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Reducing the subjectivity of intensity estimates: the Fuzzy Set approach

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Abstract
We describe a method for the encoding and the computer analysis of the macroseismic effects deduced from historical sources allowing the complete formalization of the process of seismic intensity assessment. It makes use of a multi-criteria decisions-support algorithm, based on the theory of the Fuzzy Sets. Analyzing the texts of the available sources for the 1919 Mugello ($M_s = 6.2$) and 1920 Garfagnana ($M_s = 6.5$) earthquakes, the observed effects are classified independently of any macroseismic scale. Each sentence reported on the sources is «decomposed» into five syntactic elementary components and represented by a set of alphanumeric codes for further processing by computer codes. This retains the maximum adherence to the original sources and avoids forced interpretations and losses of information due to the need to fit each observed effect to a description of the scale. Moreover, this scheme also allows to gather equivalent effects by reassigning them the same code, and using this new classification in further processing. This procedure could even be useful to define a new macroseismic scale on the basis of a statistical analysis of different effect occurrences.

Key words *macroseismic intensity – Fuzzy Sets – Mugello – Garfagnana*

1. Introduction

Intensity scales were originally compiled to classify the effects of earthquakes by direct observation and had not really conformed to an efficient usage with written sources. What is more they had been formulated and improved without a statistical analysis of real data but only on the basis of a qualitative comparison of some frequent effects based on expert experience. For these reasons, much of the information available in documentary sources cannot be used to assess the intensity degree and is actually ignored. Moreover, the intensity assessment includes subjective choices based not only on the definitions of the scale but also on implicitly assumed criteria (not explicitly defined by the scale) which depend on the personal experiences and beliefs of the investigators. Thus, the same framework of effects may be differently evaluated in terms of intensity by different investigators.

In a recent work, of which this contribution represents an abridged version, Vannucci *et al.* (1999) propose formalizing the intensity assessment procedure by a computer algorithm able to trace the successive steps of the intensity assignment process. The aims were both to use all the information available on sources and to reduce the subjectivity of intensity estimates, thus giving macroseismic experts a tool to improve the comprehension of their own decisional processes.

Since experience with historical sources has demonstrated that the association of the earth-

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quake effects is less *hard* (more *fuzzy*) than stated in the scales, the work faced this problem in the framework of the decision making support methods using the «Fuzzy Set logic» approach (Zadeh, 1965). The procedure adopted a multi-criteria decision making model (MCDM) (Xiang *et al.*, 1987), which was already applied in the past to different fields, ranging from landscape planning to the evaluation of natural hazards.

In their work, Vannucci *et al.* (1999) took advantage of two experts on historical seismology who assigned all the expert intensities, and the weights of the different sources. In particular, the latter is an important element for the scientific approach to historical information on single earthquakes that needs to be defined *a priori* by an expert. Only an expert on historical seismology can establish the *value* of the testimonies on the basis of rigorous disciplinary criteria that are defined by the hermeneutic rules of historical research. This means that the various testimonies (sources) must be considered with regard to their contemporaneity and authoritativeness, and evaluated in their relative historical context.

2. Decision-making and macroseismic data

Decision-making is a complex human activity which can be defined as choosing, usually on the basis of many criteria, a course of action among alternatives to accomplish one or several objectives. Decision-making in the real world mostly takes place in an environment in which the objectives, constraints and consequences of possible actions are not known precisely. Before the introduction of the Fuzzy approach by Zadeh (1965) the only source of this imprecision was considered randomness, while, after him, many authors have argued that the major source of imprecision is *fuzziness*, *i.e.* the real impossibility in many cases to attribute precise properties to different subjects. The Fuzzy Sets logic tries to reproduce the mental processes of the human brain and in particular its ability, taking advantages of the tolerance of imprecision, to obtain a result even in case of a lack of complete and accurate data. Under the Fuzzy «philosophical approach», the ambiguous evidence encountered in the application of a macroseismic scale is not due to the randomness in the appearance of certain effects but to the uncertainty (or *fuzziness*) in recognizing them as belonging to different grades of the scale. So that the belonging, or better the «membership», of a given fact to the set of effects associated with a certain intensity degree, may be better defined by a real number in the interval [0,1] whose lower limits stands for not belonging at all and the highest for full belonging.

In the intensity assessment problem the different alternatives are the degrees of a macroseismic scale, while the effects actually observed at each given locality are the attributes. Two possible approaches to obtain the membership function are the subjective approach and the empirical approach. In the first case, the membership function values are assigned freely by the macroseismic expert on the basis of his proper belief, while in the second case they are derived somehow from data. The debate is open in the literature on the effectiveness of these two options. In a previous work using the same MCDM, Ferrari *et al.* (1995) showed the empirical approach is able to reproduce the expert assessments more precisely than the subjective approach. Thus, in the work by Vannucci *et al.* (1999), the membership levels of an attribute (effect) for each given alternative (intensity degree) were empirically estimated from the observed frequencies of occurrence of different effects in sites with given intensity, using a «learning» set of intensities assigned by a macroseismic expert.

The weight of each effect was determined as a function of three factors:

i) The «selectivity» of the effect, as inferred from the distribution of expert intensities in the localities where the given effect occurs (the narrower the range of intensities, the larger the assigned weight).

ii) The number of observed effect occurrences at different sites (the larger the number, the larger the weight).

iii) The reliability of the source (direct contemporary sources has higher weights than later indirect sources and macroseismic bulletins has higher weights than newspapers).

Two Italian earthquakes which occurred relatively close in time and space are analyzed: the Mugello earthquake (Lat. = 43°56′, Long. = = 11°27′) of June 29, 1919 ($M_S = 6.2$ $I_{\max} = \text{IX}$) and the Garfagnana earthquake (Lat. = 44°15′, Long. = 10°17′) of September 7, 1920 ($M_S = 6.5$, $I_{\max} = \text{X}$). Due to their proximity in space, time and energy they give an excellent chance to make cross tests on the results of this method of analysis. A computer procedure has been developed able to keep track of the entire process, from the reading of the sources to the intensity estimate. It consists of four steps:

1) Initial encoding of the database of observed effects.

2) Application of re-encoding rules in order to equivalence effects previously kept distinct.

3) Selection of most significant effects and computation of membership functions and weights.

4) Intensity evaluation with the fuzzy MCDM algorithm.

The initial encoding step is based on the decomposition of each useful sentence found in the sources into five main syntactic components. They are:

– Object/subject of the phrase.

– Quantifier of the object/subject.

– Predicate.

– Modifier of the predicate.

– Specification of the object/subject or of the predicate.

After their disarrangement, the set of descriptions forms a matrix (see table I) where each row represents a single macroseismic effect and each column a different syntactic component. By assigning a two-character code to each different word found in each column, it is possible to assign a ten-character code to each effect that thus can be analyzed later by computer techniques. An example can help us to understand this passage: the phrase: «light cracks in many stone houses» include an «object/subject» which is «houses» and a «predicate» which can be represented by the word «cracks» (notwithstanding the latter is not really a verb, it expresses the action of cracking). The term «light» represents a «modifier» of the «predicate», «many» the «quantifier» of the «object/subject» and «stone» the «specification» (in table I the highlighted row shows the result of this decomposition).

Now the first element of the phrase can be compared with the list of the words previously found in other sentences for the corresponding syntactic component (see table II). If the same word is already present in the list, the corresponding two-character code is assigned, otherwise a new code is allocated and the new word is inserted in the list with the given code. After repeating this procedure for all the five elements, our phrase «light cracks in many stone houses» will be represented by the ten-character code «d4-62-51-42-26».

This procedure is not always obvious and sometimes cannot be unique but in most cases can be carried out easily with the help of a computer code. Through this encoding scheme, it is possible to maintain an almost complete and accurate recording of the information contained in the sources without any adaptation to the descriptions of a scale.

During the *re-encoding step* it is possible to modify the classification defined in the previous step in order to make equivalent two or more effects which formerly had kept distinct. This can be done by equating different codes of the same column: for example the subject/object

Table I. Encoding phase: disarrangement of sentences into five syntactic components.

Quantifier	Object/subject	Specification	Predicate	Modifier
....	....	....	....	....
Most	People	At rest	Felt	–
Many	**Houses**	**Stone**	**Cracks**	**Light**
Few	Glasses	–	Broken	–
....	....	....	....	....

Table II. Encoding phase: sample of the correspondence lists between phrase component and the two-character codes. Note that code «01» indicates the absence of the corresponding phrase component except for the «Predicate» column which must always be present (otherwise the sentence does not make any sense).

Quantifier	Object/subject	Specification	Predicate	Modifier
01 -	01 -	01 -	01 to feel	01 -
02 2 %	02 people	02 at rest	02 to escape	02 not
03 3 %	03 glasses	03 sitting	03 to stay	03 only
....	....	....	....	....
d3 few	61 roofs	50 farmer's	41 to break	25 very light
d4 many	**62 houses**	**51 stone**	**42 to crack**	**26 light**
d5 about 1/2	63 buildings	52 calcareous	43 to dust	27 small
....	....	....	....	....

«houses» (code 62) can be made equivalent to «buildings» (code 63) or the predicate «to break» (code 41) can be made equivalent to «to crack» (code 42). The re-encoding can also be done using combinations of codes belonging to different columns for example: «railway tracks» (object/subject) «bent» (predicate) can be made equivalent to «railway line» (object/subject) «closed» (predicate). After these «re-encoding rules» are compiled, a computer program automatically makes the changes and builds a new database of observed effects. The main advantage of this procedure is that all researchers can apply their own «rules» and change them at will without modifying the original database.

In the *selection step* all the effects that are rarely observed are discarded and not processed further. In the following computation only the effects with at least five occurrences at different sites will be considered, but this threshold could even be increased to improve the reliability of the results. This selection guarantees that the computed empirical membership functions are less biased by possible anomalous cases and also reduces the danger of «overfit» (see discussion below).

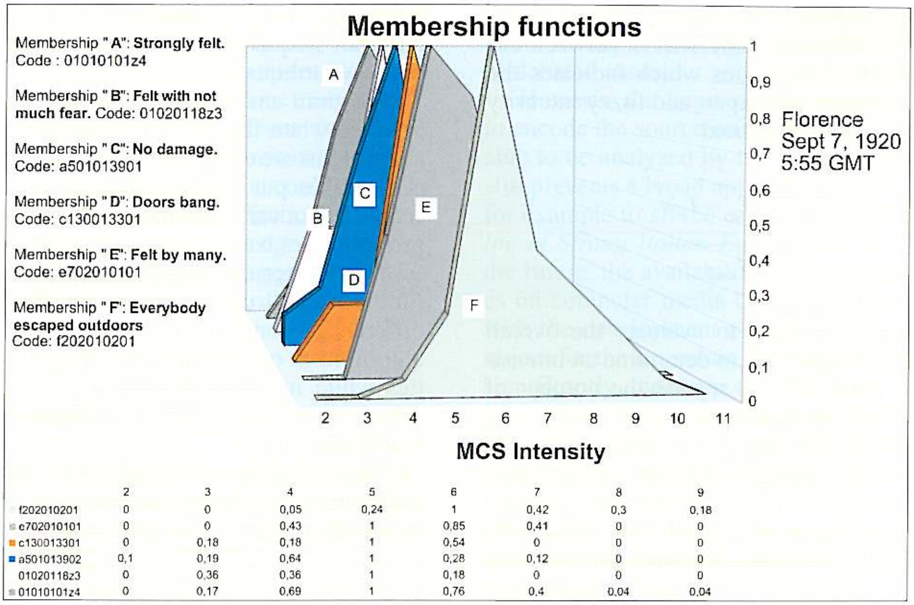
In the *intensity evaluation step*, the MCDM algorithm is applied and the «fuzzy» intensity is computed at each site. This point can be repeated independently by using different membership schemes. The algorithm also admits the simultaneous use of multiple memberships and weighting schemes thus allowing the combination of different criteria based on the beliefs of different macroseismic experts. This could be useful in particularly debated cases to establish a «consensus» intensity estimate taking into account all of the different opinions.

A graphical sketch on how the intensity assessment procedure works is shown in fig. 1 where the shapes of the empirical membership functions of the effects of the Garfagnana earthquake observed in Florence are reproduced. In fig. 2 the «aggregate» decision function is obtained by taking, for every intensity, the minimum membership value among all of the functions. The intensity degree chosen by the algorithm is the one corresponding to the maximum of the decision function.

3. Results and discussion

To check the efficiency and the reliability of the methodology to reproduce the macroseismic expert's decisions a number of statistical estimators can be computed. These are the *coefficient of variation* R^2 of the regression of the intensity estimated by the expert with the fuzzy intensity and the *average absolute difference* r_{abs} between the expert (I_E) and the fuzzy intensity (I_F) over the entire data set of evaluated localities, given by

$$r_{\text{abs}} = \frac{\sum_{1}^{N_{\text{total}}} |I_E - I_F|}{N_{\text{total}}}$$



	2	3	4	5	6	7	8	9
f202010201	0	0	0,05	0,24	1	0,42	0,3	0,18
e702010101	0	0	0,43	1	0,85	0,41	0	0
c130013301	0	0,18	0,18	1	0,54	0	0	0
a501013902	0,1	0,19	0,64	1	0,28	0,12	0	0
01020118z3	0	0,36	0,36	1	0,18	0	0	0
01010101z4	0	0,17	0,69	1	0,76	0,4	0,04	0,04

Fig. 1. Shapes of the empirical membership functions of the effects observed in the town of Florence for the 1920 Garfagnana earthquake.

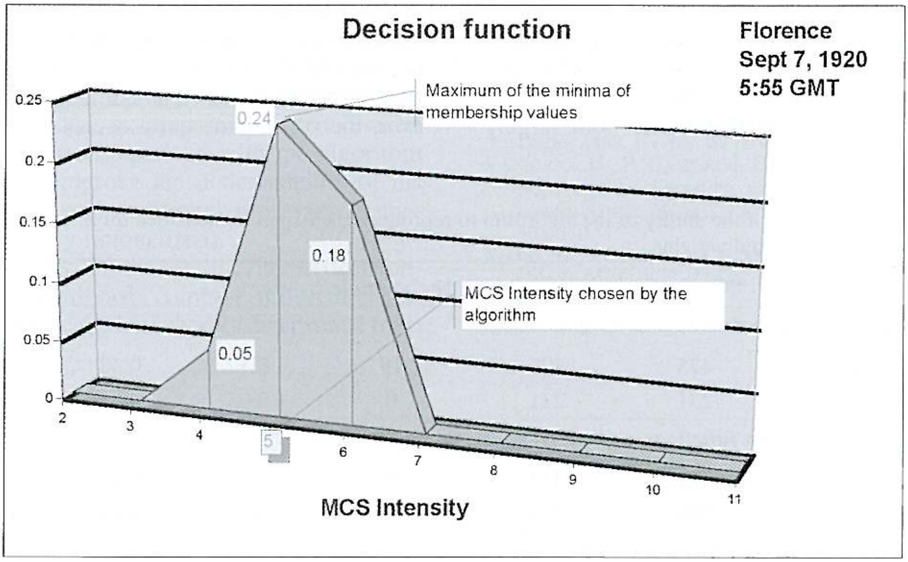


Fig. 2. Decision function: for each intensity the minimum among all of the membership functions of fig. 1. The final intensity estimate is the one corresponding to the maximum value of the decision function.

where N_{total} is the total number of evaluated localities. The *average difference* r between expert and fuzzy intensities which indicates the «offset» between the expert and fuzzy intensity estimates is also computed

$$r = \frac{\sum_{1}^{N_{total}} (I_E - I_F)}{N_{total}}.$$

Furthermore, in order to evaluate the overall ability of the algorithm to determine an intensity value, table III also reports the number of univocal intensity determinations (N single), and the number of intensity determination (N multiple) which are uncertain between two or more grades.

The first two rows of table III refer to the case when the intensity is computed using the empirical membership functions and weights estimated from the data of the same event. For both sets the small values of r and the high R^2 indicate that the algorithm satisfactorily reproduces the expert intensities (within half of a degree on average). The values of r, which are positive for the Garfagnana event and slightly negative for the Mugello one, correspond to an underestimation of the «fuzzy» intensity with respect to the expert for the former earthquake and an overestimation for the latter. These differences, which nevertheless lie both largely below the average residuals, might be caused by different frequencies of various intensities for the two earthquakes.

The third and fourth rows concern, instead, the case when the fuzzy membership function and weights are computed using the data of both earthquakes put together. We can see that the scores do not vary very much with respect to the previous ones but a slight improvement of the fit for the Garfagnana earthquake and a worsening for the Mugello event can be noted. The average difference r confirms the tendency of the fuzzy algorithm to overestimate the Mugello intensities while it shows an almost perfect coincidence (on average) of the two estimates for the Garfagnana data.

Since in previous computations the data of each earthquake are used to determine the membership functions and weights used for the same event, it is possible that the good agreement might be due to overfit. This would mean that the algorithm fitted not only the average tendencies of the data but also their statistical fluctuations. To test this hypothesis, in the fifth and sixth rows we can see the results when for each earthquake, the membership functions and weights are derived from the data of the other event. The marked decrease of the R^2 and the increase of r_{abs} (especially for the Mugello earthquake) clearly shows that some overfit is certainly present in previous computations. However, the fit remains quite acceptable for both

Table III. Evaluation of the ability of the algorithm to reproduce the expert's intensities for different empirical membership functions and weights.

Data set	No. total	No. single	No. multiple	r	r_{abd}	R^2
Own *membership functions and weights*						
Garfagnana	425	406	19	0.12	0.48	84%
Mugello	231	231	0	−0.05	0.36	87%
Merged *membership functions and weights*						
Garfagnana	431	413	18	−0.01	0.45	84%
Mugello	240	233	7	−0.23	0.44	86%
Swapped *membership functions and weights*						
Garfagnana	353	336	17	0.31	0.63	78%
Mugello	220	204	16	−0.36	0.78	70%

earthquakes notwithstanding the complete independence of the learning and testing sets. The opposite signs of r for the two events confirm the tendency indicated by previous cases with a remarkable increase in the offsets (still well below the average absolute deviations). A possible explanation of this behavior could be that, even in presence of similar effects, the expert had been more confident to assign higher degrees in the framework of a strong earthquake like the Garfagnana event rather than the weaker Mugello one.

4. Conclusions

The method of analysis of macroseismic effects described here shows in detail the process of intensity assessment that, in many cases, is followed by the macroseismic expert without a trace of the assumptions made and then sometimes could not be reproducible even by the same expert. In particular, the reliability of the different sources and the weights of the different effects, established by historical seismologists, can be taken into account explicitly.

This approach can be useful to reduce the arbitrariness of the intensity assignment process, and could actually cancel all possible sources of mistakes as far as the encoded data correctly interpret the text. It may even be a useful support tool for the macroseismic expert himself who, from the comparison with the algorithm results, can improve the understanding of his own choices and decisional processes (sometimes not fully rationalized).

The ability of the multi-criteria decision-making algorithm to combine different membership and weighting schemes determined from the intensities assigned by different experts, could be useful to obtain «objective» estimates in debated cases.

However the large amount of work needed to encode the source information in a way suitable to be analyzed by the computer algorithm still prevents a broad application of this method for example to all the earthquakes of the *Catalog of Strong Italian Earthquakes* (CFTI3). In the future, the availability of texts of the sources on computer media (as in CFTI3), together with the development of computer aided techniques for the automatic encoding of texts could significantly speed up the procedure and lead to a substantial improvement of the database. Even the application of the algorithm to the data (already encoded) of the Italian Macroseismic Bulletin of the Istituto Nazionale di Geofisica (ING) could be very interesting to integrate these data in a unified macroseismic database.

This methodology, being independent of a particular macroseismic scale, could be used, with a large enough database, to define the characteristics of a new macroseismic scale more appropriate to historical testimonies.

REFERENCES

FERRARI, G., P. GASPERINI and E. GUIDOBONI (1995): Macroseismic intensity evaluation with the «Fuzzy Sets Logic», *Ann. Geofis.*, **38** (5-6), 811-826.

VANNUCCI, G., P. GASPERINI, G. FERRARI and E. GUIDOBONI (1999): Encoding and computer analysis of macroseismic effects, *Phys. Chem. Earth (A)*, **24**, 505-510.

XIANG, W., J.G. FABOS, E.B. MCDOUGALL and M. GROSS (1987): Evaluation of landscape plan alternatives, *Univ. Mass. Res. Bull.*, no. 717, pp. 70.

ZADEH, L.A. (1965): Fuzzy sets, *Inf. Control*, **8**, 338-353.