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BASIC SOFT COMPUTING TOOLS FOR THE IMPROVEMENT OF THE ITALIAN AFTER EARTHQUAKE DESIGN PROCEDURES

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Abstract

This paper reports the first step of a research project aimed at introducing soft computing techniques in the field of post-earthquake reconstruction. In April 2009, a disastrous earthquake struck the Italian city of L'Aquila, causing 309 deaths and damaging thousands of structures. As a result, Italian authorities established a regulatory framework for rebuilding process, which determines precise limitations for the seismic improvement of damaged buildings. According to this framework, a structural design final outcome, "eligible" or "not eligible", depends on structural capacity and cost of works per square meter. The author, having worked to the seismic improvement of more than 10 RC and masonry structures damaged by the 2009 earthquake, believes that this evaluation system can be greatly improved through the use of simple soft computing tools. The goal of this work is to define a framework within which to build a fully automated methodology for decision support, with the aim of making the reconstruction process better. Fuzzy Logic seems to be the natural background for a methodology that aims to mimic the human expert judgment, in an environment where information is often vague and/or inaccurate.

Keywords: soft computing, seismic retrofitting, fuzzy logic.

Introduction

This work is the very first step of a research project whose goal is introducing soft computing techniques in the Italian state of the art decision making procedures for structural recovery of buildings. It is the result of the experience gained by the author in designing structural intervention over 10 RC and masonry buildings damaged by the 2009 L'Aquila earthquake. Although the method described here may have general value in civil engineering, the point of view of buildings retrofitting is useful to illustrate a situation in which structural designers must operate within precise external limitations. After the L'Aquila earthquake, for the seismic improvement of buildings with "usability outcome E" (or "building unusable", according to the classification given by the Italian Presidenza del Consiglio dei Ministri (PCM) 2009.b), considering the regulatory guidelines expressed in the documents "OPCM n. 3790 del 2009" (PCM 2009.c) and "*Indirizzi per l'esecuzione degli interventi di cui all'Ordinanza del Presidente del Consiglio dei Ministri n. 3790 del 17.7.2009*" (PCM 2009.a) was mandatory. In few words, within the complex regulatory framework determined by these three and other legal acts, two specific conditions emerge for the designer to be in compliance with for the seismic improvement of structures with capacity lower than 60% of regulations demand: the first one is about structural performance; it can be evaluated as the ratio between the capacity peak ground acceleration (PGA) and the demand PGA for the life safety limit state (in Italian indicated as "SLV"), both calculated according to technical standards in force (Ministero delle Infrastrutture 2008 & 2009). The second condition is a limitation of cost of intervention per square meter.

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A synthetic graphic representation of the two design criteria can be made as shown in figure, assuming that: a = 60% of PGA_{SLV}, b = 80% of PGA_{SLV}, c = 0 €/m^2, d = 400 €/m^2. The vertical axis represents the degree of acceptability of the solution. This type of approach assigns full acceptability rate (μ(x)=1) to all those intervention projects that, for cost and structural performance, fall within the domain; on the other side, it gives full non-acceptability rate (μ(x) = 0) to all the others (see Figure 1).

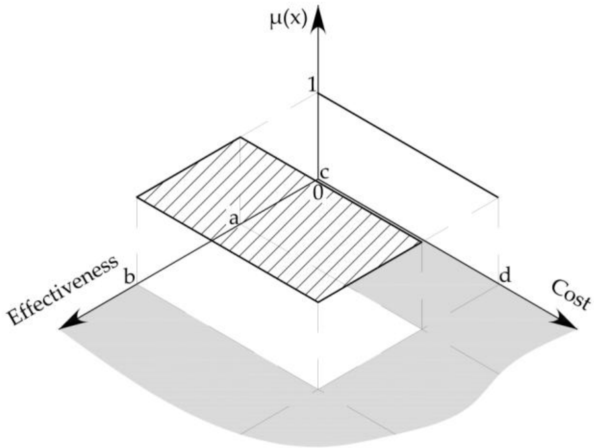

Fig.1. Acceptability domain – Currently in force approach

Following this approach, there are discontinuities of judgment in the vicinity of the edge of the domain. In other words, for the points next to the perimeter of the rectangular area (made by points with μ(x)=1), also very small cost and performance variations can produce a 100% shifting in the level of acceptability of the solution. Two very similar solutions can thus be assigned to clearly distinct degrees of acceptability. At the same time, for two points (technical solutions) deep inside the domain, no criteria for the choice between them are given. For a technical solution characterized by a low level of performance and a high cost, there is the same degree of acceptability of a highly performing and cost-effective solution.
Another important consideration is the fact that in the current approach only 2 design aspects are taken into account in a direct manner, regardless of the degree of complexity of the work.

A new kind of approach
The methodology here proposed takes into consideration the possibility of operating with any number of design aspects. The basic idea is to evaluate each of them independently from the others. In order to do so, they must be as "linearly independent" as possible. In the particular case of structural recovery projects of buildings damaged by an earthquake, in addition to structural performance and cost, it is possible to take into consideration (for example) also the total duration of works, the economic impact of a single specific process, the increase of structural performance, the number of elements modified and/or improved, the architectural modifications etc.
Given that the domain shown in Figure 1 is extremely simplistic, the first step is to introduce further aspects and to divide the domain of design values in segments (subsets) of finite length.

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The points of the domain are in this case associated with different categories of judgment, in number bigger than 2. As proposed in the literature by Tzeng and Huang (2011) and with the meaning reported in Table 1, a 7 values system can be adopted. An immediate example is shown in Figure 2, for the work duration, expressed in days. In general, the partition of the domains is defined on the basis of project requirements characterizing the work.

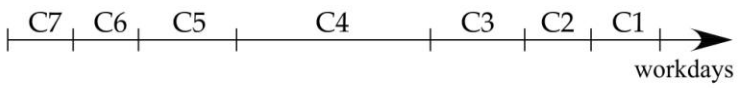

Fig.2. Partition of a domain of a design aspect into 7 categories of judgment

Table 1. Categories of judgment for domain partition

Category	**Description**
C_4, neutral	Values with no positive nor negative features.
C_5, positive (C_3, negative)	Values with no particular positive (negative) connotation, just the first step within the positive (negative) field.
C_6, good (C_2, disadvantageous)	Values characterized by a clearly fine (unsatisfactory), profitable (unprofitable), convenient (unuseful) nature.
C_7, best (C_1, worst)	Maximum positive (negative) result.

It should be specified that partitioning the domain into segments of homogeneous judgment is a process by itself, for doing which many ways are possible; for example: neural networks (Haykin 1994), rank ordering, squares algorithm, clustering method (Ross 2010) and genetic algorithm (Goldberg 1989).
In order to be used for classifying technical solutions, a fundamental property of categories is that of being distinct one from another. The definition adopted here is based on the concept of membership function μ(x). Given a domain defined over the universe X, a subset C of it and the generic element of the universe x, we have (1):

$$\mu_C(x) = \begin{cases} 1, x \in C \\ 0, x \notin C \end{cases} \quad (1)$$

This allows us to define two distinct categories simply through the following condition (2):

$$\mu_{C1}(x) + \mu_{C2}(x) < 2, \ \forall x \in X \quad (2)$$

If 2 design aspects are taken into consideration, given 7 distinct categories of judgment, the domain of acceptability already shown in Figure 1 is modified as shown in Figure 3.

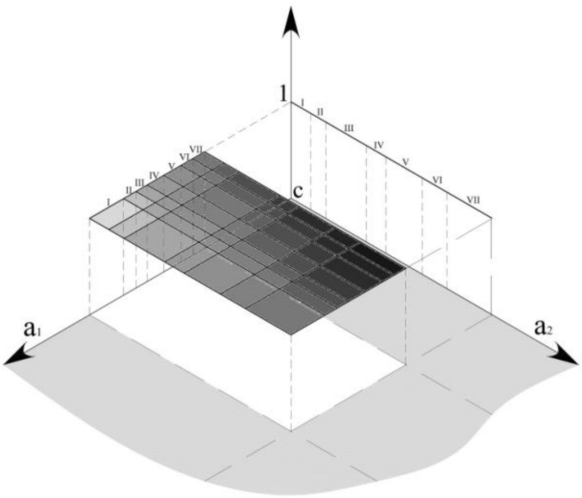

Fig.3. Domain of acceptable solutions modified by introducing 7 categories of judgment

As it is easy to see, despite the simplicity of the hypothesis adopted, the amount of information is now a lot greater than in the previous case. The possible different states increase from 2 to C^a+1. Despite that, the problem of the absence of gradual shifting from a negative to a positive zone is only reduced. Discontinuity over the border of the rectangular area and inside the domain persists. Furthermore, the categories of judgment cannot be barely overlapping to be considered “distinct” one from the other. To overcome these problems, the author suggests the use of Fuzzy Set (Zadeh, 1965) in characterizing category of judgment. The aim of that it is to be able to treat ratings not sharply defined, expressed in a manner similar to what humans do when facing an evaluation. Through this simple procedure the domain of the general aspect, already seen in Figure 2, becomes the one shown in Figure 4.

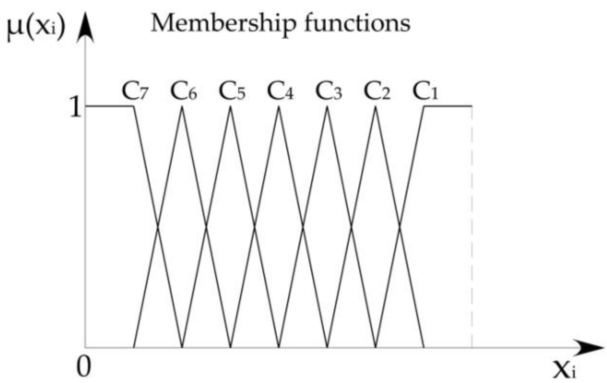

Fig.4. Domain fuzzification for the general design aspect

The number of possible states is now infinite, as $\mu(x)$ assumes real values between 0 and 1.

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Method architecture

Given a number of design aspects, having divided the domain of each of them through fuzzy categories (sets) of judgment, it is now possible to define various methodologies to assign a score, and allow the formation of a hierarchy among the technical solutions examined.

Data-categories overlapping.

When developing a technical solution for the seismic improvement of a building, many information about the various aspects of the problem are generated. The data are related to categories as structural performance, number of elements involved, costs, logistics, timing, consequences in case of an earthquake, architectural and geometric modifications. As first step of the method, for every piece of data, a comparison (here called overlapping) between that and the categories (domain subsets) has to be done. In Figure 5 four possible simple approaches are proposed; the first one has to do with numerical data in the form of crisp numbers. The other three can instead be taken when data are available as probability density functions or fuzzy numbers.

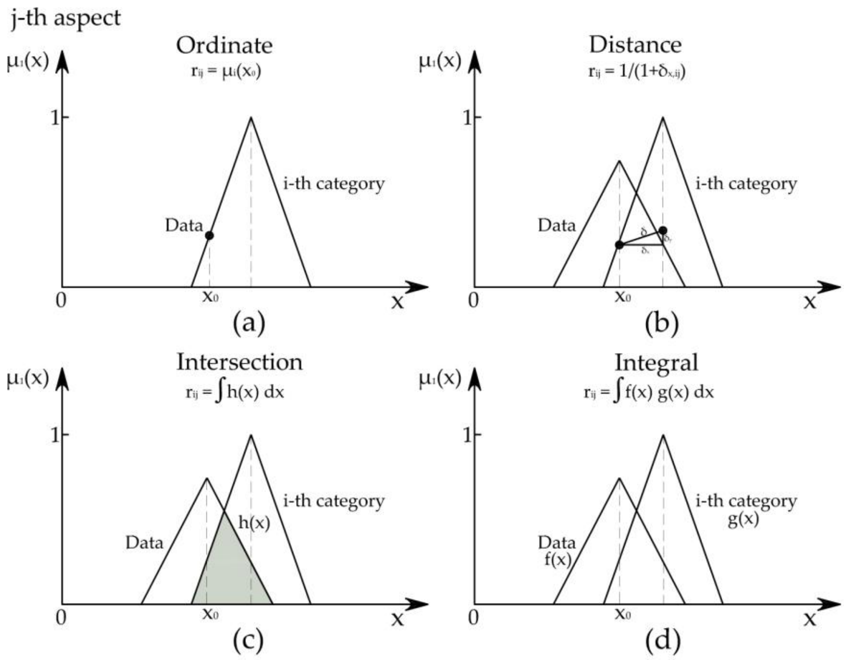

Fig.5. Overlapping methods – a. Ordinate – b. Distance – c. Intersection – d. Integral

In the Ordinate method (Figure 5.a) it is simply necessary to record the ordinate value over the fuzzy category (set). In the Distance method (Figure 5.b), projection over the x-axis of the distance between the centers of gravity of the functions is used as an indicator of compliance. In the Intersection method (Figure 5.c) the value of the intersection area is taken into consideration. This method requires to establish a conventional h_{max} for probability density functions. Finally, in the Integral method (Figure 5.d) the integral of the product of the functions is taken as an indicator. Using any of the overlapping methods, it is possible to obtain a compliance matrix **R** (3). It is composed of *c* rows (number of classes of judgment) and *a* (number of aspects) columns.

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The element r_{ij} represents the value of compliance of the piece of data for the aspect j-th, with the category of judgment i-th. The values of each column are expressed in a relative way, so that the summation of the terms r_{ih} with i = 1, ..., c is equal to 1.

$$\mathbf{R} = \begin{bmatrix} r_{11} & \cdots & r_{1a} \\ \vdots & \ddots & \vdots \\ r_{c1} & \cdots & r_{ca} \end{bmatrix} \tag{3}$$

Weight vector.
A further step consists in establishing a relative weight for each aspect. Different methodologies exist for the definition of the weight vector, including: Eigenvalue Method (Saaty 1977), Sum Method, Synthetic Extent Analysis (Chang 1996) and Geometric Mean Method (GMM, Buckley in 1985.a & 1985.b). In any case, the vector of the relative weights must be such that (4):

$$\sum_{i=1}^{a} \gamma_i = 1 \tag{4}$$

Compliance and relevance matrix.
From the matrix of compliance and the vector of weight, the matrix of compliance and relevance **M** is obtained by multiplying **R** by $\mathbf{M}_\gamma$ (5).

$$\mathbf{M} = \mathbf{R} \times \mathbf{M}_\gamma \tag{5}$$

Where $\mathbf{M}_\gamma$ is the matrix obtained putting the elements of the weights vector over the diagonal. Each term of **M** matrix is the product of the degree of compliance of a piece of data to a certain category (fuzzy set, subset of the aspect domain) and the relative value of the aspect considered, in the light of the evaluation. By summing the elements over one line, the score associated with the category is obtained (6).

$$U_k = \sum_{j=1}^{a} m_{kj} \tag{6}$$

The category with the highest score is taken as the reference category for the technical solution examined (7).

$$C = \left\{ cat_i \middle| U_i = \max(U_k),\ k = 1,\ \ldots, c \right\} \tag{7}$$

In order to have a deeper evaluation, one can calculate the center of gravity of the categories as follows (8).

$$B = \frac{\sum_{i=1}^{c} i \times U_i}{\sum_{i=1}^{c} U_i} \tag{8}$$

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Constraints.
The main purpose of this work is to create a methodology for an automated and repeatable procedure of assessment of alternative design solutions. With this aim, the simple algorithm here proposed has to be integrated by introducing a set of rules about the acceptability of the solutions. The author defines three different types of constraints.

Type 1 constraint.
Type 1 constraint is any condition relating to a compliance matrix **R**, not inconsistent with other conditions, which in general relates to the numerical values that any element r_{ij}, or the sum of several elements in a column of the matrix, $r_{hj} + \ldots + r_{kj}$, can assume.

Example:

$$\sum_{s} r_{ij} > \alpha \qquad (9)$$

In (9) j is fixed and i assumes values in S, set of natural numbers {1, ..., c}; α is real and $\in [0, 1]$.

Type 2 constraint.
Type 2 constraint is any condition, not inconsistent with others, affecting the position in the column vector of **R**, r_k, of its maximum or minimum value.
Example: Given $\{h \mid r_{hk} = \max(r_{ik}),\ i = 1, \ldots, c\}$, a possible type 2 constraint consists of the following condition: $h \geq \beta$, with β natural number $\in \{1, \ldots, c\}$. For each technical solution, one can then define a vector $\boldsymbol{\varphi}$, whose elements are conditions such as those just seen, in number at the most equal to $2a$.

Type 3 constraint.
Type 3 constraint is any condition, not inconsistent with others, determined by means of a fuzzy rule.

Example:
IF Aspect 1 is predominantly of category i **... AND** Aspect n is predominantly of category j **THEN** Action

An example of method through which implementing a fuzzy rule is that proposed by Mamdani (1975).
The acceptability of the technical solution may depend on the rate of satisfaction of some or all of the conditions imposed.

General procedure.
Once **M** matrix is obtained, by the filtering action of constraints it is possible to establish a hierarchy among a set of design solutions. The general flowchart for the methodology is shown in Figure 6.

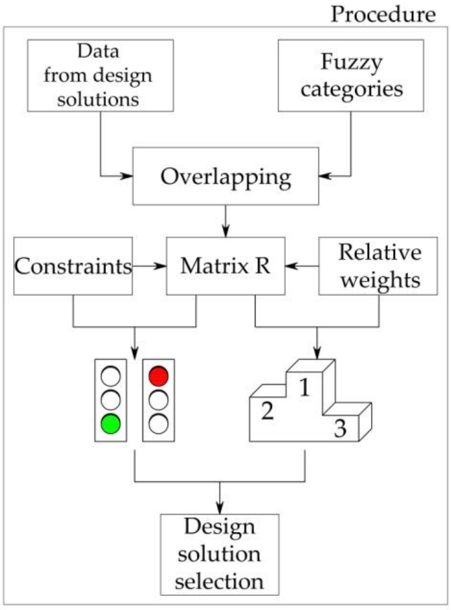

Fig.6. General procedure

Conclusions

This work originates from the experience gained by the author in the design of structural interventions on RC and masonry buildings damaged by the L'Aquila earthquake (2009). In this context, according to a specific regulatory framework, structural design had to be in compliance with strict conditions regarding the structural performance and the cost of works per square meter. The possible final outcomes for designs were just two: acceptable, not acceptable. This evaluation system appears to be improvable.

The purpose of this study is to develop a new approach to design evaluation in the context of seismic reconstruction, focused on the concept of fuzzy category of judgment (fuzzy set). The idea is that of improving currently in force procedures, by using basic soft-computing tools and methods. In other words, the author would like to introduce a fuzzy approach in a context dominated by an on/off logic.

The evaluation method, here presented in its very first step, allows technical operators to include an arbitrary number of design aspects in the assessments; after determining the compliance matrix **R**, once relative weights are defined, through the possibility of applying rules and constraints, solutions can be modeled under requirements of users and authorities. One of the advantages of this type of approach is the possibility of having complex ratings systems, automatically defined by a software, such as to be repeated at different times in the context of after earthquake reconstruction. A first case study has been recently discussed by the author (Rossi, 2015); there, 23 different technical solutions for the seismic improvement of an 8-storey RC building are evaluated, taking into consideration 14 different design aspects and according to specific constraints.

The author of this paper believes that the future of the structural design in the field of seismic improvement of damaged buildings is closely related to the automation of decision making processes; this for two main reasons.

The first one is that the possibility to proceed according to many alternatives, whose convenience is necessary to be compared, requires tools for rapid simulation of different scenarios; the second is that in this field is often required expert assessment about situations, data and methodologies that are vague, inaccurate and/or not clearly defined. This last point makes soft computing tools particularly useful.

References

Buckley, J.J. 1985.a. *Fuzzy hierarchical analysis*, Fuzzy Sets and Systems, 17 (3): 233-47.
Buckley, J.J. 1985.b. *Ranking alternatives using fuzzy numbers*, Fuzzy Sets and Systems 15 (1): 21-31.
Chang, D.Y. 1996. *Applications of The Extent Analysis Method on Fuzzy AHP*, European Journal of Operational Research, 95(3): 649-655.
Goldberg, D.E. 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley Professional, I ed.
Haykin, S. 1994. *Neural Networks: A Comprehensive Foundation*, Macmillan Coll Div.
Mamdani, E.H., Assilian, S. 1975. *An experiment in linguistic synthesis with a fuzzy logic controller*, International Journal of Man-Machine Studies, Vol. 7, No. 1, 1-13.
Ministero delle Infrastrutture 2008. *Nuove Norme Tecniche per le Costruzioni, D.M. del 14 gennaio 2008*, Gazzetta Ufficiale n. 29.
Ministero delle Infrastrutture 2009. *Circolare 2 febbraio 2009, n. 617 C.S.LL.PP. - Istruzioni per l'applicazione delle "Nuove norme tecniche per le costruzioni" di cui al decreto ministeriale 14 gennaio 2008*, Gazzetta Ufficiale n. 47.
Presidenza del Consiglio dei Ministri 2009.a. *Indirizzi per l'esecuzione degli interventi di cui all'Ordinanza del Presidente del Consiglio dei Ministri n. 3790 del 17.7.2009*, Circolare del D.to Protezione Civile 25 agosto 2009, Gazzetta Ufficiale n. 201.
Presidenza del Consiglio dei Ministri 2009.b. *Ordinanza 3753 – Primi interventi urgenti conseguenti agli eventi sismici che hanno colpito la provincia di L'Aquila ed altri comuni della regione Abruzzo il 6 aprile 2009*, Gazzetta Ufficiale n. 81.
Presidenza del Consiglio dei Ministri 2009.c. *Ordinanza n. 3790, Ulteriori interventi urgenti diretti a fronteggiare gli eventi sismici verificatisi nella regione Abruzzo il giorno 6 aprile 2009 e altre disposizioni di protezione civile*, Gazzetta Ufficiale n. 166.
Ross, T. 2010. *Fuzzy Logic with Engineering Applications*, Chichester: John Wiley & Sons, III ed.
Rossi, L. 2015. *Un metodo per la valutazione di progetti di recupero strutturale fondato sull'impiego di insiemi fuzzy*, University of Perugia: PhD thesis.
Saaty, T.L. 1977. *A scaling method for priorities in hierarchical structures*, Journal of Mathematical Psychology, 15 (3): 234-81.
Tzeng, G.-H., Huang, J.-J. 2011. *Multiple Attribute Decision Making – Methods and applications*, Boca Raton: CRC Press.
Zadeh, L.A. 1965. *Fuzzy Sets, Information and Control*, Volume 8, 338-353.