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Multicriteria Fuzzy Analysis for a GIS-Based Management of Earthquake Scenarios

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Abstract: *Objective of this article is the formulation and the implementation of a decision-making model for the optimal management of emergencies. It is based on the accurate definition of possible scenarios resulting from prediction and prevention strategies and explicitly takes into account the subjectivity of the judgments of preference. To this end, a multicriteria decision model, based on fuzzy logic, has been implemented in a user-friendly geographical information system (GIS) platform so as to allow for the automation of choice processes between several alternatives for the spatial location of the investigated scenarios. In particular, we have analyzed the potentialities of the proposed approach in terms of seismic risk reduction, simplifying the decision process leading to the actions to be taken from directors and managers of coordination services. Due to the large number of variables involved in the decision process, it has been proposed a particularly flexible and streamlined method in which the damage scenarios, based on the vulnerability of the territory, have represented the input data to derive a vector of weights to be assigned to different decision alternatives. As an application of the proposed approach, the seismic damage scenario of a region of 400 km^2, hit by the 2009 earthquake in L'Aquila (Italy), has been analyzed.*

1 INTRODUCTION

Earthquake is one of the most destructive disasters that can cause huge damages to buildings, infrastructures, and to human beings. Efforts aimed at earthquake prediction have been recently reviewed in Panakkat and Adeli (2008) and more updated contributions in the same field can be found in Adeli and Panakkat (2009) and Panakkat and Adeli (2009).

However, in spite of several advancements, a universally accepted model of earthquake prediction is still lacking. For this reason, long-term risk analysis of a region is of the utmost importance for emergency management and hazard preparedness. In particular, the most probable impacts of disasters should be analyzed in advance, especially in urban areas, to have an efficient postdisaster response (Delavar et al., 2015; Moradi et al., 2017; Ranjbar et al., 2017; Rashed and Weeks, 2003).

On a parallel side, the large amount of earthquake-induced human and economic losses is progressively shifting the focus of research from risk and loss assessment to their mitigation by means of vulnerability reduction and resilience improvement (Nejat and Damnjanovic, 2012; Opricovic and Tzeng, 2002; Franchin and Cavalieri, 2015; Leone and Zuccaro, 2016; Zuccaro and Cacace, 2014).

With specific reference to urban areas, seismic vulnerability is related to several factors such as structural typologies of the buildings, quality and age of their materials, percentage of elderly residents and children, intensity of the earthquake, quantity, and efficiency of emergency services in helping wounded people. Different factors, partly overlapping to the previous ones, affect vulnerability to landslides (Feizizadeh et al., 2014; Mavrouli et al. 2014)

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and volcano eruptions (Zuccaro and De Gregorio, 2013).

As a rule, factors affecting vulnerability are characterized by data scarcity, and misleading or conflicting information that unavoidably introduce uncertainties in data handling. Hence, fuzzy set theory can be usefully implemented to represent uncertain information more realistically.

Since its introduction over 40 years ago (Zadeh, 1965), fuzzy set theory has been used to address several problems in engineering (Zadeh, 1976; Anoop et al., 2012; Adeli and Karim, 2000; Altunok et al., 2006; Bianchini and Bandini, 2010; Dell'Orco and Mellano, 2013; Graf et al. 2012; Hsiao et al. 2012; Li et al., 2013; Sarma and Adeli, 2000a, b; Tagherouit et. al., 2011).

On the other hand, when several factors, either of tangible or intangible nature, have to be taken into account, it is necessary to establish some priorities in their choice by arranging them in a hierarchy of criteria, subcriteria, and alternatives.

To this end, the analytic hierarchy process (AHP) has been developed by Saaty (1980) and integrated into fuzzy models owing to its capability of handling multicriteria decision (MCD) issues (Buckley, 1985).

Due to its importance in solving civil engineering problems, several books have been published in recent years (Kahraman, 2008; Petrycz et al., 2011). The reader is also referred to Antucheviciene et al. (2015) for a review article on the subject, and the recent articles by Zavadskas and Vaidogas (2009), Tagherouit et al. (2011), Zhang et al. (2014), and D'Urso and Masi (2015).

The huge amount of data involved in the integration of fuzzy models and AHP has naturally paved the way to the use of geographical information system (GIS) tools to allow information derived from different sources to be suitably merged. In particular, GIS-based MCD analysis has been affirmed as a smart approach for converting spatial and nonspatial data into information that can be combined with the decision maker's own judgment to make critical decisions.

Hence, it is not surprising that after some preliminary studies mainly of theoretical nature (Carver, 1991; Banai, 1993; Malczewski, 1996), the number of applications has enormously grown (Joerin and Musy, 2000; Chen et al., 2001). The reader is also referred to Malczewski (1999) for a survey account on the subject and to Malczewski (2006) for a more recent list of applications.

The aim of the article is to formulate and implement a decision-making model, based on fuzzy multiple criteria, for the optimal management of emergencies and to illustrate its application to postseismic events. Actually, rather surprisingly, specific applications of fuzzy multiple criteria decision making to the management of postseismic damage scenarios are quite rare. Thus, we develop a model, based on fuzzy analytic hierarchical processes, to support the decision-making activity for emergency management. The model has been applied by using and analyzing data and information related to the earthquake that hit the territory of L'Aquila (Italy) on April 9th, 2009. In particular, the article is inspired by studies and research carried out under the European Project CRISMA "Modelling Crisis Management for Improved Action and Preparedness" (FP7 284552 - 2012/2015) and aims to develop these issues.

2 MULTICRITERIA ANALYSIS IN DISASTER MANAGEMENT

The extent of damage and disruption caused by earthquakes, landslides, or volcano eruptions, can be minimized by adopting systematic measures of emergency management. Within this context, it is fundamental to intervene quickly by making decisions that are as accurate and objective as possible, by identifying all viable alternatives and analyzing their consequences. A prerequisite to this end is to dispose of full information, besides the possibility to process them within models that support the decision-making activity. Once the problem has been fully set, one needs to find a suitable solution and to define the implementation strategy, analyzing every critical situation, by giving space to creativity in finding alternative solutions, and finally, by characterizing each resulting scenario (Jankowski, 1995; Opricovic and Tzeng, 2002; Jiang and Eastman, 2000).

The adopted decision will have to account for some general criteria of internal validity, affordability, and feasibility, by considering the available or obtainable resources, as well as internal and external, current, and future conditions (Martínez-Rojas et al., 2015). Decision-making problems framed within this context can be characterized by a multiplicity of significant aspects and by the presence of several goals and constraints, often not explicit or even conflicting. These can be analyzed by identifying and inserting, within a decision tree, a general objective, and at least a decision maker involved in the choice of the process, resorting to the use of multicriteria analysis models able to keep account of the conflicting nature of particularly complex situations and to explain the criteria for the selection of the alternatives in terms of specific targets (Herrera and Herrera-Viedma, 2000).

As a matter of fact, multicriteria analysis is developed for addressing situations characterized by a high number of involved options and variables that produces very often divergent results and makes it extremely difficult to identify the best solution for each considered criterion. The main issue is not a search for "objectively optimal" solutions but, rather, the support of an activity of choice through a rationalization of the decision-making process and the optimization of a set of criteria weighted according to the priorities stated by the decision makers. This new evaluation scheme leads to the identification of alternatives that satisfy a certain number of explicitly defined standards. To sum up, the elements of a decision-making structure are divided into:

- Objectives: statements regarding the condition one would like to achieve made operational through the allocation of one or more attributes of a qualitative and/or quantitative nature.
- Criteria: standards of judgment or rules useful to test the desirability of decision alternatives, including both the concept of goal and that of attribute.
- Alternatives: elements of evaluation and of choice that must be ordered on the basis of dominance scores and representing the entries of the decision matrix.

3 POSTSEISMIC DAMAGE SCENARIOS

Seismic emergency management requires specific programs for the identification of the objectives to achieve in order to organize an adequate civil protection response to particularly burdensome events. Programs of this kind manage a complex system of work force, equipment, and resources arranged and coordinated by local administrations, both in space and in time.

The initial knowledge basis, necessary for the allocation of resources to be deployed, is represented by damage scenarios, i.e., tools for forecasting possible damages due to the earthquake impact and subsequent population involvement in the affected area (Burton and Kates, 1964).

Such scenarios are defined on the basis of data relating to the vulnerability of the territory, with particular attention to the built environment, in relation to reference earthquakes. Moreover, they can provide useful information such as the location and the extent of the most severely affected area, functioning of transport infrastructures, roads and service networks, damage of buildings and the expected life losses, as well as the corresponding direct and indirect financial burden.

Within this context, it is of the utmost importance to dispose of detailed information on the effects and efficacy of future actions aiming to overcome the critical condition, resulting from decisions based on an integrated assessment that involves all the aspects of a specific problem. Methodologies used to make such choices may represent an essential tool to support decisions looking for solutions able to settle objectives of strategic planning in accordance with territorial, economic, environmental, and social criteria.

Among such methodologies, the multicriteria analysis (Hwang and Yoon, 1981; Ishizaka and Nemery, 2013) is the activity related to the implementation of decision-making strategies for complex problems and provides the most appropriate choice for an integrated approach that involves several experienced decision makers.

Thus, risk management problems, including a high number of decision alternatives, are efficiently solved by defining a hierarchical structure of dominance that links the query to a series of pairwise comparisons. This approach has been further refined through the combination of fuzzy logic methods (Xu and Zhou, 2011; Xu, 2015) that define different fuzziness degrees in the judgments of preference.

Within this context, in order to conveniently integrate all the variables contributing to the analysis of a territorial system, we have used GIS as an integrated system of information management able to aggregate data from different origins (Carver, 1991; Banai, 1993).

4 ANALYTICAL HIERARCHICAL PROCESSES BASED ON FUZZY LOGIC

Fuzzy logic is a type of probabilistic logic producing continuous values ranging from zero to one, developed by Lotfi Asker Zadeh in the early 1960s (Zadeh, 1965). Its main strength is based on the ability to operate in those situations in which one deals with linguistic variables that are difficult to translate and insert into precisely contoured sets.

The adjectives that classify the elements of any decision problem (objectives, criteria, and alternatives) are verbal labels adequately represented by membership functions, which can take any value between zero and one, thus describing how a certain property progressively changes from full occurrence to lack of occurrence (Zhang et al., 2014).

The success of this type of logic lies in its adherence to the human cognitive model when it is in charge of making choices. Actually, humans do not have particular success in quantitative forecasts, while they are relatively effective in the qualitative ones; basically, the uncertainty in the preferences raises doubts in classifying a series of alternatives based on their dominance.

While the application of the traditional analytical hierarchical process, widely used in multicriteria analysis, adequately addresses all these problems, one more and more feels the need to invoke the implementation of techniques that, borrowed from fuzzy theory, can help

Table 1
Triangular fuzzy semantic scale

Intensity of dominance (a_{ij})	*Judgment*
1;1;1	Equal importance
2;3;4	Weak predominance
4;5;6	Moderate predominance
6;7;8	Strong predominance
9;9;9	Absolute predominance
1;2;3	Values of compromise
3;4;5	
5;6;7	
7;8;9	

to overcome some weaknesses of the traditional approach.

Among methods based on fuzzy logic those that are particularly important are the fuzzy analytical hierarchical processes to support the decision-making activity for strategic planning and emergency management (Banai, 1993; Chan et al., 2008).

These can be seen as advanced methods of analysis able to overcome the problems related to the representation of uncertainty and vagueness of particular decisions characterized by multiple objectives, constraints, and criteria. They are based on the use of semantic scales of judgment linked to linguistic variables that follow the trend of differently shaped membership functions; an example of fuzzy semantic scale can be found in Table 1 (Herrera and Herrera-Viedma, 2000; Jankowski, 1995).

Choosing the type of scale, the membership function, the values in the scale according to a certain linguistic variable, is at discretion of the decision makers (Ayhan, 2013; Chan et al., 2008). Denoting by n the number of criteria to be considered, the matrix of pairwise comparisons $\tilde{A}^k$, built by an individual decision maker, will be square and symmetrical:

$$\tilde{A}^k = \begin{vmatrix} \tilde{a}^k_{11} & \tilde{a}^k_{12} & \ldots & \tilde{a}^k_{1n} \\ \tilde{a}^k_{21} & \tilde{a}^k_{22} & \ldots & \tilde{a}^k_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{a}^k_{n1} & \tilde{a}^k_{n2} & \ldots & \tilde{a}^k_{nn} \end{vmatrix}$$

where $\tilde{a}^k_{ij}$ denotes the kth preference of the generic decision maker, referred to the ith criterion with respect to the jth one, and is expressed through a triangular fuzzy number with two extreme values and a median. If there are K decision makers, individual preferences $\tilde{a}^k_{ij}$ are averaged and $\tilde{a}_{ij}$ is calculated as follows:

$$\tilde{a}_{ij} = \frac{\sum_{k=1}^{K} \tilde{a}^k_{ij}}{K}$$

In this way, it is obtained a new matrix of pairwise comparisons $\tilde{A}$ that contains the averaged triangular dominance coefficients:

$$\tilde{A} = \begin{vmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \ldots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \ldots & \tilde{a}_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \ldots & \tilde{a}_{nn} \end{vmatrix}$$

In accordance with the method by Buckley (1985), the geometric average of the values of the fuzzy comparisons for each criterion is computed:

$$\tilde{u}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij} \right)^{\frac{1}{n}} \quad i = 1, \ \ldots, \ n$$

and the vectors $\tilde{u}_i$ are collected in ascending order.

The vector sum of the fuzzy elements $\tilde{u}_i$ is considered

$$\tilde{u} = (\tilde{u}_1 \oplus \tilde{u}_2 \oplus \tilde{u}_3 \oplus \cdots \oplus \tilde{u}_n)^{-1}$$

where the symbol $\oplus$ indicates the fuzzy sum, and its reciprocal is computed.

Subsequently, one computes the weight of the fuzzy ith criterion as

$$\tilde{o}_i = \tilde{u}_i \otimes (\tilde{u}_1 \oplus \tilde{u}_2 \oplus \tilde{u}_3 \oplus \cdots \oplus \tilde{u}_n)^{-1} = (lw_i; mw_i; uw_i)$$

where $\otimes$ denotes the fuzzy product.

The value $\tilde{o}_i$ is a fuzzy number represented by three values, a lower, a medium, and an upper value of the triangular function membership.

Finally, it is necessary to defuzzify using the center of gravity method and normalize the weight:

$$M_i = \frac{(lw_i + mw_i + uw_i)}{3}$$

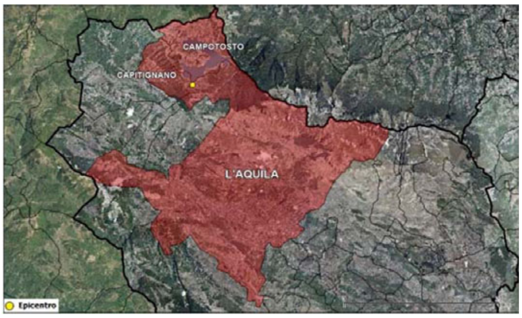
$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i}$$

Such steps must be followed sequentially to calculate the normalized weights, both for the criteria and the alternatives. Subsequently, by multiplying the weight of each alternative for the relevant criterion, the scores are computed. In agreement with these results, the alternative with the highest score will be the one suggested by the decision makers (D'Urso and Masi, 2015).

5 CASE STUDY

To illustrate a realistic application of the proposed approach, we analyze the seismic damage scenario concerning the earthquake that occurred in L'Aquila (Italy) in 2009.

The impact scenario has been assessed through the seismic impact model developed by PLINIVS Study



Latitude	*Longitude*	*Depth*	*Magnitude*
42,504	13,351	9,3 km	5.0

Fig. 1. Characteristics of the reference earthquake (Parametric Catalogue of Italian Earthquakes 2015, CPTI15).

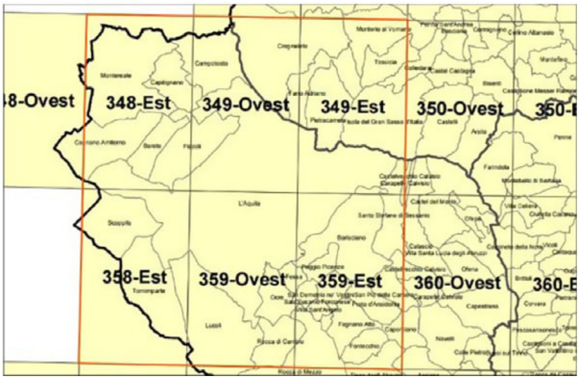


Fig. 2. Localization of the area on the Abruzzo topographic regional map.

Centre (LUPT Interdepartmental Centre, University of Naples Federico II). On the basis of risk or scenario analyses, the model is able to evaluate the physical and economic damages induced by a sequence of earthquakes on the territory exposed.

The "risk" is the likelihood that a predetermined level of damage (on people, buildings, infrastructures, economics, etc.) caused by seismic events takes place within a given time period in a certain geographic area. Therefore, risk should be understood as a cumulative assessment that takes into account the total potential damage that can be generated from different events in the same area in a predetermined amount of time.

The "scenario" represents the probabilistic distribution, in a certain geographical area, of the damage induced by a single seismic event with assigned probability of occurrence (assumed as a reference scenario).

In the emergency planning, both analyses can be used as a response to different purposes. Risk analysis is useful for comparative assessments in terms of decision making on intervention strategies (e.g., evacuation priorities, etc.) and mitigation actions. Scenario analyses are useful for quantifying the resources needed for emergency planning and organizing operational interventions, by identifying the extent of the area of interest and the territorial impact assessment.

The aim of the article is to illustrate the use of the multicriteria approach in the emergency planning, rather than describing the preexisting damage analysis model used to assess the seismic impact (PLINIVS model). For this reason, with the aim of showing a simple numerical application, it was chosen to consider the scenario analysis concerning the single seismic event of 9 April 2009 in L'Aquila (Figure 1).

For the application illustrated in the sequel, a "scenario" analyses is adopted with the purpose of supporting the choice of possible mitigation strategies.

In the assumed model, the scenario according to which a given level of damage "*l*" is achieved under the effect of a single seismic event of intensity "*i*" is assigned by the following relationship:

$$\text{Scenario}_{\mathrm{l,i}} = \int_{m} q_m \, [(H_i) \cdot (V_{l,i,m})]$$

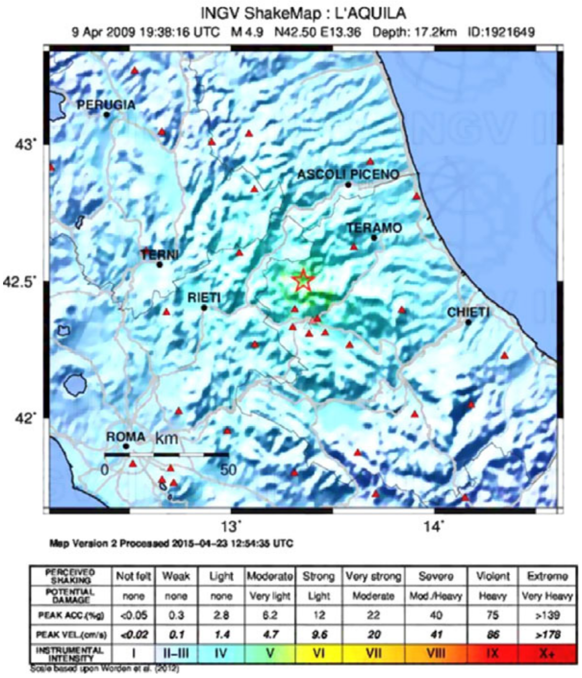
where: H_i is the likelihood that a seismic event of severity "*i*" occurs in a certain period of time and in a certain site; $V_{l,i,m}$ is the probability of achievement of a given level of damage "*l*" under the effect of a seismic event of intensity "*i*" for a given category "*m*" (vulnerability class) of risk elements; and q_m is the percentage of elements of category "*m*."

The reference earthquake under examination is the event of April 9th, 2009, 19:38:16 UTC, with a magnitude M_L of 5.0 ($M_W = 5.21$) and epicenter between L'Aquila, Campotosto, and Capitignano (Parametric Catalogue of Italian Earthquakes 2015, CPTI15, see, e.g., Figure 1). The area, schematically reported in Figure 2, lies entirely in quadrants 348 E, 349 W–E, 358 E, 359 W–E of the Abruzzo Topographic Regional Map at 1:25,000.

The particular orographic–hydrographic configuration of the area is the result of a complex Pliocene-Quaternary evolution, consisting of alternating plains and adjacent tectonic valleys, partially filled by Quaternary deposits.

This is the result of the combination of the morph-tectonic processes associated with the activity of the faults at the edges and of the erosive and depositional morph-sculptural processes linked to different environments.

In terms of ground-motion-based intensity ShakeMaps, the adopted seismic hazard H_i is provided by INGV, Italian Institute of Geophysics and Volcanology (http://shakemap.rm.ingv.it, ID 1921649). They are



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Fig. 3. INGV ShakeMap: L'Aquila, 2009 April 9, 19:39:16 UTC (http://shakemap.rm.ingv.it).

determined using the Faenza and Michelini (2010, 2011) conversion relations between ground motion parameters and the Mercalli-Cancani-Sieberg (MCS) intensity scale (Figure 3).

Only ordinary buildings have been considered as elements exposed in the analyses (*q*m). Buildings are grouped in categories (vulnerability classes), with similar behavior under the effect of seismic hazards. Specifically, the adopted vulnerability classes are the ones defined by EMS98 (acronym of European Macroseismic Scale 1998) (A, B, C, D). They are assigned by a procedure (Zuccaro et al., 2012; Zuccaro and Cacace, 2014) able to provide an assessment of the buildings' exposure on the basis of ''basic'' information collected from the Italian Census Database on buildings (DB_Census) produced by the Italian Central Statistics Institute (ISTAT, Italian acronym). In particular, statistical relations have been determined so as to link this information of general type to the vulnerability classes. This has been possible due to the examination of "specific" information on structural typologies derived from a large sample of buildings, spread out in all the Italian territory, investigated by a quick survey promoted by the PLINIVS Study Centre and collected in a unique database (DB_Plinivs).

The vulnerability $V_{l,i,m}$ that characterizes each vulnerability class used in the model is constituted by a damage probability matrix (DPM) assessed for the Italian territory through an empirical approach founded on several *in situ* damage distribution surveys (about 170,000 buildings) related to past seismic events (Zuccaro, 2004; Zuccaro et al., 2008).

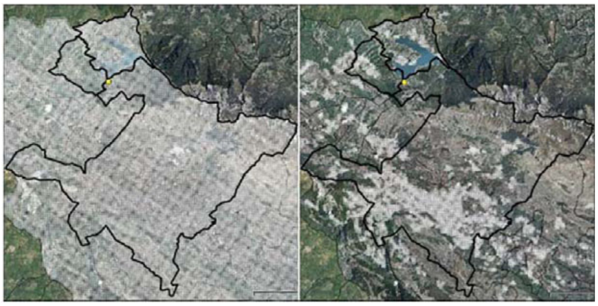


Fig. 4. Overlay of the vector grid on the raster base mapping and activation of pixels actually containing buildings.

The open-source software used for the construction of geo-referenced geographic data is the multiplatform system QGIS^{TM} within which the geographic information was entirely managed. The Abruzzo Region Orthophoto 2005, geo-referenced with a pixel size of 0.50 × 0.50 m on the ground (Figure 4), was used as base map.

To achieve a better and more effective visualization, data pertaining to this assignment have been reported in square pixels with dimensions 250 × 250 m through the overlay of an areal shape file composed of a grid shaped on the territorial boundaries with which it was decided to divide the investigated territory. Subsequently, numerical data related to the consistency and seismic vulnerability of the housing stock have been further subdivided within each square pixel. All pixels not containing buildings have been excluded and the analysis has been carried out on a total of 32,182 buildings within the investigated area, organized in a vector database associated with an attribute table containing all the necessary information, in particular the vulnerability class for each building.

On the basis of data concerning hazard, exposure and vulnerability described above, the PLINIVS seismic impact model defined three realistic scenarios.

- The first scenario (vulnerability condition 1) assumes that no structural improvement is made to the buildings. In particular, the starting point consists of 7,675 Class A buildings, 7,387 Class B buildings, 8,542 Class C buildings, and 8,578 Class D buildings.
- The second scenario (vulnerability condition 2) assumes structural improvements, by producing an upgrade of the relevant vulnerability classes. In particular, it has been supposed that Class A buildings are moved to Class B, Class B buildings are

classified at Class C, and Class C buildings are classified at Class D, while no structural improvements are made on buildings originally belonging to Class D. Under this assumption, Class A is an empty set, 7,675 buildings belong to Class B, 7,387 to Class C, and 17,120 to Class D.

- The third scenario (vulnerability condition 3) assumes more significant structural improvements. The buildings initially belonging to Classes A and B are moved to Class C, while no structural improvements are supposed to be made on the buildings belonging to Classes C and D. Thus, on account of the assumptions that characterize the vulnerability condition 3, no buildings belong to Classes A and B, 16,217 buildings belong to Class C, and 15,965 buildings to Class D.

This characterization of the territory in terms of exposure and vulnerability represents the input of the simulations that return the distribution of damage in terms of damage levels of buildings, dead, injured, and homeless people, through the combination with ShakeMaps available for the investigated area.

For what concerns the economic burden, the proposed impact model (Leone and Zuccaro, 2016) requires a distinction between direct costs (mitigation, reconstruction and/or rehabilitation, evacuation, emergency management, health care, and activities for the return at home) and indirect costs (decrease of value for psychological effects, for evacuation and life losses). Direct costs include the ones associated with upgrading of vulnerability classes (chains, floor/wall connections, injections, reinforcement of beams and pillars, use of composite materials, etc.).

The case study illustrated in the sequel is just an example. For simplicity, it does not consider the damage caused to buildings by earthquakes previous to the April 9th event.

In damage scenario 1, directly related to the vulnerability condition 1, there have been recorded 18,264 (56.75%) undamaged buildings (damage level D0), 13,844 (43.02%) buildings with damage from low to medium (damage level D1 + D2 + D3), 74 (0.23%) unusable buildings (damage level D4 + D5) (Figure 5), 51 dead, 161 injured, and 7,368 homeless. Moreover, direct costs amount to €4,946,143,188, while indirect costs amount to €2,258,083,482.

In damage scenario 2, directly related to the vulnerability condition 2, there have been recorded 20,045 (62.29%) undamaged buildings (damage level D0), 12,098 (37,60%) buildings with damage from mild to medium (damage level D1 + D2 + D3), 39 (0.11%) unusable buildings (damage level D4 + D5) (Figure 6), 36 dead, 98 injured, and 5,507 homeless. Direct costs amount to €12,216,508,437, while indirect costs amount to €2,256,926,639.

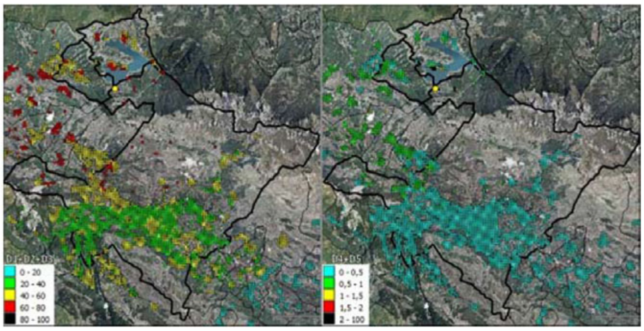


Fig. 5. Spatial distribution of the percentage of buildings per cell that have suffered a damage level D1 + D2 + D3 (left) and D4 + D5 (right) for damage scenario 1.

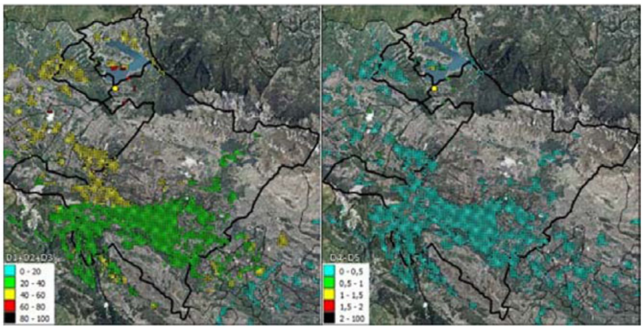


Fig. 6. Spatial distribution of the percentage of buildings per cell that have suffered a damage level D1 + D2 + D3 (left) and D4 + D5 (right) for damage scenario 2.

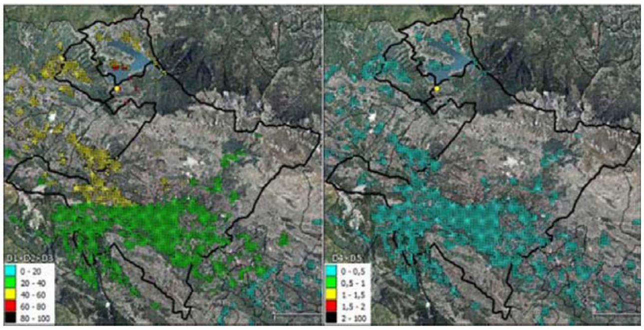


Fig. 7. Spatial distribution of the percentage of buildings per cell that have suffered a damage level D1 + D2 + D3 (left) and D4 + D5 (right) for damage scenario 3.

Finally, in damage scenario 3, directly related to the vulnerability condition 3, there have been recorded 20,745 (64.47%) undamaged buildings (damage level D0), 11,418 (35,48%) buildings with damage from low to medium (damage level D1 + D2 + D3), 19 (0.05%) unusable buildings (damage level D4 + D5) (Figure 7), 22 dead, 53 injured, and 3,940 homeless. In this last

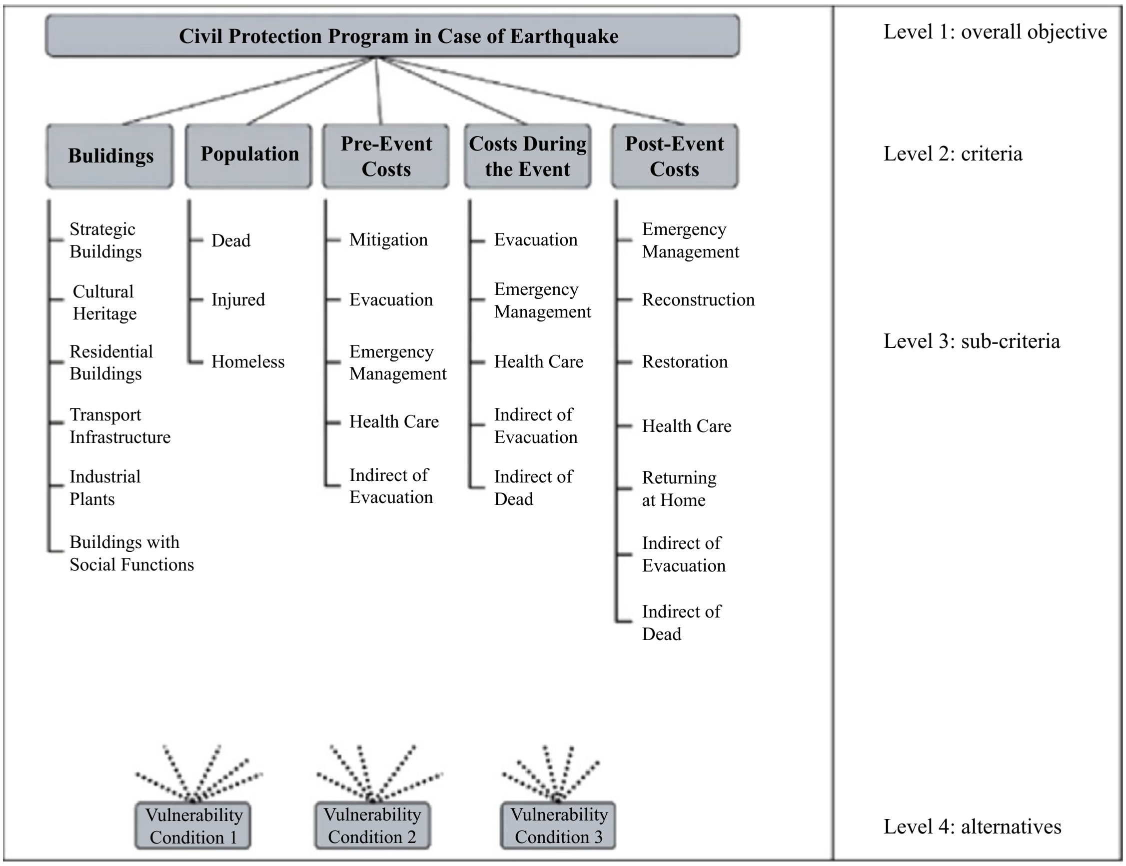


Fig. 8. The dominance hierarchy in emergency planning and management.

case, direct costs amount to €9,734,567,338, while indirect costs amount to €2,237,368,500.

The result of the study on possible scenarios represents the basis for the preparation of forecasting and prevention programs, in turn, used as reference for selecting mitigation measures related to the hazard of the event, of the vulnerability of the area and of the available financial resources.

The overlay of the event scenario on the territory exposed at risk leads to the definition of the damage scenario, a useful tool for quantifying maximum losses in terms of human lives and damage to buildings, infrastructures, and services. Based on the simulation of the effects induced by the reference earthquake, one can size the resources to allocate in case of a real emergency and tune the intervention procedures to be activated.

6 ELABORATION OF THE DECISION-MAKING PROCESS

The context of strategic planning for emergency management evolves very rapidly and strongly influences people in charge to decide and to correctly analyze the decision variables characterized by high levels of uncertainty and risk.

The decision-making activity, due to the large number of factors that influence it, is structured in an ordered sequence of phases, necessary to bring the complex problem to a simplified scheme, easily to be dismantled into hierarchical levels.

The objective of this work is to draw up a program of civil protection in case of earthquakes. Such a program, calibrated on hypothetical plausible situations and based on the existing state of fact, is a dynamic tool open to updates and revisions, subject to the identification and definition of multiple criteria, composed of different levels and that is prepared and configured to anticipate, prevent or deal with an earthquake that hits the territory and the social community. It is summarized in Figure 8.

The dominance hierarchy proposed for this case identifies four levels: the first contains the overall objective (O), the second contains five criteria (C_i) that specify contents and meanings of the overall objective, and the third contains 26 subcriteria (S_i) further

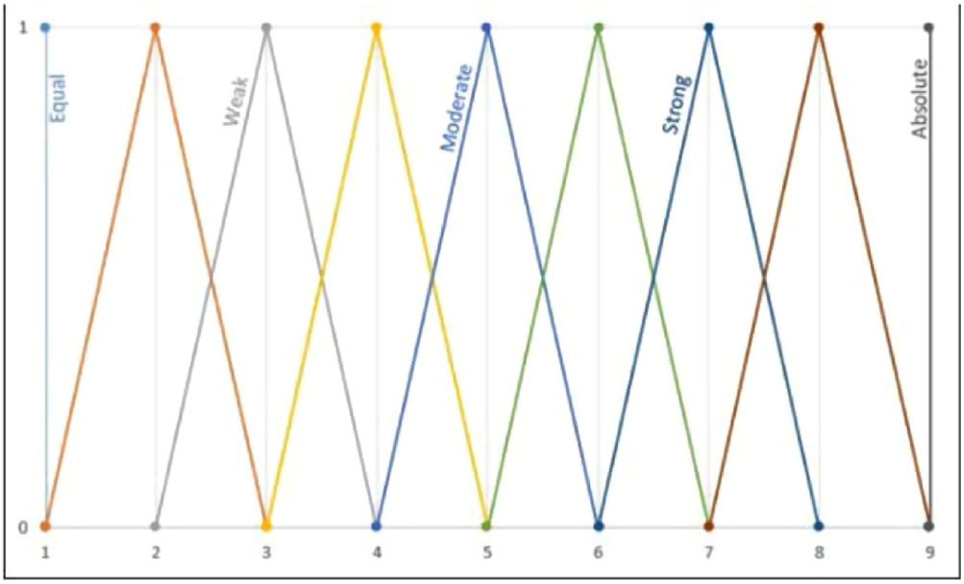


Fig. 9. Term set of the linguistic decision variable represented by triangular membership functions.

characterizing the criteria in higher level. The lowest level of the hierarchy is the fourth one where are located the three decision alternatives (A_i) to be evaluated.

These differ from each other for different seismic classification of the buildings in accordance with the GNDT first level (National Group for Defence against earthquakes).

The first phase of the decision-making process is the composition of the group of expert decision makers related to the various disciplines involved in the strategic resolution of the problem. In particular, professionals working within the Department of Civil Protection, the Coordination of Emergency Medical Service, as well as professionals in the field of territorial planning have been involved.

On the basis of previously described triangular semantic fuzzy scale, individual decision makers express their views, giving an intensity of dominance for each pairwise comparison between elements of the same hierarchical level. Individual results are therefore mediated to take account of the multidisciplinary nature of the problem.

The subsequent phase is the construction of the term set of the variable, i.e., the field of its possible values, by defining the shape of the membership function to be used. The triangular function, illustrated in Figure 9, was the result of best compromise between accuracy and computational burden.

Following the approach outlined in Section 4, one sequentially computes matrices of pairwise comparisons for each criterion, the fuzzy weight for each criterion, the normalized weight, and finally, the alternatives for each criterion. The alternative with the highest score will be the one suggested by the decision makers.

Table 2

Matrix of pairwise comparison of criteria in relation to the overall objective

O	*C*$_1$	*C*$_2$	*C*$_3$	*C*$_4$	*C*$_5$
C_1	1;1;1	$\frac{1}{7};\frac{1}{6};\frac{1}{5}$	1;2;3	1;1;1	1;1;1
C_2	5;6;7	1;1;1	3;4;5	3;4;5	3;4;5
C_3	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	1;1;1	1;1;1	1;1;1
C_4	1;1;1	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	1;1;1	1;1;1	1;1;1
C_5	1;1;1	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	1;1;1	1;1;1	1;1;1

The first matrix of pairwise comparisons, reported in Table 2, is assembled: the second-level criteria “buildings” (C_1), “population” (C_2), “preevent costs” (C_3), “costs during the event” (C_4), and “postevent costs” (C_5) are compared with each other in relation to the overall objective (O) in the first level “civil protection program in case of earthquake.”

$\tilde{u}_i$ is calculated as the geometric mean of the fuzzy comparisons:

$$\tilde{u}_1 = \left(\prod_{j=1}^{5} \tilde{a}_{1j}\right)^{\frac{1}{5}} = \left(1 \cdot \left(\frac{1}{7}\right) \cdot 1 \cdot 1 \cdot 1\right)^{\frac{1}{5}};$$

$$\left(1\cdot\left(\frac{1}{6}\right)\cdot 2\cdot 1\cdot 1\right)^{\frac{1}{5}};\left(1\cdot\left(\frac{1}{5}\right)\cdot 3\cdot 1\cdot 1\right)^{\frac{1}{5}}$$
$$=\ 0.678;\ 0.803;\ 0.903$$

$$\tilde{u}_2=\left(\prod_{j=1}^{5}\tilde{a}_{2j}\right)^{\frac{1}{5}}=(5\cdot 1\cdot 3\cdot 3\cdot 3)^{\frac{1}{5}}\ ;\ (6\cdot 1\cdot 4\cdot 4\cdot 4)^{\frac{1}{5}};$$
$$(7\cdot 1\cdot 5\cdot 5\cdot 5)^{\frac{1}{5}}$$
$$= 2.667;\ 3.288;\ 3.876$$

$$\tilde{u}_3=\left(\prod_{j=1}^{5}\tilde{a}_{3j}\right)^{\frac{1}{5}}=\left(\left(\frac{1}{3}\right)\cdot\left(\frac{1}{5}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}};$$
$$\left(\left(\frac{1}{2}\right)\cdot\left(\frac{1}{4}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}};$$
$$\left(1\cdot\left(\frac{1}{3}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}}$$
$$=\ 0.582;\ 0.660;\ 0.803$$

$$\tilde{u}_4=\left(\prod_{j=1}^{5}\tilde{a}_{4j}\right)^{\frac{1}{5}}=\left(1\cdot\left(\frac{1}{5}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}}\ ;\ \left(1\cdot\left(\frac{1}{4}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}};$$
$$\left(1\cdot\left(\frac{1}{3}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}}=0.725;\ 0.758;\ 0.803$$

$$\tilde{u}_5=\left(\prod_{j=1}^{5}\tilde{a}_{5j}\right)^{\frac{1}{5}}=\left(1\cdot\left(\frac{1}{5}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}}\ ;\ \left(1\cdot\left(\frac{1}{4}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}};$$
$$\left(1\cdot\left(\frac{1}{3}\right)\cdot 1\cdot 1\cdot 1\right)^{\frac{1}{5}}=0.725;\ 0.758;\ 0.803$$

The vector sum $\tilde{u}_i$ raised to (-1) is calculated and the vectors $\tilde{u}_i$ $(i = 1,\ldots,5)$ are sorted in ascending order:

$$\tilde{u}\ =(\tilde{u}_1\oplus\tilde{u}_2\oplus\ \tilde{u}_3\oplus\tilde{u}_4)^{-1}\ =(0.678+2.667+0.582$$
$$+\,0.725+0.725)^{-1}\ ;(0.803+3.288+0.660+0.758$$
$$+\,0.758)^{-1};\ (0.903+3.876+0.803+0.803+0.803)^{-1}$$
$$=\ 0.186;\ 0.160;\ 0.139$$

$$\tilde{u}_{\mathrm{ord}}=\ 0.139;\ 0.160;\ 0.186$$

The fuzzy weight is calculated for each criterion:

$$\tilde{o}_1=\tilde{u}_1\ \otimes\ \tilde{u}_{\mathrm{ord}}=(0.678\cdot 0.139)\ ;\ (0.803\cdot 0.160);$$
$$(0.903\cdot 0.186)=\ 0.094;\ 0.128;\ 0.168$$

$$\tilde{o}_2=\tilde{u}_2\ \otimes\ \tilde{u}_{\mathrm{ord}}=(2.667\cdot 0.139)\ ;\ (3.288\cdot 0.160);$$
$$(3.876\cdot 0.186)=\ 0.371;\ 0.525;\ 0.721$$

$$\tilde{o}_3=\tilde{u}_3\ \otimes\ \tilde{u}_{\mathrm{ord}}=(0.582\cdot 0.139)\ ;\ (0.660\cdot 0.160);$$
$$(0.803\cdot 0.186)=\ 0.081;\ 0.105;\ 0.149$$

$$\tilde{o}_4=\tilde{u}_4\ \otimes\ \tilde{u}_{\mathrm{ord}}=(0.725\cdot 0.139)\ ;\ (0.758\cdot 0.160);$$
$$(0.803\cdot 0.186)=\ 0.101;\ 0.121;\ 0.149$$

$$\tilde{o}_5=\tilde{u}_5\ \otimes\ \mathrm{u}_{\mathrm{ord}}=(0.725\cdot 0.139)\ ;\ (0.758\cdot 0.160);$$
$$(0.803\cdot 0.186)=\ 0.101;\ 0.121;\ 0.149$$

Hence, one computes the crisp weights M_i by means of the center of gravity defuzzification method:

$$M_1=\frac{(lw_1+mw_1+uw_1)}{3}=\frac{(0.094+0.128+0.168)}{3}$$
$$=\ 0.130$$

$$M_2=\frac{(lw_2+mw_2+uw_2)}{3}=\frac{(0.371+0.525+0.721)}{3}$$
$$=\ 0.539$$

$$M_3=\frac{(lw_3+mw_3+uw_3)}{3}=\frac{(0.081+0.105+0.149)}{3}$$
$$=\ 0.112$$

$$M_4=\frac{(lw_4+mw_4+uw_4)}{3}=\frac{(0.101+0.121+0.149)}{3}$$
$$=\ 0.124$$

$$M_5=\frac{(lw_5+mw_5+uw_5)}{3}=\frac{(0.101+0.121+0.149)}{3}$$
$$=\ 0.124$$

The normalized weights N_i are computed as

$$N_1=\frac{M_1}{\sum_{i=1}^{5}M_i}$$
$$=\frac{0.130}{(0.130+0.539+0.112+0.124+0.124)}\ =\ 0.127$$

$$N_2=\frac{M_2}{\sum_{i=1}^{5}M_i}$$

Table 3
Matrix of pairwise comparison of subcriteria in relation to the criterion C$_1$

C_1	S_1	S_2	S_3	S_4	S_5	S_6
S_1	1;1;1	2;3;4	2;3;4	1;1;1	3;4;5	4;5;6
S_2	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	1;1;1	2;3;4	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	3;4;5	3;4;5
S_3	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	1;1;1	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	2;3;4	2;3;4
S_4	1;1;1	2;3;4	2;3;4	1;1;1	2;3;4	3;4;5
S_5	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	1;1;1	1;2;3
S_6	$\frac{1}{6};\frac{1}{5};\frac{1}{4}$	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	$\frac{1}{3};\frac{1}{2};1$	1;1;1

Table 4
Matrix of pairwise comparison of subcriteria in relation to the criterion C$_2$

C_2	S_7	S_8	S_9
S_7	1;1;1	1;1;1	1;2;3
S_8	1;1;1	1;1;1	1;2;3
S_9	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1

$$= \frac{0.539}{(0.130 + 0.539 + 0.112 + 0.124 + 0.124)} = 0.524$$

$$N_3 = \frac{M_3}{\sum_{i=1}^{5} M_i}$$

$$= \frac{0.112}{(0.130 + 0.539 + 0.112 + 0.124 + 0.124)} = 0.109$$

$$N_4 = \frac{M_4}{\sum_{i=1}^{5} M_i}$$

$$= \frac{0.124}{(0.130 + 0.539 + 0.112 + 0.124 + 0.124)} = 0.120$$

$$N_5 = \frac{M_5}{\sum_{i=1}^{5} M_i}$$

$$= \frac{0.124}{(0.130 + 0.539 + 0.112 + 0.124 + 0.124)} = 0.120$$

The second matrix of pairwise comparisons, reported in Table 3, is assembled: the third-level subcriteria "strategic buildings" (S$_1$), "cultural heritage" (S$_2$), "residential buildings" (S$_3$), "transport infrastructure" (S$_4$), "industrial plants" (S$_5$), and "buildings with social functions" (S$_6$) are mutually compared in relation to the second-level criterion "buildings" (C$_1$).

Table 5
Matrix of pairwise comparison of subcriteria in relation to the criterion C$_3$

C_3	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
S_{10}	1;1;1	1;2;3	1;2;3	1;2;3	2;3;4
S_{11}	$\frac{1}{3};\frac{1}{2};1$	1;1;1	$\frac{1}{3};\frac{1}{2};1$	1;2;3	1;2;3
S_{12}	$\frac{1}{3};\frac{1}{2};1$	1;2;3	1;1;1	1;2;3	1;2;3
S_{13}	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1	1;2;3
S_{14}	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1

Table 6
Matrix of pairwise comparison of subcriteria in relation to the criterion C$_4$

C_4	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}
S_{15}	1;1;1	2;3;4	1;1;1	1;2;3	1;2;3
S_{16}	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	1;1;1	1;1;1	1;2;3	2;3;4
S_{17}	1;1;1	1;1;1	1;1;1	1;2;3	2;3;4
S_{18}	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1	1;2;3
S_{19}	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{3};\frac{1}{2};1$	1;1;1

The third matrix of pairwise comparisons, reported in Table 4, is assembled: the third-level subcriteria "dead" (S$_7$), "injured" (S$_8$), and "homeless" (S$_9$) are mutually compared in relation to the second-level criterion "population" (C$_2$).

The fourth matrix of pairwise comparisons, reported in Table 5, is assembled: the third-level subcriteria "mitigation costs" (S$_{10}$), "preevent evacuation costs" (S$_{11}$), "preevent emergency operating costs" (S$_{12}$), "preevent health care costs" (S$_{13}$), and "indirect costs of evacuation" (S$_{14}$) are compared with each other in relation to the second-level criterion "preevent costs" (C$_3$).

The fifth matrix of pairwise comparisons, reported in Table 6, is assembled: the third-level subcriteria "during the event evacuation costs" (S$_{15}$), "during the event emergency management costs" (S$_{16}$), "during the event health care costs" (S$_{17}$), "indirect costs of evacuation" (S$_{18}$), and "indirect costs of dead" (S$_{19}$) are compared with each other in relation to the second-level criterion "costs during the event" (C$_4$).

The sixth matrix of pairwise comparisons, reported in Table 7, is assembled: the third-level subcriteria "postevent emergency costs" (S$_{20}$), "costs of

Table 7
Matrix of pairwise comparison of subcriteria in relation to the criterion C_5

C_5	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}
S_{20}	1;1;1	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	1;1;1	1;1;1	1;2;3	1;2;3
S_{21}	3;4;5	1;1;1	1;1;1	1;2;3	1;2;3	2;3;4	2;3;4
S_{22}	3;4;5	1;1;1	1;1;1	1;2;3	1;2;3	2;3;4	2;3;4
S_{23}	1;1;1	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1	1;2;3	1;2;3	1;2;3
S_{24}	1;1;1	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1	1;2;3	1;2;3
S_{25}	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1	1;1;1
S_{26}	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{4};\frac{1}{3};\frac{1}{2}$	$\frac{1}{3};\frac{1}{2};1$	$\frac{1}{3};\frac{1}{2};1$	1;1;1	1;1;1

Table 8
Matrix of pairwise comparison of alternatives in relation to the subcriterion S_1

S_1	A_1	A_2	A_3
A_1	1;1;1	$\frac{1}{5};\frac{1}{4};\frac{1}{3}$	$\frac{1}{6};\frac{1}{5};\frac{1}{4}$
A_2	3;4;5	1;1;1	$\frac{1}{3};\frac{1}{2};1$
A_3	4;5;6	1;2;3	1;1;1

reconstruction" (S_{21}), "costs of restoration" (S_{22}), "postevent health care costs" (S_{23}), "costs of returning at home" (S_{24}), "indirect costs of evacuation" (S_{25}), and "indirect costs of dead" (S_{26}) are compared with each other in relation to the second-level criterion "postevent costs" (C_5).

Finally, 26 matrices of pairwise comparisons are assembled: the fourth-level decision alternatives "seismic vulnerability condition 1" (A_1), "seismic vulnerability condition 2" (A_2), and "seismic vulnerability condition 3" (A_3) are compared with each other, see, e.g., Table 8, in relation to the various third-level subcriteria (S_i).

The fourth-level decision alternatives "seismic vulnerability condition 1" (A_1), "seismic vulnerability condition 2" (A_2), and "seismic vulnerability condition 3" (A_3) are weighed in relation to the second-level criteria "buildings" (C_1), "population" (C_2), "preevent costs" (C_3), "costs during the event" (C_4), and "postevent costs" (C_5). The relevant weights are reported in Tables 9–13.

Table 9
Table for computing the weights of the alternatives in relation to the criterion C_1

C_1	S_1	S_2	S_3	S_4	S_5	S_6	w_{Ai}
w_{Si}	0.308	0.178	0.114	0.283	0.067	0.050	
A_1	0.097	0.097	0.097	0.097	0.097	0.097	0.097
A_2	0.348	0.348	0.348	0.348	0.348	0.348	0.348
A_3	0.555	0.555	0.555	0.555	0.555	0.555	0.555

Table 10
Table for computing the weights of the alternatives in relation to the criterion C_2

C_2	S_7	S_8	S_9	w_{Ai}
w_{Si}	0.387	0.387	0.227	
A_1	0.097	0.097	0.097	0.097
A_2	0.348	0.348	0.348	0.348
A_3	0.555	0.555	0.555	0.555

Table 11
Table for computing the weights of the alternatives in relation to the criterion C_3

C_3	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	w_{Ai}
w_{Si}	0.323	0.187	0.237	0.148	0.105	
A_1	0.755	0.125	0.333	0.078	0.255	0.384
A_2	0.143	0.371	0.333	0.293	0.255	0.265
A_3	0.102	0.503	0.333	0.629	0.491	0.351

Table 12
Table for computing the weights of the alternatives in relation to the criterion C_4

C_4	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	w_{Ai}
w_{Si}	0.291	0.206	0.249	0.156	0.099	
A_1	0.125	0.333	0.078	0.255	0.123	0.176
A_2	0.371	0.333	0.293	0.255	0.334	0.322
A_3	0.503	0.333	0.629	0.491	0.543	0.502

Table 13
Table for computing the weights of the alternatives in relation to the criterion C_5

C_5	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	w_{Ai}
w_{Si}	0.099	0.245	0.245	0.143	0.121	0.074	0.074	
A_1	0.333	0.123	0.228	0.078	0.173	0.255	0.123	0.179
A_2	0.333	0.334	0.104	0.293	0.308	0.255	0.334	0.262
A_3	0.333	0.543	0.669	0.629	0.519	0.491	0.543	0.559

Table 14
Table for computing the weights of the alternatives in relation to the overall object

O	C_1	C_2	C_3	C_4	C_5	w_{Ai}
w_{Si}	0.127	0.524	0.109	0.120	0.120	
A_1	0.097	0.097	0.384	0.176	0.179	0.148
A_2	0.348	0.348	0.265	0.322	0.262	0.326
A_3	0.555	0.555	0.351	0.502	0.559	0.527

$$\begin{aligned} w_{A1} &= (0.097 \cdot 0.308 + 0.097 \cdot 0.178 + 0.097 \cdot 0.114 \\ &\quad + 0.097 \cdot 0.283 + 0.097 \cdot 0.067 + 0.097 \cdot 0.050) \\ &= 0.097 \end{aligned}$$

$$\begin{aligned} w_{A2} &= (0.348 \cdot 0.308 + 0.348 \cdot 0.178 + 0.348 \cdot 0.114 \\ &\quad + 0.348 \cdot 0.283 + 0.348 \cdot 0.067 + 0.348 \cdot 0.050) \\ &= 0.333 \end{aligned}$$

$$\begin{aligned} w_{A3} &= (0.555 \cdot 0.308 + 0.555 \cdot 0.178 + 0.555 \cdot 0.114 \\ &\quad + 0.555 \cdot 0.283 + 0.555 \cdot 0.067 + 0.555 \cdot 0.050) \\ &= 0.570 \end{aligned}$$

The fourth-level decision alternatives “seismic vulnerability condition 1” (A_1), “seismic vulnerability condition 2” (A_2), and “seismic vulnerability condition 3” (A_3) are weighed in relation to the overall objective (O) in the first-level “civil protection program in case of earthquake,” see, e.g., Table 14.

In conclusion, the decision alternative “seismic vulnerability condition 3” (A_3) turns out to be the best compromise solution between expected losses and economic burden for the community.

7 ANALYSIS OF RESULTS AND CONCLUSIONS

From the comparison of the three different damage and economic impact scenarios, defined in terms of several initial conditions of seismic vulnerability, it is possible to visualize the aspects that influenced the fuzzy multicriteria analysis in selecting the best alternative among those proposed.

As Table 15 shows, the vulnerability condition 3 turned out to be the best compromise solution between expected losses and economic burden imposed on the community. In this scenario, the reference earthquake has damaged 11,437 buildings, on a total of 32,182 existing in the investigated area, by making 19 of them unusable. Compared with the damage scenario 1, associated with the vulnerability condition 1, there have been 2,481 damaged buildings less (55 of which unusable); if compared with the damage scenario 2, associated with the vulnerability condition 2, there have been 700 damaged buildings less (20 of which unusable). For what concerns the effects of the earthquake on the population, the damage scenario 3 is less burdensome, involving a number of casualties equal to 22 (29 less than scenario 1 and 14 less than scenario 2), a number of injured people equal to 53 (108 less than scenario 1 and 45 less than scenario 2), and a number of homeless equal to 3,940 (3,428 less than scenario 1 and 1,567 less than scenario 2).

Finally, the economic burden imposed on the community, resulting from the direct and indirect effects of the earthquake, identifies the damage scenario 3 as an intermediate solution, highlighting a total expenditure of €11,971,935,837 (€4,767,709,167 more than scenario 1 but €2,501,499,238 less than scenario 2).

8 CONCLUSIONS

A decision-making model, based on multicriteria fuzzy analysis and analytic hierarchical processes, has been

Table 15
Summary of the damage scenarios

	Damage scenario 1	*Damage scenario 2*	*Damage scenario 3*
Undamaged buildings (D0)	18,264	20,045	20,745
Buildings with damage from mild to medium (D1+D2+D3)	13,844	12,098	11,418
Unusable buildings (D4+D5)	74	39	19
Dead	51	36	22
Injured	161	98	53
Homeless	7,368	5,507	3,940
Direct costs	4,946,143,188	12,216,508,437	9,734,567,338
Indirect costs	2,258,083,482	2,256,926,639	2,237,368,500

formulated and implemented in a user-friendly GIS platform. It has been applied to the management of postseismic damage scenarios by showing how the decision process of directors and managers of the emergency systems can be based on quantitative, rather than qualitative, judgments of preference.

The model has been applied to the earthquake that hit the territory of L'Aquila (Italy) on April 9th, 2009 by selecting the most economical choice among the alternatives associated with several vulnerability scenarios.

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