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FUZZY MULTICRITERION DECISION MAKING IN IRRIGATION PLANNING†

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ABSTRACT

Multicriterion decision making (MCDM) has emerged as an effective methodology due to its ability to combine quantitative and qualitative criteria for selection of the best alternative. Concurrently, fuzzy logic is gaining importance due to its flexibility in handling imprecise subjective data. In the present study two fuzzy logic-based MCDM methods, namely similarity analysis (SA) and decision analysis (DA), are adopted and developed as a FUzzy Decision System (FUDS) and applied to a case study of the Sri Ram Sagar Project (SRSP), Andhra Pradesh, India, for selecting the best-performing irrigation subsystem. It is found that both SA and DA suggested the same irrigation subsystem as the best. It is concluded that application of fuzzy logic methodology for real-world decision-making problems is found to be effective. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: fuzzy logic; multicriterion decision making; performance evaluation; India

RÉSUMÉ

La prise de décision multicritère (MCDM) a émergé comme méthodologie efficace due à sa capacité de combiner des critères quantitatifs et qualitatifs pour le choix de la meilleure alternative. Concurremment, la logique floue gagne l'importance due à sa flexibilité en manipulant des données subjectives imprécises. Dans la présente étude deux méthodes de MCDM baséès, dans la logique floue, à savoir, l'analyse de similitude (SA) et l'analyse de décision (DA), sont adoptées et développées comme système brouillé de décision (FUDS) et appliquées à une étude de cas du projet de Sagar de Ram de Sri (SRSP), Andhra Pradesh, Inde, pour choisir le meilleur sous-système d'exécution d'irrigation. On constate que SA et DA ont suggéré le même sous-système d'irrigation comme le meilleur. On conclut que l'application de la méthodologie de logique floue pour le problème réel de prise de décision du monde s'avère efficace. Copyright © 2005 John Wiley & Sons, Ltd.

MOTS CLÉS: logique floue; prise de décision multicritère; évaluation des performances; Inde

INTRODUCTION

Multicriterion decision making (MCDM) has emerged as an effective methodology due to its ability to combine quantitative and qualitative criteria for selection of the best alternative (Pomerol and Romero, 2000).

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Concurrently, fuzzy logic is gaining importance due to its flexibility in handling imprecise subjective data. In the present study concepts of fuzzy logic and MCDM are integrated and applied to a case study for selecting the best performing irrigation subsystem. Numerous studies on fuzzy logic are reported by various researchers for decision-making analysis in water resources planning. Raj and Kumar (1998, 1999) used maximizing and minimizing set concepts of fuzzy logic to select the best reservoir configuration for the Krishna River basin in India. Yin *et al*. (1999) employed fuzzy relation analysis for multicriteria water resource management for a case study of Great Lakes St Lawrence River basin, USA. Raju and Kumar (1999) applied the MCDM approach for selection of suitable irrigation planning strategy for a case study in Andhra Pradesh and employed PROMETHEE and EXPROM for ranking. Bender and Simonovic (2000) applied fuzzy compromise programming to water resource systems planning under uncertainty and compared it with ELECTRE. Very little work is reported on performance evaluation studies in a multicriterion environment. Heyder *et al*. (1991) explored 11 distinct long-term, system-wide alternative strategies and their impacts upon irrigation delivery performance. The alternatives that were considered involve structural, managerial and/or policy changes. These are compared with respect to relative cost, social acceptability, institutional acceptability and environmental impact, as well as water delivery performance, and applied to the case study of Alamosa River and La Jara Creek irrigation systems in the San Luis Valley of south-central Colorado. Two multicriterion decision-making techniques, namely PROMETHEE and weighted average, were applied to rank the alternative strategies. Similar studies are reported by Karamouz *et al*. (2002) where they developed an algorithm to monitor and evaluate drip and pressure irrigation projects in Iran. Different indicators are identified and an analytical hierarchy process is used for evaluation. The objective of the present study is to explore the use of fuzzy decision-making algorithms in performance evaluation studies and to develop a simple, interactive decision support system.

STUDY AREA

The Sri Ram Sagar Project (SRSP) is a state sector major irrigation project in Andhra Pradesh, India, located on the river Godavari. The project is mainly meant for irrigation. Global coordinates of the site are 18°58′ latitude north and 70°20′ longitude east. The SRSP project has three canal systems, namely the Kakatiya, Saraswati and Lakshmi, serving a number of irrigation subsystems (distributaries). Crops grown in the command area are paddy (rice), jowar, maize, groundnut, sugarcane and pulses in both summer (*kharif*) and winter (*rabi*) seasons. Soils of the command area are categorised under red soils and black soils. Climate of the area is subtropical and semi-arid. There is extreme variation in temperature with average maximum and minimum values of 42.2 and 28.6°C. The relative humidity varies from 65 to 80%. In the present study, four irrigation subsystems (choice set) under the Kakatiya canal are considered and these are denoted as D_1, D_2, D_3 and D_4. These irrigation subsystems differ from each other in terms of acreages, farmers and other conditions. Figure 1 presents the location map of the Sri Ram Sagar Project, Andhra Pradesh, India.

Farmers' response survey

A farmers' response survey is conducted to understand the irrigation management characteristics, constraints in the irrigation subsystem and to identify performance indicators. Responses from 35 farmers from the four irrigation subsystems are documented. Questions were asked regarding canal gate opening details, timing, adequacy and distribution pattern (such as equitable, etc.) of water supply, status of supplementing canal supplies with groundwater, usage of high-yield variety seeds, knowledge of critical periods of crops, cost of canal water, participation in operation and management works, relationship with co-farmers and authorities and role of farmers' associations for effective participatory irrigation management. Questions were also asked about constraints which may reduce yield such as poor drainage, land development work, availability of marketing facilities, fertilizers and water, and the corresponding effect on economic and social scenarios. Suggestions from farmers are also solicited which can be useful for further improvement of the project. The main conclusions emanating from the response survey are: (1) all farmers have expressed their satisfaction with the performance of the project and agreed that they

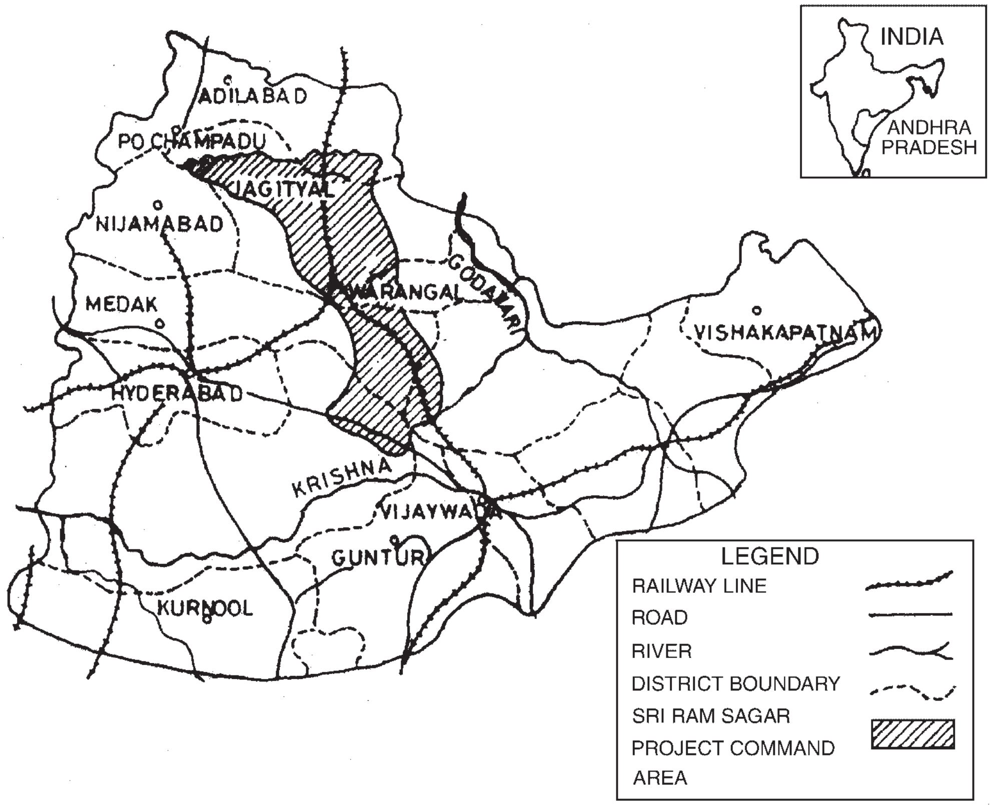

Figure 1. Location map of Sri Ram Sagar Project situated in the northern part of Andhra Pradesh, India

benefited from the project; (2) they also agreed that the participatory approach in the developmental aspects of the project yielded very good results in terms of increasing coordination among themselves and expressed that more is to be done in this regard; (3) formation of farmers' associations helps to organise themselves to utilize the resources such as water, fertilizers and seeds more effectively. The response survey also helped the authors to get acquainted with the project in terms of farmers' interaction, interview responses and formulation of performance criteria (indicators).

Formulation of indicators and payoff matrix

In the present study, instead of a single indicator of how the input (water) is being used, other indicators such as agricultural, economic and social issues are also considered. Six performance criteria, namely environmental impact (C_1), conjunctive use of surface and groundwater resources (C_2), participation of farmers (C_3), social impact (C_4), productivity (C_5) and economic impact (C_6) are formulated and evaluated for selecting the best irrigation subsystem. Out of the six, three criteria, namely environmental impact, conjunctive use of surface and groundwater resources and social impact, are related to sustainability (Raju and Duckstein, 2002). Even though many of the criteria such as productivity and economic impact are correlated or interdependent to some extent, these are assumed to be independent to assess their effect on the overall planning scenario. Brief details of the criteria are given below.

- Environmental impact issues analysed after introduction of irrigation facilities are rise in groundwater table and salinity level.
- Conjunctive use of surface and groundwater is essential to provide more reliable supply of water to crops when needed as well as to reduce the waterlogging effect.

Table I. Payoff matrix on fuzzy rating basis given by individual experts

Irrigation sub system	Expert	C_1	C_2	C_3	C_4	C_5	C_6
D_1	1	0.2	0.4	1.0	1.0	1.0	1.0
	2	0.2	0.2	1.0	0.8	0.8	0.8
	3	0.2	0.2	0.8	1.0	0.8	1.0
D_2	1	0.4	0.2	0.8	0.8	0.8	0.6
	2	0.6	0.0	0.6	0.8	0.8	0.4
	3	0.4	0.2	0.6	0.6	1.0	0.6
D_3	1	0.4	0.2	0.4	0.8	0.6	0.8
	2	0.4	0.0	0.0	0.6	1.0	1.0
	3	0.4	0.0	0.6	0.6	0.6	0.8
D_4	1	0.4	0.6	0.6	0.8	0.6	0.8
	2	0.6	0.4	0.4	0.8	0.6	0.8
	3	0.4	0.2	0.4	0.6	0.4	0.6

- Participation of farmers: farmers' knowledge of technology and new developments and participation are essential for optimum utilization of resources. It is the way in which farmers use the irrigation water that determines the success of an irrigation project.
- Social impact includes labour employment, which is measured in terms of man days employed per hectare for each crop grown.
- Productivity of various crops for various seasons for various landholdings are to be determined.
- Economic impact includes farmers' income and revenue collected for supply of irrigation water.

Information on the above criteria has been obtained from primary sources such as marketing societies and irrigation, groundwater and agricultural departments. Additional information is also obtained from secondary sources such as interviews with farmers, discussions with officials of the project, economic and statistics reports etc. Criteria C_1, C_2, C_3 are qualitative in type. Though the remaining criteria C_4, C_5, C_6 are quantitative in type, these criteria are also assumed to be qualitative, as converting productivity (yield) values of six crops to a base equivalent for two seasons under surface and well irrigation for different landholdings becomes complex and similar difficulties are faced for C_5 and C_6 also (Raju, 1995). All the above criteria are evaluated against each irrigation subsystem (termed as a payoff matrix or system versus criteria array) on a fuzzy rating basis. Three experts from the irrigation department who worked extensively on the above irrigation systems and have a good knowledge of working of the subsystem are requested to fill in the payoff matrix with evaluations ranging from 1 for excellent to 0 for unsatisfactory. Farmers' involvement is not considered for formulating this payoff matrix as they may possess less or no information about other irrigation subsystems. However, responses from their interviews and discussions with them form the backbone of the formulation process. Table I presents the payoff matrix corresponding to the four irrigation subsystems and the six performance indicators on a fuzzy rating basis for the three experts.

Estimation of weights of the criteria

The analytic hierarchy process is used to estimate weights of the criteria (Saaty and Gholamnezhad, 1982). The method deals with complex problems, which involve the consideration of multiple criteria simultaneously. The methodology is capable of:

(a) Breaking down a complex, unstructured situation into its component parts,
(b) Arranging these parts or variables into a hierarchic order,
(c) Assigning numerical values 1 to 9 to subjective judgements on the relative importance of each criterion (1 = equally important or preferred; 3 = slightly more important or preferred; 5 = strongly more important or

Table II. Pairwise comparison matrix and weights of criteria

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	Weights
C_1	1.0	3.0	2.0	0.5	0.5	0.33	0.132
C_2		1.0	3.0	0.5	0.33	0.33	0.092
C_3			1.0	0.33	0.33	0.20	0.056
C_4				1.0	1.0	0.5	0.187
C_5					1.0	0.5	0.202
C_6						1.0	0.331

preferred; 7 = very strongly more important or preferred; 9 = extremely more important or preferred; 2, 4, 6, 8 = intermediate values to reflect compromise) and

(d) Synthesising the judgments to determine the overall priorities of the criteria.

An eigenvector approach that can be solved by the power method is used to compute the priorities of the criteria in a pairwise comparison matrix. The eigenvector corresponding to maximum eigenvalue (λ_{max}) is computed. Since small changes in elements of a pairwise comparison matrix imply a small change in λ_{max}, the deviation of the latter from matrix size N is a deviation of consistency. This is represented by $[(\lambda_{max} - N)/(N - 1)]$ and termed as the consistency index (CI). Random index (RI) is the consistency index of the random matrix obtained by calculating the consistency index for a randomly filled matrix of size N. The ratio of CI to average RI for the same order matrix is called the consistency ratio (CR). A CR of 0.1 or less is considered acceptable.

Interaction with farmers and discussion with officials helped the decision maker to assess the importance of criteria. For example, it was mentioned during discussion and interactions that the economic impact was slightly more important than the environmental impact. Accordingly, values were chosen from Saaty's scale and noted in the pairwise comparison matrix. Similarly, other elements in the pairwise comparison matrix were noted. Table II presents the pairwise comparison matrix for criteria.

Maximum eigenvalue, consistency index, random index and consistency ratio for the pairwise comparison matrix are 6.243, 0.049, 1.24 and 0.04 respectively. It is found that the consistency ratio is less than 0.1, indicating that judgements given by the decision maker are satisfactory. Weights of the criteria for environmental impact, conjunctive use of water resources, farmers' participation, social impact, productivity and economic impact are found to be 0.132, 0.092, 0.056, 0.187, 0.202 and 0.331 respectively as shown in Table II. It is observed that economic impact and productivity are given the top two priorities by the decision maker, whereas farmers' participation occupied the last position. These weights are further used in decision-making analysis. However, equal weights are also considered to examine the sensitivity of the ranking.

FUZZY MULTICRITERION DECISION MAKING APPROACH

Two fuzzy multicriterion decision making methods, namely similarity analysis (SA) and decision analysis (DA), are applied to the present planning problem.

Similarity analysis (SA)

Similarity analysis (SA) uses the concept of degree of similarity measure and the alternative with a higher degree of similarity with respect to a reference alternative is considered to be the best (Chen, 1994). In this methodology, criteria are represented by interval-valued fuzzy sets (real interval) between zero and one. Characteristics of the alternative $a\,(a = 1, 2, \ldots A)$ for various criteria $C_1, C_2, \ldots, C_j$ (with weightage of the criteria $W = w_1, w_2, \ldots, w_j$) are represented as interval-valued fuzzy sets as below:

$$a = (C_1[y_{a1}, y'_{a1}],\ C_2[y_{a2}, y'_{a2}], \ldots, C_j[y_{aj}, y'_{aj}]) \tag{1}$$

where $[y_{aj}, y'_{aj}]$ represents the fuzzy interval for the ath alternative for then jth criteria within the ranges of $[0 \leq y_{aj} \leq y'_{aj} \leq 1]$ with $1 \leq a \leq A$. Here A and j represent the number of alternatives and criteria. Equation (1) can also be represented in matrix notation as below:

$$A = [y_{a1}, y'_{a1}],\ [y_{a2}, y'_{a2}], \ldots, [y_{aj}, y'_{aj}] \tag{2}$$

The objective is to choose such an alternative as the best, whose characteristics are most similar to the interval-valued fuzzy reference alternative set, R, which is expressed in the matrix notation as below:

$$R = [x_1, x'_1], [x_2, x'_2], \ldots, [x_j, x'_j] \tag{3}$$

where $[x_j, x'_j]$ represents the fuzzy interval for the reference alternative for jth criteria. Similarity between the interval-valued fuzzy reference alternative set R and given alternative A for a specified weight set W is computed in the form of similarity measure, S (A, R, W), as follows (Chen, 1994):

$$S(A, R, W) = \frac{\sum_{j=1}^{J} [1 - (|y_{aj} - x_j| + |y'_{aj} - x'_j|)/2 * w_j]}{\sum_{j=1}^{J} w_j} \tag{4}$$

Similarity measure values vary from zero to one. The higher the value of $S(A, R, W)$, the higher the similarity between the interval-valued fuzzy sets A and R. In the present study the similarity measure is aimed at for selection of the best alternative. More information about similarity measures is given in the Appendix.

Decision analysis (DA)

Decision analysis (DA) uses the concept of decision (membership) function and the alternative with a higher value of decision function is considered to be the best (Ross, 1995). In this methodology the decision function D is defined as

$$D = M(C_1, w_1) \cap M(C_2, w_2) \cap \ldots\ldots \cap M(C_j, w_j) \tag{5}$$

where M ( ) is a decision measure involving criteria and weights. The decision measure for a particular alternative a is defined as

$$M(C_j(a), w_j) = w_j \rightarrow C_j(a) = \bar{w}_j \cup C_j(a) \tag{6}$$

The decision function for the above scenario is given as

$$D = \bigcap_{j=1}^{J} (\bar{w}_j \cup C_j) \tag{7}$$

and the optimum solution a^* is the alternative that maximizes D. Defining dummy variable E_j as

$$E_j = (\bar{w}_j \cup C_j) \tag{8}$$

the membership function form $\mu_{E_j}(a)$ for variable E_j is

$$\mu_{E_j}(a) = \max[\mu_{\bar{w}_j}(a), \mu_{c_j}(a)] \tag{9}$$

The optimum decision function, expressed in membership form, is given as

$$\mu_D(a^*) = \min\{\mu_{E_1}(a), \mu_{E_2}(a), \ldots, \mu_{E_J}(a)\} \tag{10}$$

RESULTS AND DISCUSSION

Two fuzzy MCDM methods, viz. similarity analysis (SA) and decision analysis (DA), are programmed in a Visual Basic environment (Cornell, 2001) in the form of a decision support system and named as FUDS (FUzzy Decision

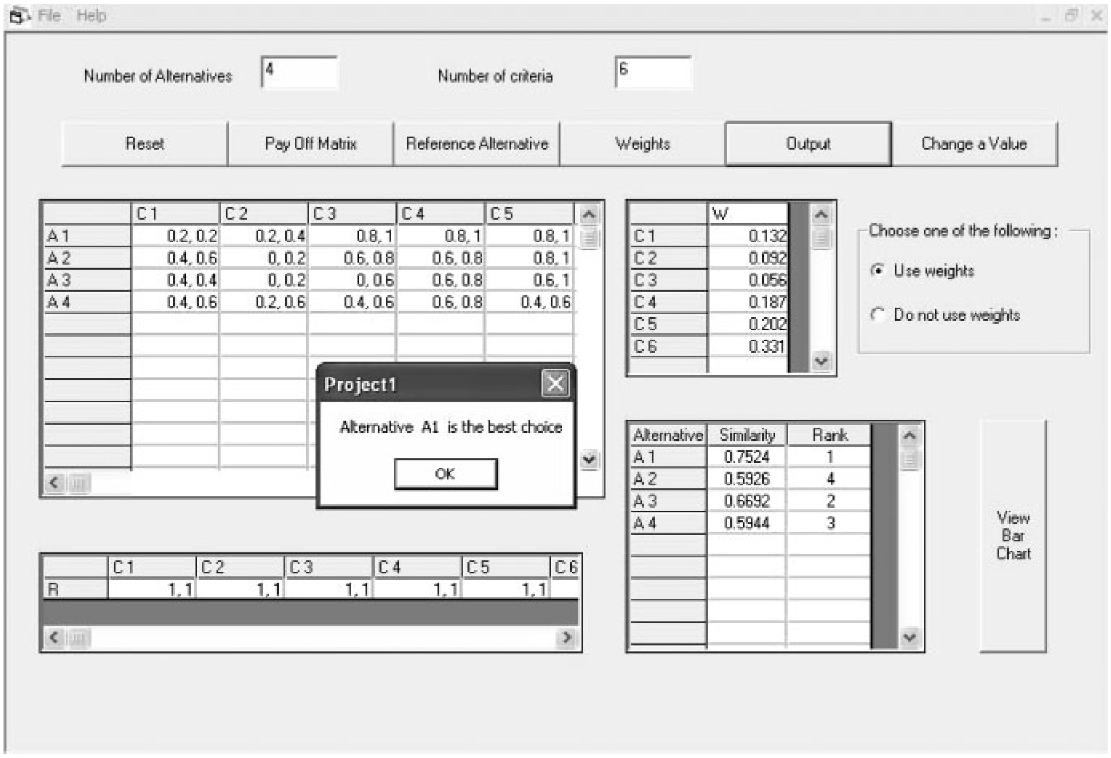

Figure 2. Sample screen of similarity analysis module

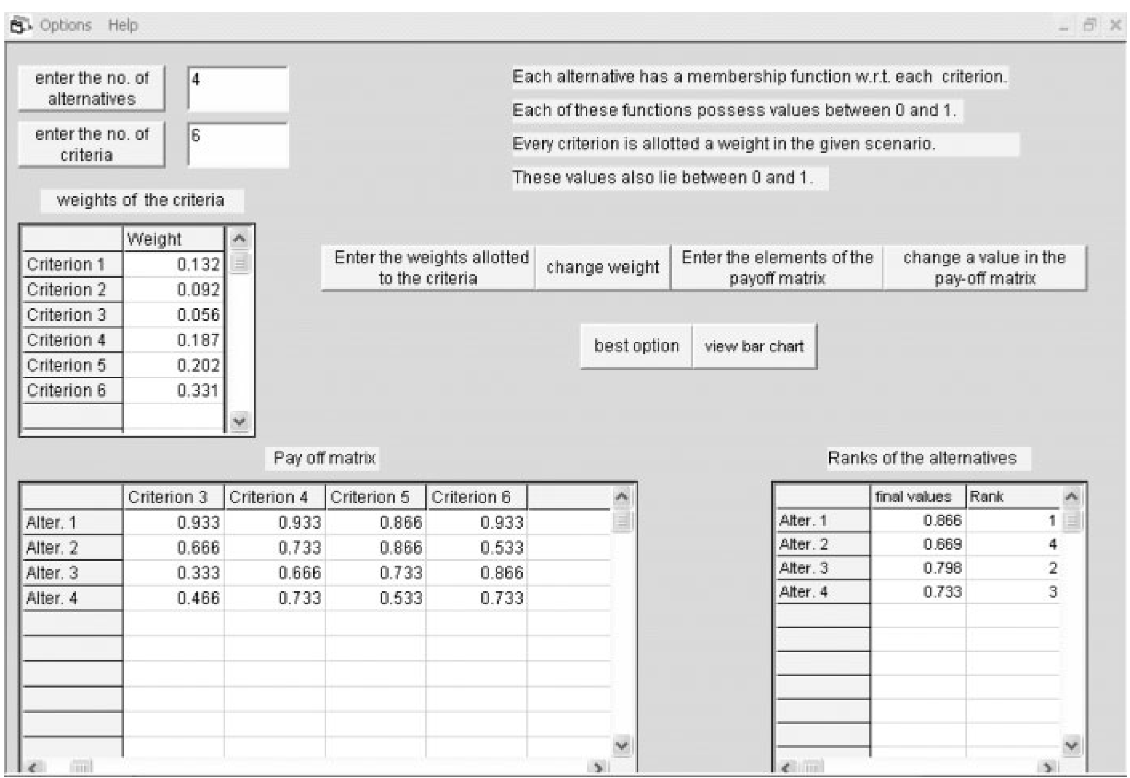

Figure 3. Sample screen of decision analysis module

Table III. Payoff matrix in the fuzzy interval form

Irrigation sub system	C_1	C_2	C_3	C_4	C_5	C_6	Degree of similarity and rank	Decision function and rank
D_1	[0.2, 0.2]	[0.2, 0.4]	[0.8, 1.0]	[0.8, 1.0]	[0.8, 1.0]	[0.8, 1.0]	0.7524 (1)	0.866 (1)
D_2	[0.4, 0.6]	[0.0, 0.2]	[0.6, 0.8]	[0.6, 0.8]	[0.8, 1.0]	[0.4, 0.6]	0.5926 (4)	0.669 (4)
D_3	[0.4, 0.4]	[0.0, 0.2]	[0.0, 0.6]	[0.6, 0.8]	[0.6, 1.0]	[0.8, 1.0]	0.6692 (2)	0.798 (2)
D_4	[0.4, 0.6]	[0.2, 0.6]	[0.4, 0.6]	[0.6, 0.8]	[0.4, 0.6]	[0.6, 0.8]	0.5944 (3)	0.733 (3)

System). Figures 2 and 3 present the sample screen of SA and DA approach modules of FUDS respectively. In both the modules common inputs are number of alternatives, criteria, payoff matrix and weights of criteria. Provision for changing the payoff matrix values and weights are also incorporated in both the modules. Provision for graphical representation of ranking pattern in the form of a bar chart is also made.

Similarity analysis (SA) module

Based on the evaluations given by the three experts (Table I) for each criterion for each alternative (i.e. three values), the lowest and highest values are considered for the interval for that scenario. For example, for alternative 1 and criterion 2, three experts have given their fuzzy rating as 0.4, 0.2 and 0.2. Accordingly the interval was given as [0.2, 0.4]. If all the experts gave the same rating such as 0.2, 0.2 and 0.2 then the interval was given as [0.2, 0.2]. Table III presents the payoff matrix in the interval form. Weights of the criteria are estimated from the analytic hierarchy process. The reference alternative for each criterion is taken as (1, 1). The module computes the degree of similarity between the given alternative and the reference alternative (as per Equation 4). A higher degree of similarity of an alternative with respect to the reference alternative is considered to indicate that it is the best. A sample calculation of degree of similarity of D_1 is shown in the Appendix. Similarity measures for irrigation subsystems D_1 to D_4 are computed and found to be 0.7524, 0.5926, 0.6692 and 0.5944, indicating that D_1 is the best. Table III presents degree of similarity measures and corresponding ranking pattern of the four irrigation subsystems.

Decision analysis (DA) module

This methodology requires only one value as input for each alternative versus criterion instead of interval. For this purpose average values of the payoff matrix in Table I are used as input. For example for alternative 1 and criterion 2, an average of 0.4, 0.2, 0.2 is taken. Similarly, other elements of the payoff matrix are computed. The decision (membership) function is obtained using Equations (7)–(10). See sample calculation of D_1 in the Appendix. The alternative having the highest value of decision (membership) function is taken to be the best (Equation 10). Remaining alternatives are ranked accordingly. It is observed that irrigation subsystem D_1 is found to be the best with decision membership function value of 0.866, followed by D_3 with a value of 0.798 with rank 2.

SENSITIVITY ANALYSIS

The effect of changing the weights of criteria on the ranking pattern for both SA and DA is also studied. These changes of weights may also represent scenarios that refer to different situations that may be expected in the planning situation. For this purpose, the value of each weight of the criterion is increased and then decreased as much as possible without changing the relative order of the criteria. Productivity is the second-largest criterion occupying a weightage of 0.202. The nearer values are 0.331 (economic impact) and 0.187 (social impact). Therefore two sensitivity runs are performed for this criterion to investigate the influence of values up to 0.330 and 0.188 on the ranking respectively. This represents the range that maintains the same order. Similar studies are also done for other criteria. Table IV shows the ranges of weights of criteria employed. In total, 10 combinations of

Table IV. Ranges of weights for sensitivity analysis

Criteria	Weight	Min	Max
Economic impact	0.331	0.331	—
Productivity	0.202	0.188	0.330
Social Impact	0.187	0.133	0.201
Environmental impact	0.132	0.093	0.186
Conjunctive use of water resources	0.092	0.057	0.131
Farmers' participation	0.056	—	0.091

weight are evaluated for each method. It is observed that all 10 combinations fell into two groups of ranking pattern 1, 4, 2, 3 and 1, 3, 2, 4 (in the order of alternatives) for SA and one group 1, 4, 2, 3 in case of DA. Similarly, study is also made with equal weight for each of the criterion. It is found that the ranking pattern is 1, 2, 4, 3 in the case of SA and 1, 1, 1, 1 (tie for all alternatives) in the case of DA. Sensitivity analysis indicated that the rankings of the irrigation subsystems remained essentially the same as far as the first position is concerned. It is thus observed that integration of fuzzy logic with real-world irrigation planning problems is very effective, particularly with multiple experts and in a subjective data environment.

CONCLUSIONS

A decision support system, FUDS, is developed involving two fuzzy multicriteria decision-making methods and applied to an existing irrigation system in Andhra Pradesh, India. It is found that weights of the criteria have a significant effect on the ranking pattern. However, the first position remains unchanged. It is observed that integration of fuzzy logic with real-world irrigation planning problems is very effective, particularly with multiple experts and in a subjective data environment. The fuzzy decision support system, FUDS, is found to be useful due to its interactive nature, flexibility in approach and evolving graphical features and can be adopted for any similar situation to rank alternatives. The present study is limited to four irrigation subsystems due to resource limitations. However, more irrigation subsystems may be studied in a multicriterion context to explore the full potential of FUDS.

ACKNOWLEDGEMENTS

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APPENDIX

Description of similarity measure

Chen (1994) proposed the concept of similarity measure. These are explained in three situations.

Case 1. Similarity measure $S(X,Y)$ between two real values X and Y can be measured as $S(X,Y) = 1 - |X - Y|$ where $S(X,Y) \in (0,1)$. Larger value of $S(X,Y)$ represents higher similarity between X and Y. If $S(X,Y)$ equals 1, it indicates that X and Y are the same.

Case 2. If X and Y are two real intervals in [0, 1], where $X = [x_1, x_2]$ and $Y = [y_1, y_2]$, then

$$S(X,Y) \quad \text{or} \quad S([x_1,x_2],[y_1,y_2]) = 1 - \frac{|x_1 - y_1| + |x_2 - y_2|}{2}$$

Case 3. Similarity measure S (A, R, W) of alternative A with reference to R for a given weight set W ($W = w_1, w_2, \ldots, w_j$) is given as (Chen, 1994)

$$S(A, R, W) = \frac{\sum_{j=1}^{J} [1 - (|y_{aj} - x_j| + |y'_{aj} - x'_j|)/2 * w_j]}{\sum_{j=1}^{J} w_j}$$

where A and R are two real intervals in [0, 1] and represented as

$$A = [y_{a1}, y'_{a1}],\ [y_{a2}, y'_{a2}], \ldots, [y_{aj}, y'_{aj}]$$

$$R = [x_1, x'_1],\ [x_2, x'_2], \ldots, [x_j, x'_j]$$

Sample calculations for similarity analysis (SA)

Calculations of degree of similarity are with reference to Table III using Equation (4). Normalized weights of the six criteria are 0.132, 0.092, 0.056, 0.187, 0.202, 0.331. Substituting values in Table III for irrigation subsystem D_1 and substituting $\sum_{j=1}^{J} w_j = 1$, in Equation (4), the degree of similarity for irrigation subsystem D_1 is computed as follows:

$$\left[1 - \frac{|0.2 - 1.0| + |0.2 - 1.0|}{2}\right] \times 0.132 + \left[1 - \frac{|0.2 - 1.0| + |0.4 - 1.0|}{2}\right] \times 0.092$$
$$+ \left[1 - \frac{|0.8 - 1.0| + |1.0 - 1.0|}{2}\right] \times 0.056 + \left[1 - \frac{|0.8 - 1.0| + |1.0 - 1.0|}{2}\right] \times 0.187$$
$$+ \left[1 - \frac{|0.8 - 1.0| + |1.0 - 1.0|}{2}\right] \times 0.202 + \left[1 - \frac{|0.8 - 1.0| + |1.0 - 1.0|}{2}\right] \times 0.331 = 0.7524$$

Sample calculations for decision analysis (DA)

Calculations of decision measure are based on average values in Table I. $\bar{w}_j = 1 - w_j$ where w_j are weights of six criteria (0.132, 0.092, 0.056, 0.187, 0.202, 0.331); $\bar{w}_j$ values for six criteria are 0.868, 0.908, 0.944, 0.813, 0.798, 0.669.

As per Equation (7):

$$D = (\bar{w}_1 \cup C_1) \cap (\bar{w}_2 \cup C_2) \cap (\bar{w}_3 \cup C_3) \cap (\bar{w}_4 \cup C_4) \cap (\bar{w}_5 \cup C_5) \cap (\bar{w}_6 \cup C_6)$$

Defining dummy variable E_j as

$$E_j = (\bar{w}_j \cup C_j) \tag{8}$$

Equation (8) can be expressed in the membership function form resulting in Equation (9):

$$\mu_{E_j}(a) = \max[\mu_{\bar{w}_j}(a), \mu_{c_j}(a)]$$
$$\mu_{E_j}(a) = \{\max[\mu_{\bar{w}_1}(a), \mu_{c_1}(a)], \max[\mu_{\bar{w}_2}(a), \mu_{c_2}(a)], \max[\mu_{\bar{w}_3}(a), \mu_{c_3}(a)],$$
$$\max[\mu_{\bar{w}_4}(a), \mu_{c_4}(a)], \max[\mu_{\bar{w}_5}(a), \mu_{c_5}(a)], \max[\mu_{\bar{w}_6}(a), \mu_{c_6}(a)]\}$$
$$= [(0.868 \cup 0.2), (0.908 \cup 0.266), (0.944 \cup 0.933), (0.813 \cup 0.933), (0.798 \cup 0.866), (0.669 \cup 0.933)]$$
$$= [(0.868, 0.908, 0.944, 0.933, 0.866, 0.933)]$$

As per Equation (10),

$$\begin{aligned}\mu_D(a^*) &= \min\{\mu_{E_j}(a)\}\\ &= \min\{\mu_{E_1}(a), \mu_{E_2}(a), \ldots, \mu_{E_j}(a)\}\\ &= \min[(0.868, 0.908, 0.944, 0.933, 0.866, 0.933)] = 0.866\end{aligned}$$

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