Mitigation of urban vulnerability through a spatial multicriteria approach

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Abstract

Seismic risk management is generally carried out through strategies aiming to reduce building seismic vulnerability, working on structural features and not considering that the concept of vulnerability can be adopted also referring to the whole urban system. In order to adopt a different approach, considering not only building and infrastructure vulnerability and according to the goal of managing seismic risk reducing urban vulnerability, it is strategic to identify in peace time (before disastrous events) which elements, which activities, which functions of a city have prior importance after the event, to guarantee a rapid response and the reestablishment of normal conditions: this means identifying the resilient city.

This study aims to define a methodological approach to identify the resilient city, adopting spatial multicriteria techniques and establishing resilient system identification considering functional, social, morphological, geological and dimensional characteristics of the considered urban system. In particular, some tests, considering a first set of criteria including accessibility, closeness to urban centres and main facilities, closeness to hydrographical networks, slope, map of seismic hazard, areas at high hydro-geological risk and seismic vulnerability of buildings, have been carried out on a town in Basilicata Region (southern Italy), mainly composed of an old part located on a hilltop, a modern part in the valley and a lot of rural settlements. Multicriteria analysis has been led adopting an additive rule, based on a simple additive weighting method.

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

Introduction

Traditionally, natural risks are assessed considering their three major components, hazard, exposure and vulnerability [21]. Hazard is intended as the probability that an event occurs with a certain return period and in a certain area and it concerns natural characteristics of the natural phenomenon. Exposure concerns the presence of people and human manufacts in a certain area. Finally, vulnerability is intended as the intrinsic capacity of hazard-exposed elements to resist, which is their tendency to be subjected to damages or to collapse[9].

Therefore, risk assessment is carried out mainly through assessment and evaluation of physical and natural factors related to hazard, while analysis concerning elements related to human presence is often not enough detailed, deepened and structured[2]. Moreover, in the last decades the concept of physical vulnerability has been enriched by the concepts of functional and systemic vulnerability. Functional vulnerability refers to the consequences, for a community, potentially deriving by the impossibility to use important elements which have been damaged or collapsed[4]. Systemic vulnerability is referred to the whole of functional and spatial characteristics of a system, responsible for the global response of the system itself to a disastrous event[8].

Even if the concept of vulnerability has been extended to functional and systemic concepts, seismic risk management is still generally carried out through strategies aiming to reduce building seismic vulnerability, working on structural features and not considering that the urban system must be considered as a whole. Vulnerability, therefore, appears in the literature with a wider meaning, related to urban scale.

Since cities are complex systems where physical environment, society and government activities interact each other and where global functioning depends on functioning of each element of the system, as in a network, where each node contributes to the global system, as argued by Manyena[16] seismic risk prevention should be treated at urban scale. Moreover, it has been observed that physical damages are not unique components of global damage: it is important to consider that earthquakes have some ripples on economic, social and political activities and that they have a strong role onto city capacity to react to a catastrophic event. In the light of such considerations, it is important to assess also delayed damages. Unfortunately, at present, there is not yet a unique definition of delayed damage, nor are there enough researches and studies concerning it. Some authors e.g. Mercuri[17] or Galderisi[10], define delayed damage as the damage related to consequences of physical damages during a certain period after an earthquake and on others subsystems; other authors define delayed damage as a dynamic damage, with the meaning of a loss of efficacy and effectiveness during the period between the catastrophe and the re-equilibrium[3,14].

Probably a synthesis of both approaches can be considered. For instance building damages can lead to a location of temporary dwellings occupying areas usually employed for other uses or natural zones, thus producing a decrease of environmental quality with a certain degree of irreversibility. The lesson learned from earthquake of March 2011 in Japan produced a domino effect on other systems and on related subsystems. In a few hours a transition occurred from low structural and infrastructural damages to elevated damages concerning the environmental system and its elements (ecosystem, radiation, soil, wastewater, drinking water, solid waste etc.) as well as other systems.

In the last years, another concept, related to vulnerability, can be used in order to describe systems and their behaviour to face catastrophic events: resilience. This concept has been developed in the field of ecology, as the property of a system that measures its ability to absorb changes and to return to an equilibrium state after a temporary disturbance[12]; in the last years, resilience has become a usual term in the field of risk management: the International Strategy for Disaster Reduction, Hyogo Framework for Action 2005-2015, for instance, is called "building the resilience of nations and communities to disasters" and it defines resilience as a property of a community or a society, describing its capacity to adapt by resisting or changing, in order to reach and to maintain an acceptable level of functioning and structure and that is strictly related to the capacity of a social system of organizing itself, learning from past disasters[22].

Resilience becomes strategic considering post-emergency phases. A disastrous event is followed by a period during which activities will lead towards a normality condition, as the one previous the event. The longer this period is, the less the system is resilient and as much as the disastrous event produces damages, the system is vulnerable and costs necessary to come back to re-equilibrium will be high.

As resilience is a property of a system and it characterizes also its components, we can argue that, according to the goal of managing seismic risk and reducing urban vulnerability, it is strategic to identify in peace time (before disastrous events) which elements, which activities and which functions of a city have prior importance after the event, to guarantee a rapid response and the reestablishment of normal conditions: this means identifying the *resilient city*, taking into account the following considerations:

- The necessity of a path system into the urban area, in order to guarantee healthy connections between strategic buildings and towards the outside of settlement;
- The necessity of a path system and of an open space system, in order to guarantee escape routes and healthy spaces during the emergency phase;
- The necessity to make these paths redundant, in order to guarantee at least an alternative to displacements in case of breakdown;
- Least, but surely not last, the importance of a sense of belonging to a community, with some particular traditions. In order to manage post-emergency phases and roads towards re-equilibrium, it is important to identify places and activities of a town considered by its population as the identity of the town itself and which make people conscious of their belonging to the community.

Material and Methods

In order to identify the resilient city, the adopted methodological approach considers multicriteria techniques with the aim of taking into account the different aspects that contribute to the resilience of a whole system, such as functional, social, morphological, geological and dimensional characteristics of a considered urban system.

Considering that, according to Roy[18], multicriteria analysis is *a decision-aid and a mathematical tool allowing the comparison of different alternatives or scenarios according to many, often conflicting, criteria in order to guide the decision maker toward a judicious choice*. In this study, alternatives and criteria have an explicit spatial dimension, so that model becomes spatial and can benefit from using Geographic Information Systems[6,7,18]; GIS, indeed, provides a powerful set of tools for manipulation and analysis of spatial information[5].

Some tests have been carried out on a sample city, which is Marsicovetere municipality, in Southern Italy. The sample city is located within a high seismic hazard area, Val d'Agri, that the OPCM 3274, 20.03.2003 and following laws, classify within the higher risk class. In the past, several earthquakes hit the area and in particular on 16 December 1857 an earthquake provoked more than nine thousands victims in the area.

Marsicovetere municipality is the most dynamic town in the valley. In the last decades, a development propulsion related in particular to the petroleum extraction activity, characterized Val d'Agri area, but the great part of activities, administrative bureaus, health services, shopping centres, etc. have developed in Marsicovetere area, influencing also its urban development. At present time, the municipality is divided into two main settlements, the old centre, where a minimal part of inhabitants live and the new settlement in the flat area, called Villa d'Agri; development in this flat area started during the '50s, but the great part of buildings has been realized during the last 30 years.

Figure 1 shows Val d'Agri region, while figure 2 represents a zoom on the area, so that it is possible to localize Marsicovetere boundaries. Figure 3 is a photo of Marsicovetere and Villa d'Agri settlements, showing that

Marsicovetere occupies the higher part of the territory and Villa d'Agri the flat one.

Spatial multicriteria analysis has been adopted following a logic scheme as shown in figure 4. In order to identify a solution for a certain decisional problem applying a spatial multicriteria analysis, during the intelligence phase, alternatives and criteria must be defined. Alternatives will be evaluated and scored through their performances on criteria that are attributes describing a certain characteristic.

The resilient city identification problem can be defined as follows: in a certain area, several elements interact each other. They are roads, buildings, natural characteristics and so on, and each of them has its own resilience, as a result of its characteristics. As the attended result of analysis is a synthetic map, representing areas where resilience must be improved, the decisional problem has been modelled defining a grid covering the whole municipal area. Each cell of this grid is therefore characterised by a certain degree of resilience, depending on elements present in the cell and their own resilience characteristics. Cells are decisional alternatives of the multicriteria problem.

Therefore, resilience characteristics depend on several attributes. The measure of such attributes on each cell represents the evaluation of the performance of the decisional alternative on a certain criterion. Therefore, a criterion represents the spatial distribution of an attribute measuring the degree to which its associated objective is achieved[15]. It is represented as a map layer and it is indicated as criterion map.

Results

Analysis does not consider exhaustive family of criteria, but the choice has been influenced by availability of data. In particular, five criteria have been considered, which are accessibility, urban centre proximity, slope, hydrographical network distance and structural vulnerability. For each of them, a criterion map has been produced, evaluating performances of each cell related to the considered attribute. Accessibility is a criterion aiming at measuring the availability of healthy paths and their redundancy. It has been obtained by some map algebra operations on the road network, adopting Cost Weighted Distance and obtaining a value for each cell, as higher as the cell is more accessible.

Urban centre proximity criterion is composed by two sub-criteria. The first one takes into account proximity to strategic buildings. The second one takes into account proximity to urban areas, considering the existence of several small settlements spread on the area. The first sub-criterion is strategic in order to manage emergency actions, considering that closeness to buildings as hospitals or Civil Protection buildings is strategic during the first hours after an event, where injured people need care and actions to be taken need to be planned within evolving situations. The second sub-criterion is more related to a post-emergency phase, when people need to be close to their home, so that, if they can not yet come back to live there, they do not feel completely lost and confused.

The two sub-criteria are both strictly related to accessibility criterion, but formally, they have been obtained not considering road network and calculating Euclidean distance of each cell from strategic buildings and from urban settlements, respectively, without referring to road network. The two sub-criteria maps have been obtained considering that a cell is as better as it is closer respectively to a strategic building or to an urban settlement.

In order to assess possible locations for safety areas, where to organize shelter areas for homeless people, it is important to take into account morphological aspects. In particular, slope and hydrographical network have been considered. Starting from a digital terrain model, a slope map has been calculated and then a criterion map has been calculated, considering that a cell is as better as its slope is lower. Moreover, high slope is a predisposing factor for landslides that can be activated following a seismic event.

At the same time, it is possible that after an earthquake a flood occurs; for this reason, hydrographical network distance has been calculated rating cells, so that a cell is as better as it is further from the hydrographical network. One more criterion has been considered, limited to the urban settlements of Marsicovetere and Villa d'Agri, in reason of the availability of information; the criterion takes into account structural vulnerability of buildings and a cell is as better as its vulnerability is low.

Once criterion maps have been defined, a standardization phase has been carried out, in order to adopt an additive rule and making possible comparisons between criterion maps. A linear scale transformation has been adopted, through maximum score procedure, that consists of a transformation of raw data into standardized criterion scores, applying a proportional transformation for each object, through a simple formula. 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 criterion interpretation difficult. In order to consider restrictions and limitations imposed by nature or rules, so that in certain areas certain actions are forbidden, constraint maps have been considered and modelled as territory portions to subtract from criterion maps, as a hole in territorial extension, as represented in figure 5 [13].

As for criteria, the identification of constraints has been limited by the availability of information; in particular, high seismic hazard areas, seismic micro-zonation, high landslide risk areas, flooding areas and areas physically occupied by buildings and roads have been considered.

First, areas with a high seismic hazard are considered not safe; to take into account this aspect, seismic hazard, as defined by Italian National Institute of Geophysics and Volcanology (INGV), according to OPCM (Ordinance of Italian Prime Minister) 3519[23], has been taken into account. Seismic hazard values are expressed as peak horizontal acceleration with 10% probability of exceedance in 50 years. Second, in order to define urban development, knowledge about local effects is becoming more and more important. Territory is classified in reason of the combination of soils, which can produce some local amplifications of seismic wave, or some other effects: according to OPCM 3274[24], soils have been classified considering their strata profile.

At the same time, and considering the necessity of localizing shelter areas, high landslide risk and flooding areas, as delimitated by Local Basin Authority (authority responsible for the plan concerning hydrogeological risk), have been erased. Finally, in order to identify safe areas, where localizing shelter areas, all spaces physically occupied by some manufacts, such as buildings or roads, have been erased.

The criterion maps obtained evaluating performances of cells on the several attributes must be at this point aggregated, adopting a certain decision rule. Considering, therefore, that not all criteria have the same importance, generally, they are aggregated considering a weight, representing the importance, and are obtained as the expression of decision makers: during the modelling phase, stakeholder value systems must be considered and introduced into analysis evaluating the relative importance of criteria for each stakeholder. In the study case, where no decision maker was present, a simulation has been carried out; more precisely, three scenarios have been built, considering different weights combination. The first scenario considers that criterion maps have all the same importance, so that weights have the same value, 1 (Set A). The second scenario considers that criterion maps linked to functional aspects, as accessibility and built-up areas proximity, are more important than others (Set B). The third scenario considers that criterion maps linked to safety, as slope and hydrographical network proximity, are more important than others (Set C).

Weights have been calculated adopting a pair wise comparison method, referring to Saaty[19]. Each scenario, therefore, has been carried out adopting a decision rule, that is a procedure allowing to order alternatives to choose the most preferred one[20]. In the study case, additive decision rules have been considered, adopting a simple additive weighting method[11], based on the concept of a weighted average and obtaining a synthetic final map from the criterion maps, as the one represented in figure 6, where each cell, A_i, is calculated according to the following expression:

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

where $x_{i,j}$ is the score of the cell on the j^{th} criterion and w_j is its weight. In figure 7, three different scenarios are presented.

Conclusion

The applied methodology can be considered suitable to identify the resilient city, even if there are several critical aspects to be considered. As declared, the simplest methods have been chosen, considering both standardization phase and decision rule. More sophisticated methods would produce better results, allowing also to go over the compensatory effect produced by methods based on averages. At this stage of research, therefore, the simplest methods have been chosen in order to test applicability of the method, considering also the insufficiency of information.

The developed geographic information system is lacking in several kinds of informative layers: lifelines, but also information about main activities on territories, information about people, information about people who do not live in Marsicovetere, but work there and spend there great part of their workday and so on. The next steps, therefore, are represented by collecting such data, modelling them into criterion maps and refining them step by step, also adopting other procedures.

At the best, we aim to adopt an electre method, in order to overpass all problems related to aggregated decision rules. Another step of future research will be the adoption of a seismic scenario, in order to evaluate what can happen with the most probable earthquake. Beyond such technical considerations, other remarks concern the role of resilient city in government. 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 considered elements.

Figure 1: Val d'Agri area in the context of Basilicata Region, in the South of Italy

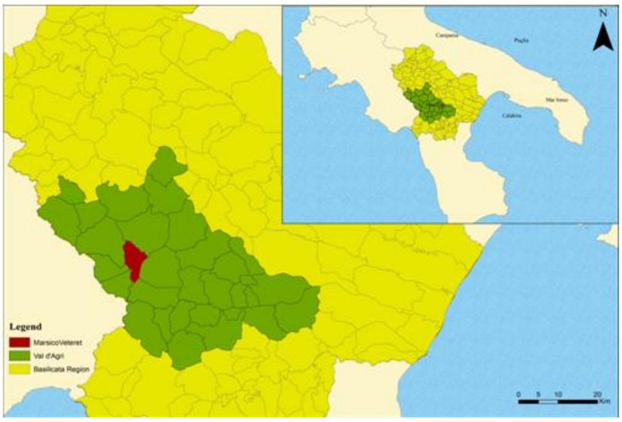

Figure 2: Zoom on Val d'Agri area and Marsicovetere Municipality boundaries

Figure 3: A photo of Val d'Agri area

Concerning the Italian situation, it has been highlighted that:

- Civil Protection is demanded to manage activities of prevention and protection;
- Each municipality should adopt an Emergency Plan, aiming at defining a possible risk scenario and the subsequent actions to manage the emergency;
- Emergency plans do not consider the possibility of intervening to mitigate risk before seismic event occurrence.

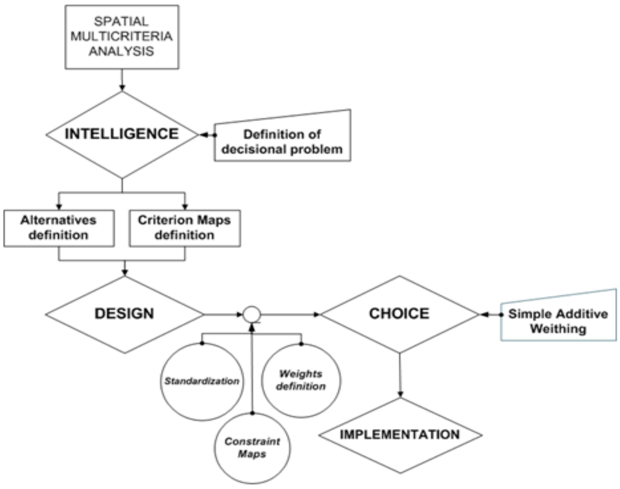

Figure 4: Scheme of the methodological approach

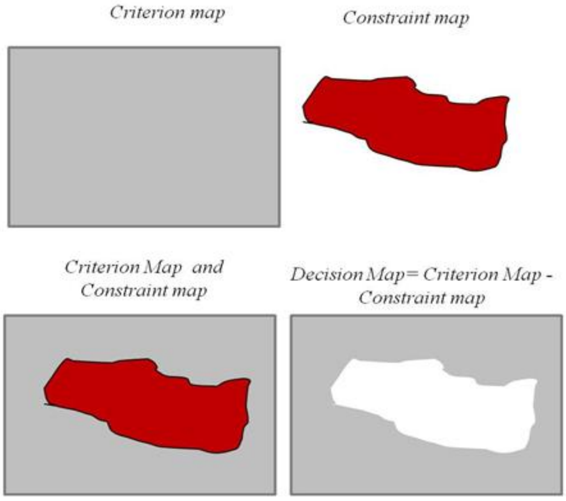

Figure 5: Criterion Maps and Constraint Maps

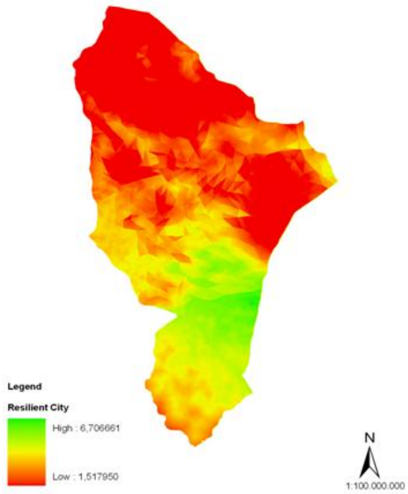

Figure 6: The map of resilient city of Marsicovetere according to Set (A). Greenest areas are candidates to the resilient city

Facing such considerations, at the moment resilient cities do not yet represent a useful tool in risk mitigation. Their identification and the defined methodology 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[1], this means also defining a context where horizontal and vertical exchanges in social systems are encouraged to contribute to discussions about risks, enhancing their perception and highlighting importance of prevention.

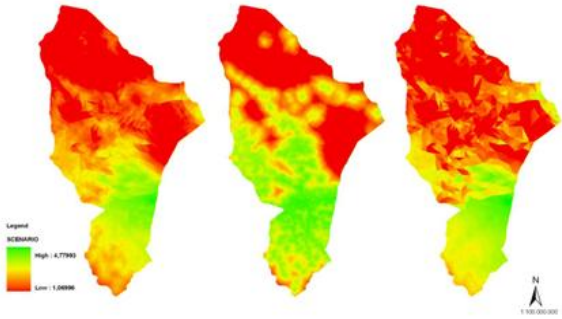

Figure 7: The three evaluation scenarios. Greenest areas are candidates to the resilient city

References

1. Barnett J., Adapting to Climate Change in Pacific Island Countries: The Problem of Uncertainty, World Development Elsevier Science Ltd., Great Britain, **29 (6),** 977-993 **(2001)**

2. Besio M., Dalla carta del rischio al piano integrato della sostenibilità territoriale, Urbanistica, INU, Roma 117 **(2001)**

3. Caldaretti S., Fabietti W. and Riggio A., La vulnerabilità sismica dei sistemi territoriali, DEI, Roma **(1987)**

4. Chirico A. et al., Progetto GERIA, La Gestione dei rischi naturali per la messa in sicurezza del territorio. Dossier tematico Valutazione di Vulnerabilità Sistemica nel territorio trans-frontaliero **(2002)**

5. Carver S., Integrating multi-criteria evaluation with geographical information systems, *International Journal of Geographical Information Science,* **5(3),** 321-339 (**1991**)

6. Chakhar S. and Mousseau V., An algebra for multicriteria spatial modelling, *Computers, Environment and Urban Systems*, **31(5)**, 572--596 **(2007)**

7. Chakhar S. and Mousseau V., Spatial Multicriteria Decision Making, In Shekhar Shashi and Xiong Hui, eds., Encyclopedia of GIS, Springer **(2008)**

8. Fabietti W. (ed), Vulnerabilità e trasformazione dello spazio urbano, ALINEA Editrice, Firenze **(1999)**

9. Fera G., La città antisismica, Gangemi **(1997)**

10. Galderisi A., Città e terremoti, Metodi e tecniche per la mitigazione del rischio sismico, Gangemi Editore, Roma **(2004)**

11. Heywood I., Oliver J. and Tomlinson S., Building an explanatory multi-criteria modelling environment for spatial decision support, *Innovation in GIS*, **2,** 127-136 **(1995)**

12. Holling C.S., Resilience and stability of ecological systems, *Review of Ecology and Systematics,* **4**, 1-23 (**1973**)

13. Keeney R.L., Siting energy facilities. Academic Press, USA **(1980)**

14. Las Casas G. and Scardaccione G., Contributi per una geografia del rischio sismico: analisi della vulnerabilità e danno differito, In Di Gangi M., ed., Modelli e metodi per l'analisi delle reti di trasporto in condizioni di emergenza:contributi metodologici ed applicativi, Editrice Ermes, Potenza **(2005)**

15. Malczewski J., GIS and Multicriteria Decision Analysis, John Wiley and Sons, USA **(1999)**

16. Manyena, The concept of resilience revisited, *Disasters*, **30(4),** 433-450 **(2006)**

17. Mercuri C., La scheda per la valutazione della vulnerabilità urbana, In Segnalini O., ed., Metodi e strumenti per i centri storici delle Marche, Gangemi Editore, Roma **(2000)**

18. Roy B., Multicriteria methodology for decision aiding, Kluwer Academic Publishers, Dordrecht **(1996)**

19. Saaty T.L., The analytic hierarchy process, McGraw-Hill, USA **(1980)**

20. Starr M.K. and Zeleny M., MCDM: state and future of the arts, In Starr M.K. and Zeleny M., eds., Multiple criteria decision making, North-Holland, Amsterdam, 5-29 **(1977)**

21. UNDRO, Natural Disasters and Vulnerability Analysis, Report of Experts Group Meeting, Geneva **(1980)**

22. UN/ISDR, Report of the World Conference on Disaster Reduction, Hyogo, Japan **(2005)**

23. Ordinanza del Presidente del Consiglio dei Ministri della Repubblica Italiana 3519 (28/04/2006) "Criteri generali per l'individuazione delle zone sismiche e per la formazione e l'aggiornamento degli elenchi delle medesime zone" http://zonesismiche.mi.ingv.it/documenti/ordinanza_3519.pdf **(2006)**

24. Ordinanza del Presidente del Consiglio dei Ministri della Repubblica Italiana 3274 (20/03/2003) "primi elementi in materia di criteri generali per la classificazione del territorio nazionale e di normative tecniche" http://zonesismiche.mi.ingv.it/documenti/gazzetta.pdf **(2003)**.

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