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The enhancement of the cell-based GIS analyses with fuzzy processing capabilities

Tahsin A. Yanar, Zuhul Akyürek *

Middle East Technical University, Department of Geodetic and Geographic Information Technologies, 06531 Ankara, Turkey

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Abstract

In order to store and process natural phenomena in Geographic Information Systems (GIS) it is necessary to model the real world to form computational representation. Since classical set theory is used in conventional GIS softwares to model uncertain real world, the natural variability in the environmental phenomena cannot be modeled appropriately. Because, pervasive imprecision of the real world is unavoidably reduced to artificially precise spatial entities when the conventional crisp logic is used for modeling.

An alternative approach is the fuzzy set theory, which provides a formal framework to represent and reason with uncertain information. In addition, linguistic variable concept in a fuzzy logic system is useful for communicating concepts and knowledge with human beings. FuzzyCell is a system designed and implemented to enhance commercial GIS software, namely ArcMap® with fuzzy set theory. FuzzyCell allows users to (a) incorporate human knowledge and experience in the form of linguistically defined variables into GIS-based spatial analyses, (b) handle imprecision in the decision-making processes, and (c) approximate complex ill-defined problems in decision-making processes and classification. It provides eight membership functions, inference methods,

* Corresponding author.

E-mail addresses: e122330@metu.edu.tr (T.A. Yanar), zakyurek@metu.edu.tr (Z. Akyürek).

methods for rule aggregation, operators for set operations and methods for defuzzification.

The operation of FuzzyCell is presented through case studies, which demonstrate its application for classification and decision-making processes. This paper shows how fuzzy logic approach may contribute to a better representation and reasoning with imprecise concepts, which are inherent characteristics of geographic data stored and processed in GIS.

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1. Introduction

Geographic Information Systems (GIS) are computer-based systems that store and process (e.g. manipulation, analysis, modeling, display, etc.) spatially referenced data at different points in time [1]. Geographic data, stored and processed in GIS, form a conceptual model of the real world [1]. The abstraction of the real world to construct the conceptual model unavoidably results in differentiation between objects of the real world and their representation in GIS (i.e., computer) [2,3]. Because, classical set theory used in a conventional GIS is inadequate to express the natural variability in the environmental phenomena [2]. As it is stated by Heuvelink and Burrough [4] there will often be meaningful discrepancies between reality and its representation since the reality is forced into rigid data storage formats.

Fuzzy set theory offers a way to represent and handle uncertainty present in the continuous real world. Fuzzy set theory is unique in that it provides a formal framework to process linguistic knowledge and its corresponding numerical data through membership functions [5]. The linguistic knowledge is used to summarize information [6] about a complex phenomenon and is used to express concepts and knowledge in human communication, whereas numerical data is used for processing [7].

The cost of developing and implementing fuzzy processing tools may have been, in the past, an obstacle to incorporating fuzzy sets in GIS [8]. Today, it is relatively rare for a commercial GIS software system to support fuzzy information processing because, as Robinson [8] states, this obstacle still remains. IDRISI GIS software package can be an exception for this issue [9]. Other tools, outside GIS software packages, have been developed and can be found in the literature. The MATLAB Fuzzy Systems Toolbox is one of these packages which can be used to model mobile spatial objects [10]. When commercially available GIS software systems supporting fuzzy information processing are analyzed, it is observed that most of them are not generic and they are problem specific.

Especially, fuzzy classification and identification in GIS have been widely used for many different problem domains including soil classification [11,12], crop-land suitability analysis [13], identifying and ranking burned forests to evaluate the risk of desertification [14]. The main reason for the investigation of the use of fuzzy classification is the classification error, especially, when dealing with linguistic concepts such as “level” or “gentle” [15]. Fuzzy classification is able to integrate uncertainty due to vagueness and indiscernibility [16]. Although the above works use fuzzy logic to overcome weakness of crisp logic, there are other examples where fuzzy logic is integrated into GIS software to allow a more realistic classification and assessment of natural phenomena [17,18].

Stefanakis et al. [15] addressed weakness of crisp logic in decision processes and proposed the use of fuzzy set theory in GIS decision-making. Fuzzy decision making can be used for different kinds of purposes such as seeking the optimum locations for real estates [19], assessing vulnerability to natural hazards [20,21] or estimating risk [22–24].

In this study, our objective is to incorporate human knowledge and experience in the form of linguistically defined variables into raster based GIS through the use of fuzzy set theory. This paper shows that fuzzy model approach can be used in place of classical approach in classification and decision-making processes. Specifically, we enhanced a commercial GIS software namely ArcMap[®] to support fuzzy information processing and it is named as FuzzyCell. FuzzyCell, which is generic, enables decision-makers to express their constraints and imprecise concepts that are used with geographic data through the use of natural language interfaces. Differences in several properties of the proposed software and available GIS software systems in the literature are given in Table 1.

2. Methods and tools

FuzzyCell has been developed on a commercial GIS software namely, ArcMap[®], which is a major GIS desktop system. FuzzyCell can be viewed as a scheme for capturing experts’ knowledge on a specific problem. Through the use of linguistic variables, experts’ experiences in the problem domain, even though they naturally involve imprecision, are converted to fuzzy rules. Therefore, FuzzyCell allows users to handle imprecision in the decision making process by knowing only the fuzzy logic background.

Component Object Model (COM) environment is used for developing fuzzy inference system for ArcMap, where COM is a protocol that connects one software component, or module, with another and defining the manner by which objects interact through an exposed interface. The implementation of the fuzzy inference system tool for ArcMap is divided into two parts:

Table 1
Comparison of different systems

System	Intended use	Membership functions	T-Norm/T-CoNorm operations	Hedges	Inference	Aggregation	Defuzzification	Software
FUZZYLAND [17]	Classification	Bell-shaped	Min./Max./Product	Very/Approximately/Quite/Not/User Defined	×	Min./Max./Weighted Sum	Classification table	ARC/INFO 7.1.1
MapModels [18]	Classification	*	Gamma Operators	User Defined	×	Gamma Operators	×	ArcView
REGIS [19]	Decision-making for real estate	Linear/S/Logarithmic	*	×	Fuzzy Rule Based System	Max./Weighted Sum	Available	ARC/INFO
FFIREDESSYS [24]	Decision-support system for the estimation of forest fire risk	Triangular/Trapezoidal/	×	×	Knowledge-Base/inference engine (backward/forward chaining)	×	×	*
MCE-RISK [23]	Risk-based decision-making for natural hazards	Triangular/Trapezoidal/Gaussian/Generalized Bell/Sigmoidal/Left-Right functions	×	×	×	Weighted Linear Combination/Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)/Compromise Programming	×	*
FUZZY-SRA [21]	Modelization and analysis of the vulnerability of aquifers	Triangular/	Addition/Multiplication	×	×	×	*	MapObjects
FuzzyCell [25]	Classification/Decision-making	Triangular/Trapezoidal/Gaussian/Bell-shaped/Sigmoidal/S/Π ₁ /Π ₂ /Left-Right functions	Drastic Product/Drastic Sum/Bounded Difference/Bounded Sum/Einstein Product/Einstein Sum/Algebraic Product/Hamacher Product/Hamacher Sum/Minimum/Maximum	NOT/User Defined	Clipping Method/Scaling Method	Max./Sum/Probabilistic-OR	Center of Area/Bisector of Area/Mean of Max./Largest of Max./Smallest of Max.	ArcGIS 8.1 ArcMap Application

*—unknown; ×—not available.

- (1) Fuzzy Inference Engine implementation,
- (2) Fuzzy Inference System Module implementation.

The general architecture design and workflow of the fuzzy inference system for cell-based information modeling is shown in Fig. 1. Commercial GIS application uses Fuzzy Inference System through public interface defined by Fuzzy Inference System Module. However, commercial GIS application and Fuzzy Inference System act as two separate applications, since Fuzzy Inference System is designed an ActiveX module.

A fuzzy rule-based, expert like system for cell-based GIS analyses can be designed by setting up linguistic variables, defining fuzzy rules and specifying fuzzy model properties (i.e., selecting inference and aggregation methods, conjunction and disjunction operators and defuzzification method) using the interfaces of FuzzyCell. Defining linguistic variables (e.g., “slope”) involves finding important input variables (e.g., “flat”, “gentle”) from all possible input variables and specifying membership functions. Fig. 2 shows the user interface to define membership functions for linguistic terms. In FuzzyCell, the value of a linguistic variable can be a linguistic expression involving a set of linguistic terms, hedges (e.g., “very”, “more or less”) and connectives (e.g., “and”, “or”). Using these definitions, rules and given input raster maps, FuzzyCell produces an output raster map. To produce output maps, a crisp output is needed to specify the value of each pixel in the raster map. Therefore, fuzzy conclusion is converted into a crisp conclusion using selected defuzzification method.

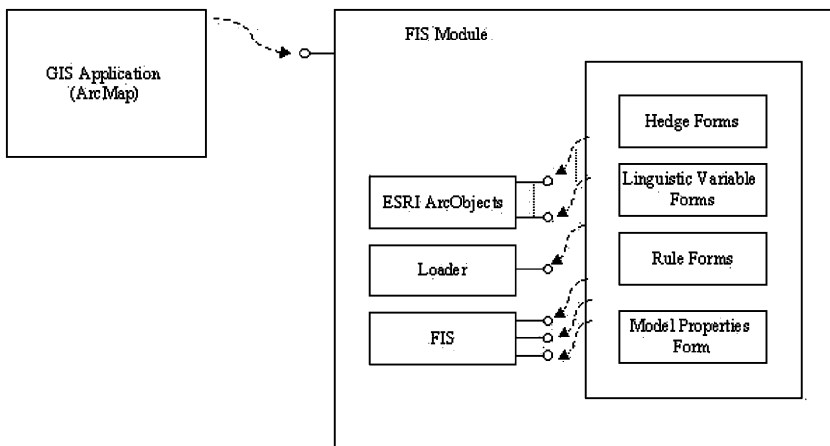


Fig. 1. Architectural design and workflow of fuzzy inference system for GIS.

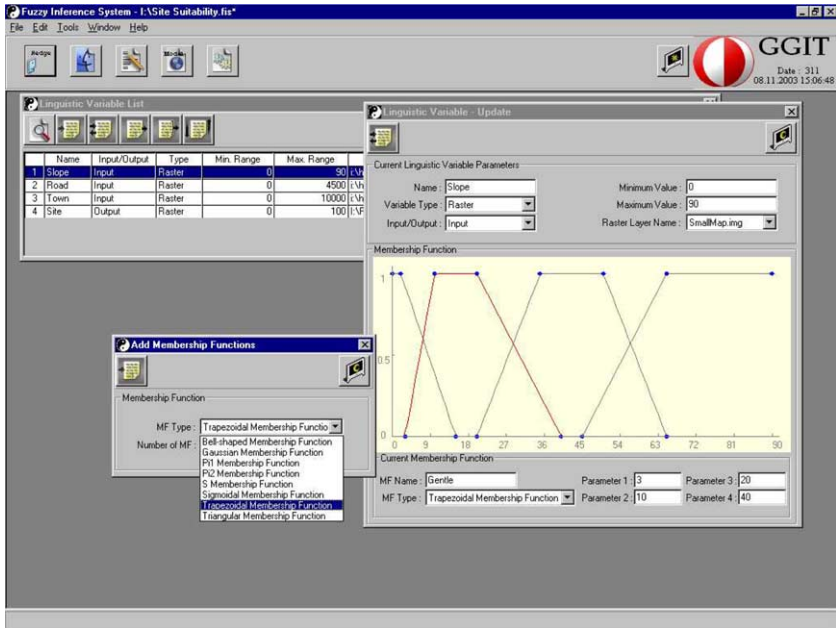


Fig. 2. Membership functions for linguistic variable “Site”.

3. Applications

3.1. Classification

Classification is defined as identification of a set of features as belonging to a group [1]. In the classical sense in order to test for belonging to a group, each group is separated from other groups with sharply defined intervals. For example, in a raster based GIS, a cell is assigned to a group if value of the cell is between the values describing that group. However, it is very difficult to work with vague concepts, which are easily comprehended by humans. The developed system can be used to classify the study area into classes, which are defined as linguistic terms (i.e., classes do not have sharply defined intervals).

Example 1. To characterize a value of the slope by a natural label “gentle”, it is necessary to define the meaning of the term “gentle”. Suppose that the meaning of the term “gentle” is defined as shown in Fig. 3(a). The main purpose of the system is to assist the user to take decisions using experts’ experiences in the decision-making process. Experts’ knowledge are captured by fuzzy if–then rules which are in the form of IF *A* THEN *B* where *A* and *B* are terms with a fuzzy meaning. What actions will be taken when the rule’s

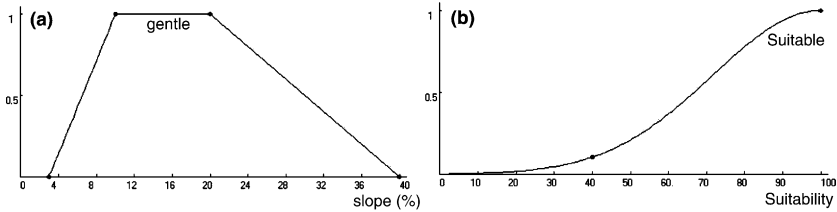


Fig. 3. Defining membership functions (a) membership function for linguistic term “gentle”, (b) consequent variable “suitable” and its meaning.

antecedent is partially satisfied is not known yet. The consequent of the rule must also be defined. One possible consequent variable is “suitable” with meaning depicted in Fig. 3(b). There are plenty of choices for consequent variable and its membership function (i.e., meaning) depending on the problem or even depending on wish. The scale of the consequent linguistic variable “suitable” is selected as [0,100]. Output values will lie in the scale of the consequent variable. Depending on the scale and the meaning of the output variable (i.e., suitable) used in the example, in the output raster map pixel values close to 100 means pixel definition is close to linguistic term “gentle”. Finally, to classify slope map of the study area, the rule

$$\text{IF slope is gentle THEN site is suitable.} \tag{1}$$

is used. Input slope map of the study area is derived from digital elevation model and is depicted in Fig. 4(a). Result of the classification based on Rule (1) listed above is depicted in Fig. 4(b). In the fuzzy result map, upper parts of the region mostly has “gentle slope” with varying degrees. Higher pixel values imply pixel definition is more close to “gentle”. All pixels in the input slope map are then classified as “gentle” with varying grades. Each pixel value in the output map defines the grade of “suitability” to describe the cell as having a “gentle slope”. The exact Boolean expression of Rule (1) is:

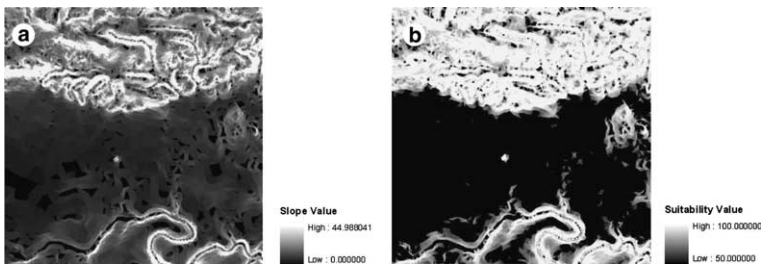


Fig. 4. (a) Slope map of the study area. (b) Fuzzy result map showing “gentle slope”.

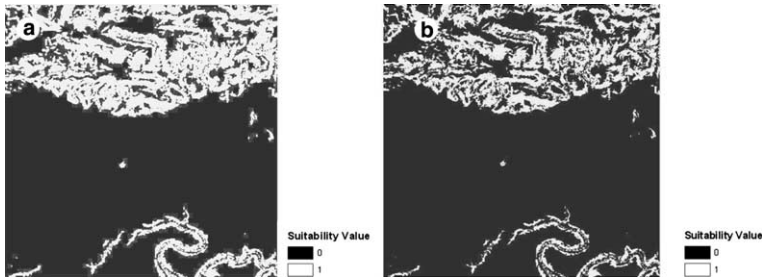


Fig. 5. (a) Classified locations according to Boolean expression. (b) Classified fuzzy (“gentle slope”) map.

IF cell has slope value between 10% and 20%

THEN cell is defined as gentle. (2)

Result of applying Boolean expression to the input slope map is depicted in Fig. 5(a). A location with slope equal to 10.1% is characterized as “gentle”, while another location with slope equal to 9.9% is not. For decisions based on multiple criteria, it is usually the case an entity which satisfies majority of constraints posed by decision-maker and is marginally rejected in only one of them to be selected as valid by decision-maker. However, based on crisp logic a location with 9.9% will be rejected, even it satisfies all other constraints. Gray areas in Fig. 4(b) (i.e., fuzzy result) represent locations that partially satisfy the constraint where these locations are excluded in Fig. 5(a) (i.e., Boolean result). Specifically, 31.4% of the total area is represented by different tones of gray (i.e., locations that partially satisfy the constraint) in the fuzzy result map, however these locations are characterized as “not gentle” in the Boolean result map. Suppose that if Fig. 4(b) (i.e., fuzzy classification) is classified as locations equal to 100 are assigned to 1 and others are assigned to 0, the result is the same as applying Boolean expression (2) to the input slope map. Fig. 5(b) illustrates result of classification of fuzzy result. As it is easily seen that Fig. 5(a) and (b) are the same. Therefore, the result of fuzzy classification includes the result of the conventional classification (i.e., crisp logic in classification). In addition, fuzzy classification gives better results because all the pixels of input slope map contribute to the answer of the rule with a grade.

A fuzzy model describes functional mapping relationship from a set of input variables to a set of output variables using a set of fuzzy if–then rules. Fuzzy model in Example 1 defines a relationship from input linguistic variable “slope” to output linguistic variable “suitable”. The antecedent of a fuzzy model is defined by fuzzy partitions of input space. Generally, a fuzzy partition of an input space is a set of fuzzy subspaces whose boundaries partially overlap and whose union is the entire input space [7].

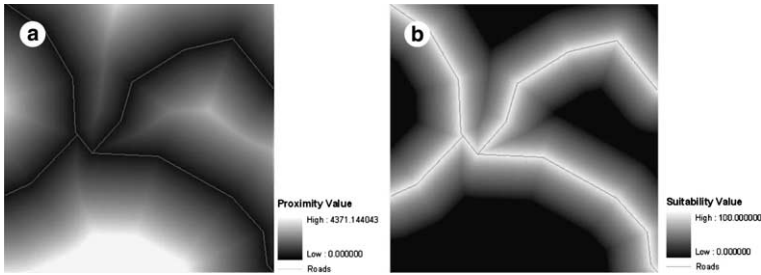


Fig. 6. (a) Roads and proximity to roads. (b) Fuzzy result map showing locations close to roads.

Example 2. It is common in most site selection problems to find sites that are close to roads. In classical approach one solution is with creating buffer zones with the defined upper limit for the term “close”. This example illustrates fuzzy approach in place of using buffer zones for finding locations “close to roads”. Roads in the study area and proximity to roads are depicted in Fig. 6(a). Suppose that the meaning of the linguistic term “close” and the linguistic term “suitable” are defined as shown in Fig. 7, and classification is based on the rule:

$$\text{IF distance to road is close THEN site is suitable.} \tag{3}$$

Result of the classification based on Rule (3) and the model properties listed above is depicted in Fig. 6(b). It is seen that the result of applying fuzzy classification resembles the buffer zones. In classical approach every location in the buffer zone has equal degree (i.e., true or 1). In the result of fuzzy classification, locations having grade equal to 100 (i.e., maximum suitability) represent these locations. In addition, fuzzy classification presents locations that partially satisfy the constraint “close to roads”. These locations are represented by different tones of gray depending on suitability values. Note that suitability decreases as we moved away from the roads.

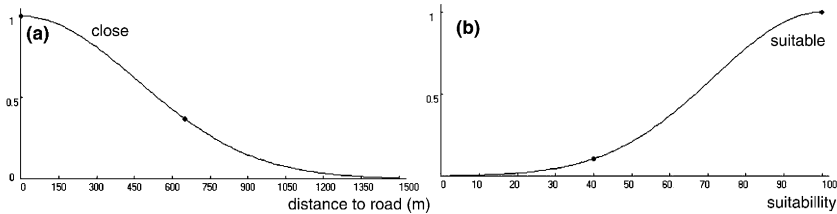


Fig. 7. Membership functions for linguistic term (a) “close” and (b) “suitable”.

3.2. Hedges

Meaning of a linguistic term can be modified using linguistic hedges. The developed system provides interfaces for decision-makers to define hedges. After defining hedges, the meaning of a linguistic term in a rule can be modified using hedges.

Example 3. The hedge “very” does not have a well-defined meaning in everyday use. However, in essence the hedge “very” has an intensive effect on linguistic term it operates. As hedge “very”, hedge “too” also has an effect of narrowing the membership function, while hedge “enough” widens the membership function. Because the criteria “too close to roads” should be more stringent than “close to roads”, while the criteria for “enough close to roads” should be relaxed. Definitions of hedges “too” and “enough” are listed below:

$$\mu_{\text{Too}(F)}(x) = [\mu_F(x)]^2, \quad (4)$$

$$\mu_{\text{Enough}(F)}(x) = [\mu_F(x)]^{0.4}. \quad (5)$$

Definitions given above can change depending on the problem, depending on context a linguistic term used, or depending on wish. Using the definitions of hedge “too” (4) and hedge “enough” (5) the meaning of the constraint “close to roads” is modified to obtain the following rules:

IF distance to road is too close THEN site is suitable, (6)

IF distance to road is enough close THEN site is suitable. (7)

Fig. 8 depicts the results of applying Rules (6) and (7) to the proximity map shown in Fig. 6(a), respectively. Since it is difficult to satisfy the criteria “too close to roads” than “close to roads”, not all locations that satisfy the criteria “close to roads” satisfy the criteria “too close to roads”. In addition, the degree

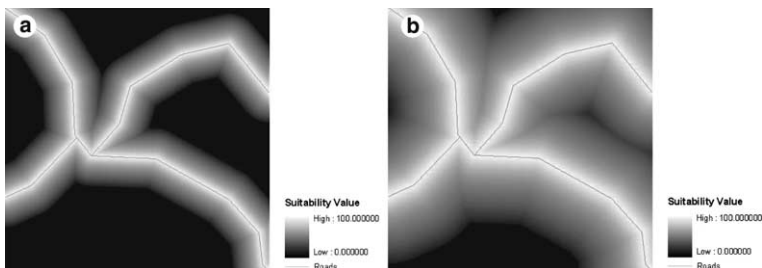


Fig. 8. The result map showing (a) “too close to roads”, and (b) “enough close to roads”.

of satisfying the constraints “too close to roads” and “close to roads” for a specific location is not the same. The degree of satisfying the constraint “too close to roads” is less than the degree of satisfying the constraint “close to roads”. Therefore, the result of adding hedge “too” to modify the meaning of the rule results in narrowing the zone shown in the fuzzy map. On the other hand, it is easy to satisfy the criteria “enough close to roads” than “close to roads”. Therefore, more locations satisfy the constraint “enough close to roads”. Moreover, the degree of satisfying the constraint “enough close to roads” is higher than the degree of satisfying the constraint “close to roads”. Hence, hedge “enough” has an effect of widening the zone shown in the fuzzy map.

3.3. Decision making

One of the main tasks in GIS is making decisions using information from different layers. The decision-making is affected by many factors and sometimes needs many criteria. In numerous situations involving a large set of feasible alternatives and multiple, conflicting and incommensurate criteria, it is difficult to state and measure these factors and criteria [26]. Indeed most of the information about the real world contains uncertainties.

Threshold model is a common type of operation in decision-making. In the threshold model, low and high threshold values limit the exact boundaries of criteria. When the underlying logic in GIS is crisp logic, then results of applying threshold values in decision-making processes are zero or one. Maps consisting of zero and unity values are produced for each criteria using threshold values that define the meaning of the criteria by only low and high threshold values (i.e., boundaries which are sharp or clear-cut). Then the overall result is obtained through the map overlay. Such models can cause problems since they are inherently rigid. On the other hand, FuzzyCell can be used to make decisions capturing uncertain information using fuzzy set methodologies. In the sequel a set of criteria is used to select suitable sites for industrial development.

Example 4. To select suitable locations for industrial development humans may pose criteria such as “If site has flat or gentle slope and if site is close to roads and town then site is suitable for industrial development”. It is simple for humans to comprehend and make decisions based on these vague terms. However, the conventional GIS cannot answer such vague questions. The exact Boolean criteria for the industrial development site selection is:

$$\begin{aligned} \text{Site is suitable if } & (\text{slope} \leq 20\%) \text{ and } (\text{distance to road} \leq 1000 \text{ m}) \\ & \text{and } (\text{distance to town} \leq 5000 \text{ m}). \quad (8) \end{aligned}$$

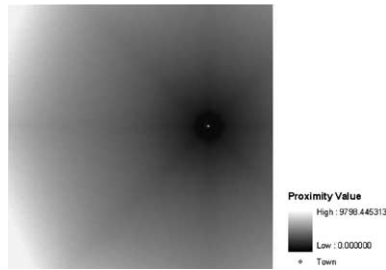


Fig. 9. “Proximity to town” raster map for decision-making process.

Associated input raster maps are: “slope map” is depicted in Fig. 4(a), “proximity to roads” is depicted in Fig. 6(a), and map showing “proximity to town” is depicted in Fig. 9. Boolean answer to question (8) is simple. First, for each criterion (i.e., slope, distance to road and distance to town) a map containing 0s and 1s is produced. Pixel values that are less than the threshold values are assigned one in the output map and zero otherwise. Second, the overall result is produced by overlaying these three maps using logical AND operation. Boolean result is depicted in Fig. 10(a). The proposed system can be used to find fuzzy answer to site selection problem. In addition, the developed system allows using vague definitions in the criteria. Hence, the rule listed below is used to approximate conceptual model of the problem in expert’s opinion (i.e., human cognition) and generate fuzzy answer to site selection problem:

IF slope is flat or
 slope is gentle and
 distance to road is close and
 distance to town is close

THEN site is suitable. (9)

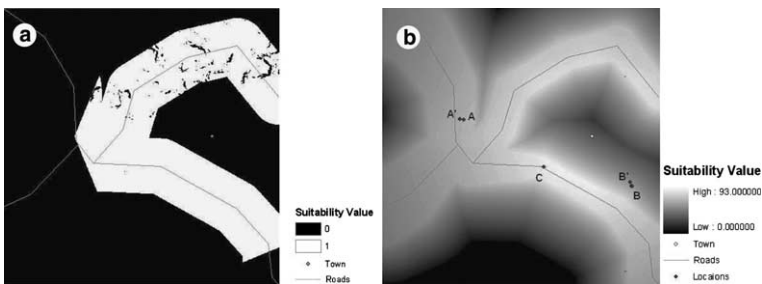


Fig. 10. (a) Result of Boolean analysis for suitable sites. (b) Fuzzy result to site selection problem using one rule.

Rule (9) approximates what industrial site selection problem means to user by using linguistic terms instead of precise numerical values and rule is very similar to the problem definition introduced earlier. Membership functions for linguistic terms are depicted in Fig. 11. Membership functions can be chosen by the user arbitrarily based on user’s experience, hence the membership functions for two user could be quite different depending upon their experiences and perspectives. Note that linguistic term “close” is used twice, one stands for “close to roads” and other stands for “close to town” and two different membership functions were defined for linguistic term “close”. This illustrates the fact that membership functions can be quite context dependent. Fuzzy result is depicted in Fig. 10(b). It is easily seen that fuzzy result provides a result set of locations whose attribute values partially satisfy the constraints, whereas Boolean result provides only a set of locations whose attribute values satisfy all constraints. When the underlying logic in GIS is crisp logic, locations satisfying all constraints are assigned to unity and others are assigned to zero. However, all pixels in the fuzzy output map have a suitability degree for industrial development based on satisfaction of each criterion. For instance, locations that are not close to town are not included in the Boolean result set. Hence, locations that fail to satisfy criteria “distance to town ≤ 5000 m” even with 1 m are excluded from the result set disregarding their slope and closeness to roads. The location labeled *A* in Fig. 10(b) has properties as listed below:

- slope = 3%,
- distance to roads = 300 m,
- distance to town = 4953.1 m.

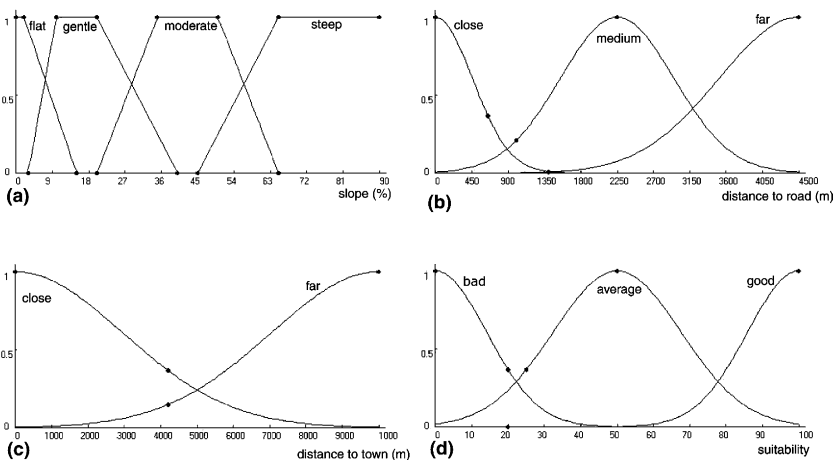


Fig. 11. Membership functions for (a) “flat” and “gentle” slope, (b) “close to roads”, (c) “close to town”, and (d) “suitability”.

Since, properties of location A are in the defined threshold values, location A is assigned to 1 in the Boolean result map indicating it is a suitable location. Another location near to point A is labeled as A' and has the following properties:

- slope = 2.1%,
- distance to roads = 190 m,
- distance to town = 5045 m.

Location A' fails to satisfy the Boolean criteria because distance to town is a little bit higher than the defined threshold value. Therefore location A' is assigned to 0 in the Boolean result map indicating it is not a suitable location. Location A' has even better slope value and more close to road but it is classified as unsuitable location based on the value of distance to town, note that distance between location A and A' is less than 100 m. On the other hand, the proposed system graded suitability of location A with 77 and it graded location A' with 76 (out of 100) for industrial development.

Input maps store information about real world which are continuously changing properties. Applying threshold values in Boolean analysis leads to lose information stored in the input maps. Since, the result of Boolean analysis only consists of 1s and 0s which indicate it is a suitable location or not, the user has no idea about best or worst locations satisfying all constraints. On the other hand, fuzzy site selection analysis provides locations in orderly manner; each location has a suitability degree. For example, consider points in Fig. 10(b) A , A' , B , B' , and C . Table 2 gives property values and results associated with the locations. It is noted that location A , B , and C are suitable locations according to Boolean analysis. Since values of locations A , B , and C are 1 in the output Boolean map, the user has no idea about which is better for industrial development. Fuzzy result provides this information to user with no further processing requirements.

Example 5. To select suitable sites for industrial development three rules are defined as follows:

Table 2
Properties of locations and results of Boolean and fuzzy analysis

Locations	Slope (%)	Distance to road (m)	Distance to town (m)	Boolean result	Fuzzy result
A	3.0	300	4953.1	1	77
A'	2.1	190	5045.0	0	76
B	1.4	995.7	2352.4	1	70
B'	1.7	1051.2	2227.5	0	68
C	1.1	50	2197.3	1	90

Rule 1. IF slope is flat and
 distance to road is close and
 distance to town is very close
 THEN site is suitable. (10)

Rule 2. IF slope is flat and
 distance to road is close and
 distance to town is close
 THEN site is average. (11)

Rule 3. IF slope is not flat and
 distance to road is not close and
 distance to town is far
 THEN site is bad. (12)

Membership functions for linguistic terms are depicted in Fig. 11. The developed system produced fuzzy result as depicted in Fig. 12. This example illustrates the fact that experiences of a GIS user on a specific decision-making process can be approximated easily using the developed fuzzy inference system for cell-based information modeling.

4. Discussion

The classical set theory used in conventional GIS software imposes artificial precision on inherently imprecise information about real world and fails to model the way of human thinking about the real world. Therefore, the abstraction

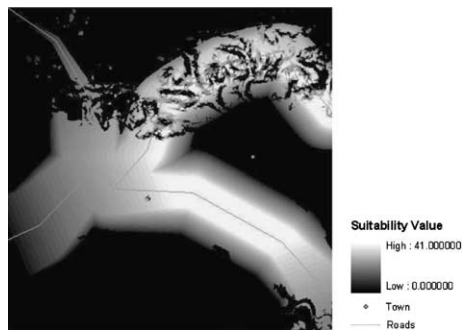


Fig. 12. Fuzzy result to site selection problem using multiple rules.

of the real physical world unavoidably results in differentiation between objects of the real world and their representation in GIS. Fuzzy logic offers a way to represent and handle uncertainty present in the continuous real world.

In this work, fuzzy logic methodologies are used to enhance cell-based information modeling. The main purpose of the developed system is to assist the GIS user to make decisions using experts' experiences in the decision-making process. Experts' experiences and human knowledge described in natural languages are captured by fuzzy if-then rules. FuzzyCell enables decision-makers to express imprecise concepts that are used with geographic data. Decision-makers can express their constraints in FuzzyCell by using the natural language interfaces. The capacity of taking linguistic information from decision-makers permits the decision-maker to develop the criteria more easily and softens the constraints and goals in order to find suitable sites.

In conventional decision-making process, for each of the criterion the study area is classified into two subregions describing whether a property value of a specific location is in the defined limit values or not. Then, maps produced for each criterion are overlaid using logical connectives (i.e., Boolean overlay). Each criterion can be weighted based on their importance to decision-maker. In this study, it is demonstrated that using the proposed software for decision-making, decision-maker has no longer need to produce maps for each criterion.

Moreover, all locations in the input space are mapped to a degree of suitability using property values of location and rules defined by the decision-maker. Therefore, values of locations in the fuzzy output map derived from fuzzy inference process can be available in orderly manner. Note that Boolean result contains only a set of 1 and 0 values. Another advantage of fuzzy inference is that fuzzy result of a decision-making process provides a set of locations whose attribute values partially satisfy the constraints posed by the user.

FuzzyCell is a GIS-based fuzzy inference system and assists the GIS users making decisions using experts' experiences in the decision-making processes. Using FuzzyCell users can approximate complex ill-defined problems in decision-making processes and classification. It provides eight membership functions, inference methods, methods for rule aggregation, operators for set operations and defuzzification methods (Table 1). FuzzyCell can be used not only to make decisions but also to classify the study area into classes, which are defined as linguistic terms (i.e., classes do not have sharply defined intervals). Using fuzzy logic methodologies in the classification avoid the high loss of information, which occurs when data are processed using conventional classification methods. Since fuzzy logic approach allows a gradual change in the class limits, intermediate conditions can be better described and gradual changes or transitions in the property values can be better expressed. Therefore, more continuous approach to classification leads to more realistic

assessment of continuous landscape. FuzzyCell provides not only a powerful tool to the GIS user to make decisions in vague concepts but also FuzzyCell

- has easy to use graphical user interfaces which enable even a newcomer to fuzzy set theory to define rules without necessarily knowing all the underlying concepts of the fuzzy set theory,
- is not dedicated to a specific GIS problem,
- covers the most commonly used membership functions,
- provides different inference methods and aggregation methods,
- has different operators for set operations (i.e., conjunction and disjunction operators),
- offers different defuzzification methods, and
- is rich with the number of possible designs.

Rules, input and output linguistic variables, membership function types and membership function parameters and fuzzy model properties can be selected depending on the problem [8]. Importance of a criterion can be dictated using these parameters. Variety of results can be obtained using different operators, different membership functions, different membership function parameters, different implication and aggregation operators, different defuzzifier operators and different rules. Parameters, rules and all other choices that form a fuzzy model differ for problems. Therefore, for a specific GIS operation which properties of fuzzy model are suitable has to be discussed before using fuzzy logic.

5. Conclusion

Fuzzy logic methodologies have been used to enhance cell-based information modeling within a commercially available GIS software system. The paper discussed the concepts of incorporating experts' experiences in the form of vague definitions to cell-based GIS analysis. The incorporation of fuzzy set theory into GIS provides an approximate and yet effective means of describing the real world which is (not precise) full of uncertainties. The advantages of fuzzy set theory can not be realized without membership functions. Both membership functions and their associated linguistic terms make fuzzy set theory superior to the classical set theory since this association allows us to express irreducible observations and measurement uncertainties. Another important feature of fuzzy set theory is its approximate solutions that are both cost effective and highly useful. The more complex the problem involved, the greater the superiority of fuzzy methods.

The focus of this research is the development of software package inside a commercially available GIS software to support fuzzy information processing rather than empirical case study analysis. In addition, because the developed

software discussed in this paper is generic, it can be used for many other decision-making and classification applications.

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