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Bibliographic Review

Fuzzy logic and applications in geographic information systems

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Abstract

For a long time, the man has been looking for models to represent reality, however, based on traditional logic, we do not consider the complexities that surround ourselves. The Fuzzy logic, by basing itself on linguistic variables, approaches this reality, inserting the uncertainty as part of modeling of the problem. Its sets are more general, because it is attributed to an element the degree of relevance between 0 and 1, which may belong to multiple groups, thus, the applicability of this tool increases considerably, making it possible to assist in decision takings in areas such as health, industry and environment. In geographic information systems, especially to integrate and analyze spatial information, the Fuzzy tool proves to be very useful, generating optimization and accuracy in results of works, besides greater data refinement and showing transitional strips that are not detected by the common models.

Keywords: Fuzzy logic, imprecision, uses, uncertainties

Lógica Fuzzy e aplicações em sistemas de informações geográficas

Resumo

Há tempos o homem procura modelos para representar a realidade, porém, baseados na lógica tradicional, não são consideradas muitas das complexidades que nos rodeiam. A lógica Fuzzy, por se basear em variáveis linguísticas, se aproxima dessa realidade, inserindo a incerteza como parte da modelagem do problema. Seus conjuntos são mais generalistas, pois atribuem a um elemento graus de pertinência entre 0 e 1, podendo este pertencer a vários grupos. Assim, a aplicabilidade desta ferramenta aumenta consideravelmente, podendo auxiliar na tomada de decisão em áreas como saúde, indústria e meio ambiente. Em sistemas de informações geográficas, principalmente para integrar e analisar dados espacializados, a ferramenta Fuzzy se mostra de grande utilidade, gerando otimização e precisão nos resultados dos trabalhos, além do maior refinamento de dados e mostrando faixas transicionais que os modelos comuns não detectam.

Palavras-Chave: lógica nebulosa, imprecisão, usos, incerteza

Lógica Fuzzy e aplicaciones en sistemas de información geográfica

Resumen

Hace tiempo el hombre busca por modelos para representar la realidad, sin embargo, con base en la lógica tradicional, no se tiene en cuenta muchas de las complejidades que nos rodean. La lógica Fuzzy, por depender de variables lingüísticas, se acerca a esta realidad, con la inserción de la incertidumbre como parte de la modelación del problema. Sus conjuntos son más generales, pues atribuyen a un elemento grados de pertenencia entre 0 y 1, donde este pude pertenecer a varios grupos. Así, la aplicabilidad de esta herramienta aumenta considerablemente, y pude ayudar en la toma de decisiones en áreas como la salud, la industria y el medio ambiente. En los sistemas de información geográfica, sobre todo para integrar y analizar la información espacial, la herramienta Fuzzy resulta de gran utilidad, generando la optimización y la precisión en los resultados del trabajo, además de un mayor refinamiento de datos y presentando bandas de transición que los modelos comunes no detectan.

Palabras clave: lógica difusa, la vaguedad, usos, incertidumbre

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Introduction

For a long time the man develops theories and tools for the solution of problems related for the everyday lives. In the ancient Greece (384 – 322 B.C.), Aristotle, father of logic science, established strict rules for the logic acceptance of valid answers, which followed the basic ideas of assumptions and conclusions (USP, 2001). From this day on, the Occidental logic adopted binary patters, i.e., each information can only accept the values false or true and the law of the non contradiction, thereby preventing further possibilities (UEM, 2001).

The research then began to use simpler models of reality to answer their questions, working with specific parts of the problem, without ranging the whole of this reality (PEREIRA, 2008), having as answer, therefore, an approximation of the real world (MOTA, 1991). Thus, there is a search to improve the understanding of explicit information and the extraction of others, many times hidden by imprecise models (LAZZAROTTO, 2005).

In such manner, the decision taking starts from answers which do not accurately correspond to the reality, due to its approximations and adjusts. The Fuzzy logic enters in this context as a tool to assist in the decision taking, through a model which ranges the imprecision factor and its answers reflecting the human reasoning (PEREIRA, 2008).

The Fuzzy logic has as basic concept the linguistic variable, i. e. words are used to classify objects instead of numbers, having as answer the possibility of certainty of the studied object belong to several groups, and with this approximate the conclusion to the human thought (NOGUCHI, 2004; LAZZAROTTO, 2005; PEREIRA, 2008).

Thus, the Fuzzy logic is a tool which includes sets of members with continuous grids, that is, elements which can belong or possibly belong to several groups, with rules that foresee the absence of strict criterion in its classification and not random criteria, therefore proving its greater generality and applicability than the classic models (ZADEH, 1965).

According to MARANHÃO and SOUZA (2003), the most important stage of the Fuzzy logic consists in the construction of adequate functions of pertinence to represent the phenomenon in the study. Considering this, in accordance with ZADEH (1965), for ranging sets of continuous grids of elements, the Fuzzy logic becomes more general than the classic sets. This greater comprehensiveness allows a wider variation in its applicability, offering a natural design to the problems where the imprecision is present. In this way the tool can go through limitations imposed in studies with analysis of special data, that possess models which needs a great data volume, some of hard obtaining, and are generally developed for different regions than those where are applied, beyond being made, in most of the times, to scales in which different interactions and processes can be important (ALVES et al., 2005).

In the environmental planning, the great volume of data required by the Geographic Information System – GIS, confers to the study reliable results, which must be handled in an integrated way (CALIJURI and RÖHM, 1994). The use of this technique of geoprocessing has been significantly increasing, since it requires analysis and representations in the form of maps for the communication of information related to the environment, making the interpretation easier (CARVALHO JUNIOR et al., 2003).

The representation of elements of the landscape, like soils, geology, vegetation and use of the land, are cartographically delimited by polygons, represented as geo-objects, and considered as an approximation and simplification of a pattern of more complex variations. Although the variations in the edges are more representative than the variations in the interior of the polygon, on the field these edges rarely represent the natural phenomenon and are associated to doubts caused by limitations of observations (BARRETO-NETO and SOUZA FILHO, 2007).

The Fuzzy logic, in this context, allows the mathematical modeling in gray areas, adequate in the description of ambiguities, uncertain and imprecision in mathematical models or conceptual models of empiric phenomenon (ZADEH, 1965).

Historic

The first notions of vague concepts logic dates from 1920, when the Polish Jan Lukasiewicz proposed degrees of pertinence of 0, ½ and 1 for objects, and it was later on expanded to infinite numbers within this interval (PUC, 2004). However, the concept of Fuzzy Logic was introduced by Lotfi A. Zadeh, professor of the University of California, Berkeley, in 1965, uniting the concepts of classical logic to the pertinences of Lukasiewicz (LAZZAROTTO, 2005).

During the 70s and the 80s, the industry used the Fuzzy concepts for the programming of machinery and equipments controllers. In 1974, Mamdani, professor of the Queen Mary College, University of London, applied the concept in controllers of steam machines, thus expanding the nuclear projects (MOTA, 1991); water treatments, in 1983 by the Fuji Electric in Japan; in 1984 Sugeno and Takagi develop a methodology of derivation of Fuzzy control (LAZZAROTTO, 2005); trains automatic operation systems, inaugurated in 1987 by the Hitachi, also in Japan, among others (PUC, 2004). Japan widely used the application of the Fuzzy logic and still does researches about this area, significantly contributing with more than 30% of the publications related to this theme.

Only in the 90s the resistance of the USA was won by the by the application of the Fuzzy logic, which was seen before as an obscure field, because of its relation with artificial intelligence, losing the credibility to the industry of the country (UEM, 2001). Today in the USA, the use of Fuzzy controllers in motors is being studied by the Environmental Protection Agency, besides of tests done by the NASA with application of the Fuzzy Theory in the Space anchorage of spaceships (USP, 2001).

Fuzzy Logic

The Fuzzy logic deals with the imprecision, acting in areas of determination of limits, based on the human intuition and not in the probabilities theory (GABRIEL et al., 2009). Such tool extends itself to the Boolean logic (LAZZAROTTO, 2005), permits the modeling of complex systems and can be integrated to new techniques, thus allowing studies of elements associations by diverse classes (GABRIEL, 2008).

Among the benefits of its use are the easiness of problems resolutions, reduction of development time, modeling of complex non linear systems and minor use of components in advanced systems (NOLASCO-CARVALHO, 2009).

Fuzzy Sets

For the understating of the Fuzzy logic, a brief introduction of its sets is necessary. Thus, considering that X is a set of points where each generic element is x, we have $X = \{x\}$. A Fuzzy set A in X is characterized by a function $f_A(x)$ which is associated to each element of X in an interval [0.1] called of pertinence function. As closer to the function, greater is the value of pertinence of x (ZADEH, 1965), (Figure 1).

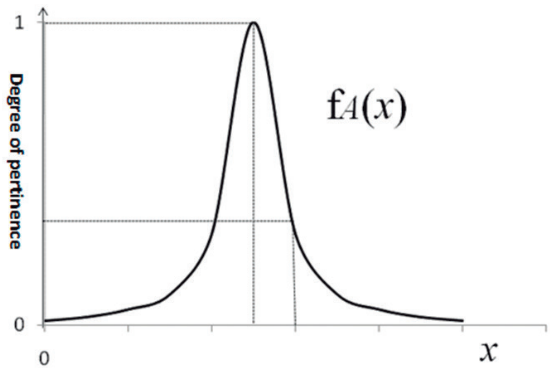

Figure 1. Graphic representation of the function of pertinence.

A classic set is a particular case of the Fuzzy set, where the pertinence of its elements can bring only two values, 0 or 1, i. e. x belongs or not to the set (ZADEH, 1965).

Standard operations between Fuzzy sets

Still considering that A and B are two subsets of X. The characteristic function *complement* of the Fuzzy set A is called of A', being defined by (Figure 2a):

$$f_{A'} = 1 - f_A$$

The characteristic function *union*, considering the functions of pertinences for the sets A and B, respectively $f_A(x)$ and $f_B(x)$, as being of the Fuzzy set C, is defined as $C = A \cup B$, with the following function of pertinence (Figure 2b):

$$f_C(x) = \text{Max}\ [f_A(x), f_B(x)], \qquad x \in X$$

This function still has associative properties: $A \cup (B \cup C) = (A \cup B) \cup C$.

The characteristic function *intersection*, considering the conditions of unions already described, is defined as $C = A \cap B$, with the function of pertinence (Figure 2c):

$$f_C(x) = \text{Min}\ [f_A(x), f_B(x)], \qquad x \in X$$

Like the union, the intersections also possess associative properties (GABRIEL, 2008; LAZZAROTTO, 2005).

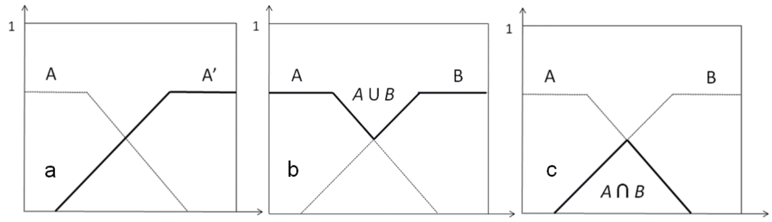

Figure 2. Operations between sets a) Complement of A', b) Union of A and B, c) Intersection of A and B. Source: adapted from GABRIEL (2008).

Fuzzy Inference System

The Fuzzy Inference Systems – FIS are models based in rules sustained by the operations of Fuzzy sets, which has as objective to obtain answers, taking into consideration the expert experience (MOTA, 1991). Several authors define diverse components which act in the stages of processing of these models (PEREIRA, 2008; NOGUCHI, 2004).

In a general way, a FIS can be structured as: *entry processor* (fuzzificator), where the sets are ordered and the pertinences defined; *rules base*, where the linguistic determinations are inserted and processed by the method of inference chosen, among them, the one from Mandani and of Sugeno and Takagi, in the system IF – THEN, i. e. with conditional sentences; and *output processor* (de-fuzzificator), which generates a representative real number as output, operating through sets (LAZZAROTTO, 2005).

Thus, the process takes into consideration the predetermined parameters, combined with the experience of the researcher or the expert, providing a numeric answer for the problem through the proposed model (MOTA, 1991).

Some applications

The applications of the Fuzzy logic are unlimited, going from the industrial area until the health. In the industry and industrial processes, the development of controllers based in Fuzzy rules, or Fuzzy logic, through specialist systems in substitution the industrial controllers, which are processors that perform functions of control in several levels of complexity, have received many contributions with the use of the Fuzzy tool (LEITE et al., 2010).

The industrial controllers are based, in theory, of controls of systems, which demand precise mathematical models for its functioning, which in the everyday becomes too complex according to MOTA (1991). Thereby, the idea would be an implementation of specialist systems as controllers, in a first hypothesis; and in second, as a module of supervision of a conventional controller. As conclusions, it was observed the good performance of the proposed controller, being indicated especially in the cases in which the mathematical model is of hard obtaining; and the better application of the supervisor module based in Fuzzy logic would be in dynamic systems, due to its greater flexibility.

Still in the industry, SELLITO (2002) describes the application of processes controllers based in Fuzzy logic in the fabrication of the clinker, raw material of cement. Its results shows gains in productivity and energy from 3 to 5%, due to the better response of the automatic system in relation to uncertainties of the experts, concluding that the application of this controllers brings satisfactory results, suggesting that the experts of production should take knowledge of such tool for its application in the decision taking processes.

In the health area, according to SOUSA et al. (2006), there are diverse levels of uncertainties and imprecision, and the decision making process ends up supporting itself on vague and stranger concepts to classical logic and in parameters of subjective nature. In such manner, the characteristic uncertainties of the biological, medical and epidemic processes, emphasizing the lack of precise mathematical models are evidenced, which transforms the Fuzzy logic in an adequate theory in the treatment of these problems (COPETTI et al., 2011).

With the objective of applying a theory of Fuzzy sets in the problems of biomedicine, especially epidemiology, the results of ORTEGA (2001) demonstrates that such tool assists in the resolution of these problems with good results. Some difficulties found related to the linguistic variables, mainly as for the classes attributions, because this data generally are much correlated. However, the models present "real possibilities of application" and, according to the author, are of easy comprehension for the professionals of the health area.

In the environmental area the applications of the Fuzzy logic are also very wide. Many works used the tool in ecological and environmental zoning (ESCADA, 1998; RUHOFF et al. 2005; PAULA and SOUZA, 2007; NÄÄS et al., 2010), where the same assists and guides the process of decision making, especially for having greater flexibility and improving the imprecision. Its application extends to the hydrological modeling (BARRETO-NETO and SOUZA FILHO, 2007) where the neighboring diffuse zones of geo-objects can be better analyzed; allocation of sanitary landfill (SAMIZAVA et al. 2006), in which the subjectivity for the decision maker is reduced.

In the agriculture, its use assists in determination of zones and conditions of crop management. NÄÄS et al. (2010) estimated the impact of the bovine meat production in the country by the global warming through a Fuzzy model, assessing the risk of the pastures capacity decrease and prediction of the production reduce in function of the impact in beef cattle productivity and following increase in production cost. His results point out for a rise in 80 to 160% in the production cost, concluding that these scenarios can compromise the international competitiveness of the sector. VALENTE et al. (2012) determined coffee management areas through a Fuzzy *k-means* algorithm as areas limiter, observing that the best results were obtained for the electric conductivity parameters of the soil, agreeing with the results of MOLIN and CASTRO (2008).

Applications in GIS

The Geographical Information Systems – GIS are computational systems for the geographical information processing (CALIJURI and RÖHM, 1994).

In these systems, the Fuzzy logic is applied in the pixels limits imprecision for the determination elements within the satellite image. Including the uncertainty in the information processing, is revealed, many times, a transition between the pre-established elements classes (PEREIRA, 2008).

Comprehending a modeling of spatial data in which the entry data, or maps, previously rasterized, must be initially simplified through a fuzzification, the Fuzzy logic has pertinence functions that allow the standardization of the original data with the variability between 0 and 1 (MARANHÃO and SOUZA, 2003). In this way, the use of a Fuzzy pertinence function allows the alteration of the map in ordered data or in intervals, determined of subjective manner.

Next, the values of pertinence are combined by the choice of operators, allowing the discrimination in a coherent form of the areas of interest, and becoming potentially useful in the application of digital processing methods of images and spatial modeling (CARRINO et al., 2011).

In this sense, the study of PINHEIRO (2003) describes the characteristic of two satellites of better resolution and methods for the correction of its images. Despite the images precision, spatial distortions and lack of cartographic precision cause errors which can be corrected with geometrical models. The images classification can also incur in errors, thus some methods, like the Fuzzy classifiers, assist in the images uncertainties quantification, especially in cases where is not possible to define strict limits between elements classes.

The collected data and the considered and combined remote sensing through different Fuzzy logic operators, which consists in a more flexible adaptation of the Boolean logic, since it accounts with a greater quantity of available operators (ZACCHI et al., 2010), allow to generate information that fits into the researcher needs, helping in the management, analysis and presentation of the generated information. As well as the soil and weather characteristics for the soybean in the south regions of the country, which were determined in the zoning work of CARVALHO JUNIOR et al. (2003). Using geoprocessing techniques, through the information crossing, its results showed that the agropedoclimatic zoning by geoprocessing was possible, generating large volumes of information.

Likewise, SIMÕES and CRÓSTA (2005) study attempted to show the viability of the GIS use in speleological surveys, assisting in the decision making regarding these areas. MOREIRA et al. (2002) characterized the lithological contact type in processes of spatial analysis, with application of linear Fuzzy functions to create continuous surfaces which express better the spatial distribution of each lithological unit. Its results indicated that the technique allows a better refinement of the data modeling, improving its spatial representation in continuous surfaces.

The internal and external geometries assess the quality of a satellite image, where the first indicates the similarity degree between the image and the captured surface and the external geometry establishes the accuracy of the image coordinates in relation to a referential. The geometrical correction has as objective to model the effects made by the many sources of distortions introduced at the moment of the image acquisition. The pixels grouping in the image is one of these correction forms, and can be made by the oriented processing towards the object, basing in a Fuzzy classifiers system (PINHEIRO, 2003). Thus, CUNHA et al. (2001), objecting to obtain a better characterization of the potential mineral for the exploration of chromium, used a evaluation technique by multi criteria analysis as a geoprocessing tool, defined through the Considered Fuzzy operator. The authors selected areas with characteristics of interest and observed the importance of the tool use associated to the GIS, in activities of mineral research to support the generation of a prospective model.

The GIS use associated to the Fuzzy logic permits a better organization of the data, as reported by SIMÕES and CRÓSTA (2005), besides the easiness in its interpretation and maps generation, especially focusing areas with greater speleological potential through the lithological information crossing, of relief and among others, indicating the places with geologic patterns of interest. Furthermore, allows a better data analysis, serving as tool in public politics of use and conservation of these areas.

With the objective of assessing the so called "geotechnologies" in the cartography of soils, NOLASCO-CARVALHO et al. (2005), used the GIS with Fuzzy inference in the determination of the map of soils in a region of the Bahia state. Alongside with information about the vegetation, geology and data og the digital terrain model associated to the pedologist knowledge, the authors demonstrated that the use was successful, especially if compared to the conventional map. With the inclusion of the uncertainties in the model, the generalizations were reduced, creating transition areas and improving the results. The author also suggested that the methods reduces stages and fastens the process, and they suggest that the method should be validated on field and repeated in other areas.

Still with this purpose, through the Fuzzy logic in comparison to the USLE model (Universal Soil Loss Equation) (WISCHMEIER and SMITH, 1978), ALVES et al. (2005), made studies about the erosive potential of soils in a municipality of the Rio de Janeiro state. Their conclusions pointed out the Fuzzy model as the most simple, since it showed similar results of the USLE model with the use of only two variables - slope and soil cover – whereas the second needs five variables, which optimized the field visits and the management, use and coverage of the soil.

Another application of the Fuzzy logic in GIS is the systematic mapping. The study of MARANHÃO and SOUZA (2003), with the intention of creating a methodology to facilitate this kind of mapping, crossed information of socioeconomic indicators of many Brazilian regions, thus creating thematic maps to assist in the work of public agencies that manage information, therefore covering a deficit data that started from the 90s with a decrease of the country industrialization. According to their results, the Fuzzy modeling of maps is the result of the expert knowledge, reflecting the idea of the model, and its use can guide the choice of indicators that provide support to the needs of the systematic cartography.

The planning of soil use is also an application area of the GIS based in the Fuzzy logic, where studies of mass movement, as well as the allocation of industrial spaces, are significant examples in the determination of the spatial occupation. The study of SILVA et al. (2002) raises this question, showing that with the use of the Fuzzy logic in the mapping of mass movement, in this case the soil mass arising from the "serrana" area, the municipality of Caraguatatuba – SP was benefited through the establishment of boundaries of decision, especially with relation to the vulnerability classes, which presented a gradation in the thematic classification, thus allowing the creation of occupation zones.

The allocation of industrial districts is discussed by PÉRICO and SEMIN (2006) and SOARES et al. (2004). In both studies the proposed methodology using normalizers of criteria based in Fuzzy logic brought positive results, uniting the relevant information and generating dynamic maps which can be altered according with the local structural changes, always bringing updated and precise information as for the strategical position for the economical planning. KURTENER and BADENKO (2000) developed methodological tools for the use and management of the soil, integrating the knowledge already consecrated in GIS with Fuzzy models, applied especially for the analysis of soil contamination by heavy metals, soil acidification study, besides offering subsides for the management and conservation.

Thus, according to STASZCZAK et al. (2004) the Fuzzy logic presents itself as a tool, which offers conditions for the imprecise variables control, that involves the interference process in the procedure in which they contribute for the decision takings, involving the expert knowledge in the determination of classes of acting and through the conditional rules of action.

Conclusions

The inclusion of the uncertainties in the models makes the determination of sets limits easier, with greater data refinement and showing transitional strips that the common models do not detect.

The use of linguistic variables also allow a better development of models, especially those dependent of complex mathematical models and offers precise answers to the problems.

And the consequent reduction of stages of work and its completion time enables the use of the Fuzzy logic in the many areas of the human knowledge.

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