to choose the best or the most preferred alternative. Among several decision rules which can be adopted, in the study case additive decision rules have been considered, and in particular the simplest method, simple additive weighting method [20], based on the concept of a weighted average, expressed in the (3)

$$A_i = \sum_j w_j x_{i,j} \tag{3}$$

where A_i represents the object-alternative (point, line, polygon or grid cell), $x_{i,j}$ is the score of the alternative on j^{th} criterion and w_j is the weight of the j^{th} criterion.

4 Resilient City in Marsicovetere (South of Italy)

In order to validate the use of a spatial multicriteria approach to identify resilient city, Marsicovetere municipality (Southern Italy) has been chosen as a sample city, in reason of the importance that this municipality shows in a wider area, Val d'Agri. In last decades this area has been the scene of a development propulsion; main activities, administrative bureaus, health services, shopping centres, etc. are born in Marsicovetere area; development concentrates on valley area, named Villa d'Agri, where today the main part of inhabitants live, also thanks to road network configuration.

Moreover, Val d'Agri is a seismic area, classified in the higher risk class[1], and in the past has been hit by strong and devastating earthquakes.

Figure 6 shows the study area context. Directions of main road crossing territory are highlighted.

Fig. 6. Marsicovetere area, image from google maps

4.1 Data Acquisition and Criterion Maps Design

Considering the procedure described in figure 3, definition of decisional problems led to recognize that this particular problem is characterized by the absence of a priori defined alternatives: each grid cell is potentially an element of resilient city, and its suitability depends on several aspects, to evaluate through a multicriteria approach.

[1] Considering in force law, Ordinanza PCM 3274, 20.03.2003 and following.

Unfortunately, the design phase highlighted the important gap between informative layers. Acquired data do not allow to run analysis for all system listed in figure 1, so that some of them have been omitted, as lifelines.

Available information have been organized in order to define the following criterion maps:

- Accessibility: in order to define accessibility system, road network has been used to identify areas of territory with a certain degree of accessibility. This means that through Euclidean distance function, a criterion map has been built, where grid cells have increasing values with the increase of their distance from roads. In standardization step, formula (2) has been adopted, in order to obtain a high value for the areas close to roads. If a seismic event occurs, areas more accessible, closer than others to roads, are more suitable to receive people and/or to become shelter areas.
- Slope: after digital terrain model definition, a slope map has been calculated, and then, adopting formula (2) areas with soft slope have been considered more suitable to receive people and/or to become shelter areas.
- Urban centre proximity: this criterion highlights importance of proximity of shelter areas to urban centre, not only in reason of their greater accessibility, but also from a psychological point of view. After an earthquake, often, people do not want to leave their houses and places where their time is spent. Criterion map has been obtained applying Euclidean distance function to built-up areas, and then applying formula (2), similarly to accessibility criterion.
- Hydrographic network distance: in order to guarantee safe conditions, proximity of shelter areas to rivers and streams must be avoided, due to overflowing risk. This criterion has been obtained starting from hydrographic network, applying Euclidean distance function and then formula (1): grid cells with higher values are more suitable to become shelter areas.

Weight definition step, generally, should involve decision makers, in order to elicit their perception of criterion relative importance and to define numerical weights. Due to the experimental nature of the study case, a simulation led to weight definition. In particular, three weight sets have been exploited, considering (Set A) firstly criterions with same importance, then (Set B) stressing importance of criterions linked to functional aspects (accessibility and built-up areas proximity), and finally, (Set C) stressing importance of safety (slope and hydrographical network proximity).

The simple additive weighting procedure, then, has been iterated, obtaining three different evaluation scenarios.

At this point, an open and safe areas system can be identified, through subtraction of constraint maps. Areas physically occupied by buildings and roads are considered as constraints; moreover, areas where a hydro-geological constraint (in particular, areas with high landslides risk and flooding areas) is imposed by some territorial or urban plan, are considered as constraints.

Results are showed in figure 7. Darkest areas are the candidates to resilient city.

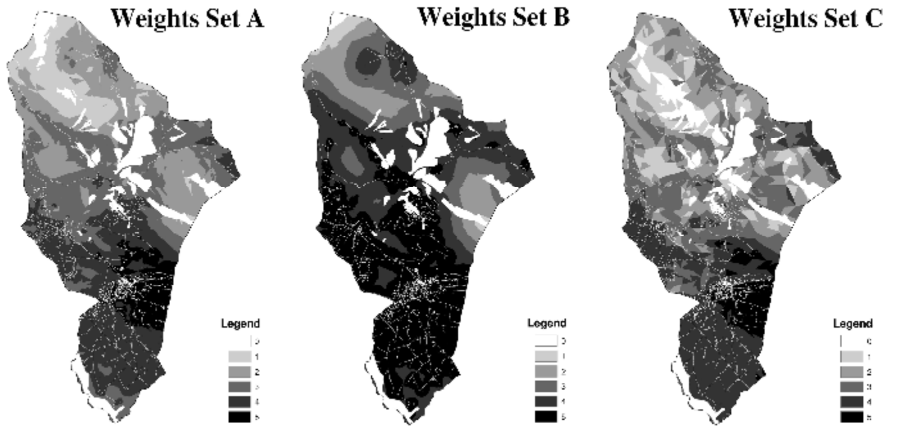

Fig. 7. Analysis results: darkest areas are candidates the resilient city, respectively considering the three sets of weights

5 Conclusion and Future Research

The applied methodology can be considered suitable to identify the resilient city, even if there are several critical aspects to consider.

As declared, simplest methods have been chosen, considering both the standardization phase and decision rule. More sophisticated methods probably would produce better results; choosing other multicriteria approach, moreover, might allow to go over the compensatory effect produced by methods based on average; another difficulty related to simple additive weighting methods is on the hypothesis of not additivity between criterions, not always guaranteed.

Another important aspect is the already declared lack of some information. The developed geographic information system is lacking in several kinds of informative layers: lifelines, but also information about main activities on territory, information about people, information about people who do not live in Marsicovetere, but work there and spend there main part of their day, information about seismic hazard and so on. In addition, at the same time, some available information have not yet been used, as buildings vulnerability. Such information require to be combined with a seismic scenario, in order to evaluate what can happen with the most probable earthquake.

Our last remarks concern the role of resilient city in government and the true contribution that its identification can produce in terms of seismic risk mitigation. At present, Civil Protection is demanded to manage activities of prevention and protection, but its role sometimes contrasts with the role of municipalities, which define urban plans, not always considering natural risks on their territory. Resilient city could become the link between Municipalities and Civil Protection, and its identification is only a first step towards risk mitigation: identified elements need a deeper analysis, a continuous monitoring and, if necessary, economic resources to guarantee their survival to disastrous events. According to Barnett [11], this means also defining a context where horizontal and vertical exchanges in social systems are encouraged to contribute to discussions about risks, enhancing theirs perception, and highlighting importance of prevention.

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