The Integration of GIS And Fuzzy Multi-Objective Linear Programming - an Interactive Decision Making Tool in Sustainable Use of Agricultural Land

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SUMMARY

GIS and Fuzzy Multi-Objective Linear Programming (Fuzzy MOLP) are combined to solve the multi-optimization problem – economic efficiency, employment, and environment – in agricultural land-use planning. This method is applied to Bao Lam District, Lam Dong province, Viet Nam. First, GIS is used to create a land suitability map for the study area. Next, based on this suitability map to formulate the MOLP with 4 objectives as follows: maximize gross output (Z1), minimize cultivation cost (Z2), maximize employment (Z3) and maximize land cover in order to reduce soil erosion (Z4). The application and its results demonstrate how the method enables decision makers to identify the most suitable land-use alternatives by changing relative weight of each objective before deciding the most appropriate option for Bao Lam District.

TÓM TẮT (Vietnamese language)

GIS kết hợp với fuzzy MOLP được ứng dụng để giải bài toán tối ưu đa mục tiêu - hiệu quả kinh tế, nhu cầu lao động và bảo vệ môi trường - trong bố trí sử dụng đất nông nghiệp. Phương pháp này được ứng dụng cho khu vực huyện Bảo Lâm – tỉnh Lâm Đồng. Trong đó, đầu tiên GIS được ứng dụng để thành lập bản đồ thích nghi đất đai cho khu vực. Tiếp theo trên cơ sở sản phẩm nhận được từ GIS giải bài toán tối ưu đa mục tiêu mờ (fuzzy MOLP) để tìm kiếm giải pháp sử dụng đất thích hợp thoả mãn tối ưu đồng thời 4 mục tiêu: tối đa về giá trị sản xuất, tối thiểu về chi phí, tối đa về nhu cầu sử dụng lao động, tối đa mức độ che phủ nhằm giảm thiểu rửa trôi và xói mòn đất. Kết quả thực hiện cho thấy phương pháp sử dụng có thể giúp người ra quyết định tương tác, lựa chọn được phương án thoả mãn và phù hợp với định hướng phát triển của huyện Bảo Lâm.

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1. INTRODUCTION

Agriculture land allocation is one of the most important aspects in the Agriculture and Rural Planning and Development. Land allocation exercise is based on land use suitability evaluations. When combining the GIS technology and Expert Method to evaluate land use suitability, ones obtain results as presented in table 1.

Table 1: Land suitability of land use types

LMU-ID	LUT_1	LUT_2	…	LUT_n	*Area (supply)*
LMU_1	S_{11}; $[Val_{11}]$; $[X_{11}]$	S_{12}; $[Val_{12}]$; $[X_{12}]$	…	S_{1n}; $[Val_{1n}]$; $[X_{1n}]$	*$[S_1]$*
…			…		...
LMU_m	S_{m1}; $[Val_{m1}]$; $[X_{m1}]$	S_{m2}; $[Val_{m2}]$; $[X_{m2}]$	…	S_{m3}; $[Val_{mn}]$; $[X_{mn}]$	*$[S_{mn}]$*
Area (demand)	*$[S_{LUT1}]$*	*$[S_{LUT2}]$*		*$[S_{LUTn}]$*	

Note, S_{ij}: land suitability; $[Val_{mn}]$: input/output value of LUS_{mn}; $[X_{mn}]$: area of LUS_{mn}

In this table, a Land Mapping Unit (LMU) is an area of land whose characteristic is homogeneous. Let assume the study area has m LMU. A Land Use Type (LUT) is one of the n potential land use categories considered in this model. S_{ij} represents suitability level of an LMU_i for a certain LUT_j. There are four suitability levels: high (S1), moderate (S2), marginal (S3), and not suitable (N).

When a LUT is applied for a certain LMU, it is called a land use system (LUS). Thus, in this model there are (mxn) LUS. Let's call X_{ij} the area of LUS_{ij}. Note that if S_{ij} of LUS_{ij} is "not suitable", then X_{ij} of that LUS_{ij} will be equal to zero. Each LUS_{ij} requires an production input and gives a production output. The input is production costs associated with fertilizers, pesticide, labors, and irrigation. The output could be measured in terms of gross output, or gross margin, income, or cost benefit ratio. In this model, input and output values corresponding to a LUS_{ij} called Val_{ij}.

For demonstration purpose, let consider Bao Lam district of Lam Dong province as the study area. In Bao Lam, if coffee is planted on LMU1, then Suitability level is S2, and *Val* will have the following values: i) gross production output is 61, 600 Million VND per hectare per year;

ii) production cost is 30,190 Million VND per hectare per year, and iii) Labor requirement is 160 man-day per hectare per year.

The question is each particular LUS should occupy how much area, so that the total Land Use in a study area will require the least production cost, deliver highest production output, at the same time meet employment required for local community, and finally minimize negative environmental effect. Thus, agriculture land use allocation is a multi objective optimization problem, which can be solved using different approaches

Single Objective Approach: Up to now, the linear programming model has been applied in a number of land use planning studies (Williams, Daniel G., 1981 [9]; Dyktra, D.P 1984 [2]; Sethi L.N. et al., 2002 [8]). In these studies, the most important objective is optimized, whereas the remaining objectives are treated as constraint conditions. Burke and Kendal [3] in their study (2005) observed that in several cases, this approach did not lead to feasible solution.

Multi Objective Approach: Multi-Objective Linear Programing (MOLP) has also been applied in land use planning studies. This approach treats the multi-objective problem by converting it into single objective optimization, by introducing a set of objective weights (F.B. Abdelaziz, 2007) [5]. Note that decision makers can not determine a satisfying vector of weight right from the beginning. Instead they will interact with the model, modifying the weight vector step by step, until a suitable alternative is established. Therefore, this approach is called interactive method.

Each practice, different objectives are measured in different measurement units. … To overcome this challenge, objectives are represented in a fuzzy form in which each objective function takes a value between 0 to 1. Each objective function indicates the satisfaction of decision maker towards the respective objective. The fuzzy form is closer to intuitive thinking of decision makers, and therefore it is easier for them to select alternatives. The interactive method used in conjunction with fuzzy objectives is called interactive fuzzy satisfying method. According to Sakawa [6], this method is very suitable for MOLP problem.

The current study applies the interactive fuzzy satisfying method to solve the MOLP with sample data of Bao Lam district, Lam Dong province in Vietnam.

2. ALGORITHM OF INTERACTIVE FUZZY SATISFYING METHOD

2.1. Introduction of MOLP: The MOLP is described as follows

The objective function: Max (Min) $Z(x) = (Z_1(x), Z_2(x),\dots Z_k(x))^T$

Subject to: $x \in D = \left\{ x \in R^n \mid Ax \le B, x \ge 0 \right\}$,

In which : + $Z_i(x)$ are objectives, $Z_i(x) = C_i x$; $C_i = (C_{i1}, C_{i2},\dots, C_{in})^T$, $i=1,2,\dots,k$;
+ A is a matrix m x n; B is a matrix 1x m; D is a set of constraints.
+ X are decision variables (area of LUSs).

2.2. The Algorithm

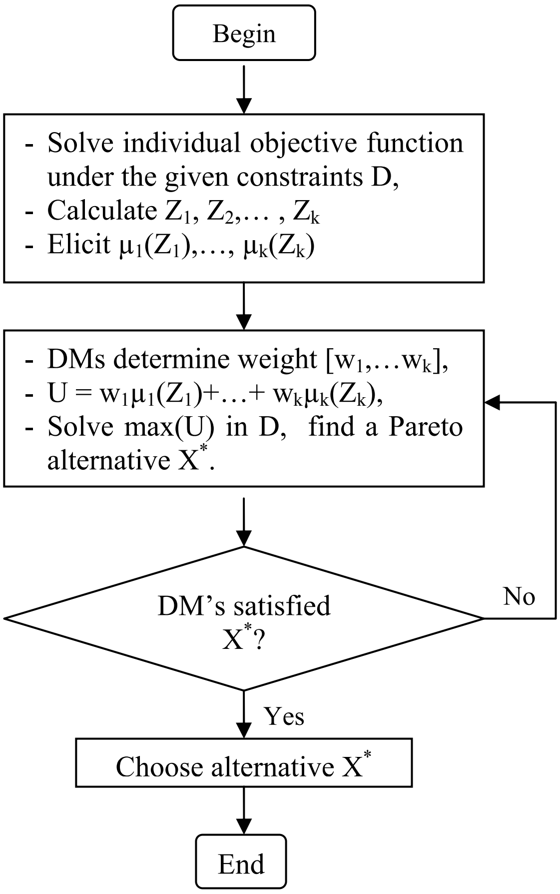

Figure 1: Algorithm of interactive fuzzy satisficing (M.Sakawa, 2002)

The MOLP is solved by the Interactive fuzzy satisficing method with algorithm as figure 1:

(i) Solve individual objective function under the given constraints D; Calculate each objective function (Z_1, ,…, Z_k); To determine membership function for each of the objective functions ($\mu_1(Z_1)$, $\mu_2(Z_2)$,…, $\mu_k(Z_k)$).

(ii) Determine respective priorities of objective functions (a set of weight $[w_1, w_2 \ldots w_k]$).

(iii) Establish an Aggregated objective function:

$$U = w_1\mu_1(z_1) + w_2\mu_2(z_2) + \ldots + w_k\mu_k(z_k) \rightarrow \max$$

(iv) Solve a linear programming U under given constraints D, find a Pareto alternative X^*.

- If DM is not satisfied alternative X^* then return to step (ii).
- If DM is satisfied alternative X^* then choose X^*.

3. APPLICATION OF THE METHOD TO SOLVE AN AGRICULTURAL LAND ALLOCATION PROBLEM

The studied area is Bao Lam District, Lam Dong Province, the central highland of Viet Nam. There are five major Land use types (LUT) for Bao Lam. They are: annual crop (LUT1), mulberry (LUT2), coffee (LUT3), tea (LUT4), fruit trees (LUT5).

Step1: Apply GIS to build a land suitability map of Bao Lam [1] and create a suitability attribute table (table 2).

Table 2: Land suitability of land use types - Bao Lam Dist. –Lam Dong prov. - Vietnam

Suitable Types	LMU (code)	**LUT1** Annual crop	**LUT2** Mulberry	**LUT3** Coffee	**LUT4** Tea	**LUT5** Fruit-tree	Area (ha)	Percent (%)
1	1, 2	S1	S2	S2	S2	S2	8,038	5.5
2	3	S2	S1	S2	S1	S2	6,585	4.5
3	5	N	S1	S3	S2	S3	1,780	1.2
4	6, 7	N	N	S1	S1	S2	5,205	3.6
5	8	N	N	S2	S1	S2	3,217	2.2
6	10	N	N	S2	S2	S3	1,518	1.0
7	15	N	N	S3	S1	S2	1,287	0.9
8	9, 11, 12, 16, 17, 18	N	N	S3	S2	S3	35,905	24.5
9	4, 13, 14, 19, 20, 21, 22, 23, 24	N	N	N	N	N	81,161	55.5
Area of rivers and streams							**1,653**	**1.1**
Area of administrative boundary							**146,349**	**100.0**

Step 2: Formulate a MOLP model for land allocation for Bao Lam

Bao Lam is an agriculture district with agriculture production contributes to 75% of total gross output of the province, of which, contribution from cultivation is 90%. Agriculture labors is 86% of the total labors in the district, whose unoccupied time per year is about 26-28%. This ratio is said to be reduced to 15% by 2015.

Thus, in planning of land use for Bao Lam three issues have to be taken into considerations: increasing economic value, creating more agriculture works, and reducing negative environmental impact. These considerations are converted into four objectives: maximize gross output (Z1), minimize cultivation cost (Z2), maximize labor requirement (Z3), and maximize land cover in order to reduce soil erosion (Z4). From these requirements, the MOLP is formulated as follows:

(1) Establish objective functions:

Assume that:
P_{ij} is the gross output per hectare of LUT_j at suitability zone i,
C_{ij} is the cost for cultivating per hectare of LUT_j at suitability zone i,
L_{ij} is the labor requirement per hectare of LUT_j at suitability zone i,

Maximize gross output objective (Z1): $\sum_{i=1}^{9}\sum_{j=1}^{5} P_{ij}X_{ij} \rightarrow \max$

Minimize cultivation cost objective (Z2): $\sum_{i=1}^{9}\sum_{j=1}^{5} C_{ij}X_{ij} \rightarrow \min$

Maximize employment objective (Z3): $\sum_{i=1}^{9}\sum_{j=1}^{5} L_{ij}X_{ij} \rightarrow \max$

Maximize land cover objective (Z4): $\sum_{i=1}^{9}\sum_{j=3}^{5} X_{ij} \rightarrow \max$

Values of the parameters P, C and L corresponding to each LUT at a given S are provided in the table 3.

Table 3: Parameters of economic returns and labor requirement of LUTs

Suitability classes	**LUT1** Annual crop	**LUT2** Mulberry	**LUT3** Coffee	**LUT4** Tea	**LUT5** Fruit-tree
Return on farm (million VND/ha/year) – P parameter					
S1	20.300	26.400	77.000	39.595	
S2	17.420	21.560	61.600	30.240	21.948
S3	13.800	18.040	48.400	22.330	16.330
Cultivation cost (million VND/ha/year) – C parameter					
S1	11.571	13.429	39.270	14.560	
S2	10.600	11.025	30.190	12.870	8.796
S3	7.100	11.970	26.620	11.055	7.080
Labor requirement (labor day/ha/year) – L parameter					
S1	250	300	155	350	
S2	263	315	163	368	160
S3	276	331	171	386	180

Source: Sub-National Institute for Agricultural Planning and Projection (2008)

(2) Establish resources constraints functions:

X_{ij} is the decision variable which demonstrates the area of LUT_j at suitability zone i.

Total area of suitability zone 1: $\sum_{j=1}^{5} X_{ij} \le 8038, i = 1;$ (show on table 2 above). For other suitability zone, constraints are:

$$\sum_{j=1}^{5} X_{ij} \le 6.585, i = 2; \quad \sum_{j=1}^{5} X_{ij} \le 1780, i = 3; \quad \sum_{j=1}^{5} X_{ij} \le 5205, i = 4; \quad \sum_{j=1}^{5} X_{ij} \le 3217, i = 5;$$

$$\sum_{j=1}^{5} X_{ij} \le 1518, i = 6; \quad \sum_{j=1}^{5} X_{ij} \le 1287, i = 7; \quad \sum_{j=1}^{5} X_{ij} \le 35905, i = 8; \quad \sum_{j=1}^{5} X_{ij} \le 81161, i = 9;$$

Step 3: Solve the MOLP, following the algorithm of figure 1

The algorithm of interactive fuzzy satisficing is applied to solve MOLP, the process is shown in figure 1.

(i). Run the linear programming for each objective function to determine its respective membership function
LINGO application software is used, and the results are presented in table 4.

Table 4: The individual value of each objective function

Objective function	Gross output (Mill. VND/ha)	Cultivation cost (Mill. VND/ha)	Labor requirement (labor day/ha)	Land cover (ha)
Z1: Maximize gross output	2.991.741	1.483.190	13.653.916	63.535
Z2: Minimize cultivation cost	2.037.230	998.544	14.626.164	49.801
Z3: Maximize employment	2.147.377	1.067.386	15.861.074	49.535
Z4: Maximize land cover	2.721.651	1.319.175	14.244.156	63.535

In the fuzzy environment, the objective functions express the degree of satisfaction of the decision makers, with membership function as below :

$$\mu_1(Z_1) = \frac{Z_1 - 2{,}037{,}230}{2{,}991{,}741 - 2{,}037{,}230} = \frac{Z_1 - 2{,}037{,}230}{954{,}511}$$

$$\mu_2(Z_2) = \frac{1{,}483{,}190 - Z_2}{1{,}483{,}190 - 998{,}544} = \frac{1{,}483{,}190 - Z_2}{484{,}646}$$

$$\mu_3(Z_3) = \frac{Z_3 - 13{,}653{,}916}{15{,}861{,}074 - 13{,}653{,}916} = \frac{Z_3 - 13{,}653{,}916}{2{,}207{,}158}$$

$$\mu_4(Z_4) = \frac{Z_4 - 49{,}535}{63{,}535 - 49{,}535} = \frac{Z_4 - 49{,}535}{14{,}000}$$

(ii) Determine priority level of each objective function:

Often, decision makers change the set of weights of objective functions until they arrive at an satisfaction set. In cases where decision makers can not decide a desired set of weights, the Analytical Hierarchy Process technique (Satty, 1980) can be applied to support decision makers.

(iii). Establish an aggregated objective function:

$$U = w_1\mu_1(Z_1) + w_2\mu_2(Z_2) + w_3\mu_3(Z_3) + w_4\mu_4(Z_4) \rightarrow \max \ (*)$$

$$(*) \Leftrightarrow \; w_1 \times \frac{Z_1}{954{,}511} - w_2 \times \frac{Z_2}{484{,}646} + w_3 \times \frac{Z_3}{2{,}207{,}158} + w_4 \times \frac{Z_4}{14{,}000}$$

$$- w_1 \times \frac{2{,}037{,}230}{954{,}511} + w_2 \times \frac{1{,}483{,}190}{484{,}646} - w_3 \times \frac{13{,}653{,}916}{2{,}207{,}158} - w_4 \times \frac{49{,}535}{14{,}000} \to \max$$

$$\Leftrightarrow \; w_1 \times \frac{Z_1}{954{,}511} - w_2 \times \frac{Z_2}{484{,}646} + w_3 \times \frac{Z_3}{2{,}207{,}158} + w_4 \times \frac{Z_4}{14{,}000} \to \max \;\; (**)$$

In which, w_1, w_2, w_3, w_4 are weights of objectives Z1, Z2, Z3, Z4 respectively

Thus, the original MOLP problem is now equivalent to the ** problem, which subject to the same set of original constraints. ** problem is a linear programming problem, which then again can be solved easily by LINGO Software.

(iv) Solve the problem

From development viewpoint, the highest priority is given to economic development, as long as the proposed solution will meet social requirement and minimize negative impact on the overall environment. As a result, there are two scenarios to be considered:

Scenario 1 (Most preferred): Economic> Social> Environment
Scenario 2: Economic>Environment> Social

In which, economic consideration has two objectives: Z1 and Z2; social consideration has one objective Z3, and environmental consideration has Z4

To obtain all possible solutions of an MOLP problem will take a lot of time, especially where the MOLP handles many objectives (M Sakawa, 2002 [6]). By allowing decision makers to interact with the model, the most satisfied solution could be obtained much quicker, in some cases, just after few iterations of the process.

The principle to determine a set of weights is defined as follows

For scenario 1: $w_1 \geq w_2 \geq w_3 \geq w_4$
For scenario 2: $w_1 \geq w_2 \geq w_4 \geq w_3$

Besides the alternative of balance of weights, i.e. $w_1 = w_2 = w_3 = w_4 = 0.25$, the other alternatives will be considered, in which the value of each w will be changed by $\lambda=0.1$. In all considered alternatives, value of any w is always larger than 0.

Thus, all alternatives of weight sets are determined and given in table 5. By substituting each alternative of weight set into the ** problem, then run the ** problem using LINGO Software. Finally one can obtain the value of the aggregated objective function U and its respective membership functions for the said objectives, which are presented in table 5.

Table 5: The scenarios and alternatives of land use

Scenarios	Alternatives	Set of weight				U	Membership function			
		W_1	W_2	W_3	W_4	(*)	$\mu(Z_1)$	$\mu(Z_2)$	$\mu(Z_3)$	$\mu(Z_4)$
	Objectives	1				1.000	1.000	0.000	0.000	1.000
			1			1.000	0.000	1.000	0.440	0.019
				1		1.000	0.115	0.858	1.000	0.000
					1	1.000	0.717	0.338	0.267	1.000
	balance	0.250	0.250	0.250	0.250	0.560	0.459	0.573	0.544	0.663
Scenario 1	1	0.300	0.300	0.200	0.200	0.575	0.660	0.404	0.279	1.000
	2	0.300	0.300	0.300	0.100	0.598	0.065	0.947	0.981	0.000
	3	0.400	0.400	0.100	0.100	0.558	0.623	0.457	0.385	0.873
	4	0.400	0.300	0.200	0.100	0.562	0.635	0.427	0.542	0.714
	5	0.400	0.200	0.200	0.200	0.568	0.560	0.498	0.336	0.886
	6	0.500	0.300	0.100	0.100	0.497	0.446	0.549	0.383	0.714
	7	0.500	0.200	0.200	0.100	0.587	0.662	0.397	0.525	0.714
	8	0.600	0.200	0.100	0.100	0.603	0.663	0.400	0.478	0.747
	9	**0.700**	**0.100**	**0.100**	**0.100**	**0.629**	**0.663**	**0.400**	**0.498**	**0.747**
Scenario 2	**10**	**0.300**	**0.300**	**0.100**	**0.300**	**0.598**	**0.549**	**0.527**	**0.506**	**0.748**
	11	0.400	0.300	0.100	0.200	0.576	0.615	0.447	0.466	0.748
	12	0.500	0.200	0.100	0.100	0.536	0.663	0.400	0.498	0.747

(*) u is an aggregated objective function

Step 4: *Analysis to identify the most satisfied solution*

Looking at the table 5, one could easily see that:

- Scenario 1 has 9 alternatives, from 1 to 9, of which alterative 9 brings the highest value of U, which is 0.629.
- Scenario 2 has 3 alternatives, from 10 to 12, of which alternative 10 gives the highest value of U, which is 0.598.

It is clear that U10 is less than U9. However membership function of all objectives of alternative 10 are larger than 50% of expected value (μ(Z1)=0.549, μ(Z2)=0.527, μ(Z3)=0.506, μ(Z4)=0.748). Where as two membership functions of alternative 9 are less than 50% of expected values (μ(Z2)=0.400), μ(Z3)=0.498).

Therefore, alternative 10 is the most satisfied alternative and is selected as the solution for the land use planning problem of Bao Lam. Specific land allocation following alternative 10 are given in table 6.

- Area of annual crop is 1,525 hectares allocated on suitability type 1.
- Area of mulberry is 4,000 hectares allocated on suitability type 1: 2,220 hectares, on suitability type 3: 1,780 hectares.

- Area of coffee is 28,000ha allocated on suitability type 1: 4,283 hectares, on suitability type 2: 6,585 hectares, on suitability type 5: 3,217 hectares, on suitability type 6: 12,397 hectares.
- Area of tea is 18,000 hectares allocated on suitability type 4: 4,283 hectares, on suitability type 7: 1,287 hectares, on suitability type 8: 11,508 hectares.
- Area of fruit-tree is 12,000 hectares allocated on suitability type 8.

Table 6: Land allocation of chosen alternative (alternative 10)

Suitability Type	LUT1 Annual crop	LUT2 Mulberry	LUT3 Coffee	LUT4 Tea	LUT5 Fruit-tree	Area (ha)
1	1,535	2,220	4,283			8,038
2			6,585			6,585
3		1,780				1,780
4				5,205		5,205
5			3,217			3,217
6			1,518			1,518
7				1,287		1,287
8			12,397	11,508	12,000	35,905
9	Non-agriculture land					81,161
Total of alt.10	1,535	4,000	28,000	18,000	12,000	
Area of rivers and streams						1,653
Area of administrative boundary						146,349

4. CONCLUSION

To determine best agriculture land distribution for a studied area, an integrated model method is introduced. GIS is used to create suitability input data for a multi objective linear programming, LINGO is used to solve linear planning problems, and AHP to determine relevant set of weights of the considered objectives. The multi-objective problem is converted into a linear programming problem by using the algorithm of interactive fuzzy satisfying method.

The integrated method enables direct interactions with decision makers in the process of determining the best desirable set of relative weights of the considered objectives. In this way, development viewpoint of the government as well as preference of local farmers are taken into consideration. As a result of this, the land distribution solution obtained from the model was very well received by the decision makers of the studied district, which in turn will guarantee the application of the solution.

GIS is a useful technique for spatial analysis including building land resources database, analyzing land suitability and visually supporting decision makers in land distribution. Integration of the Fuzzy MOLP with GIS supports decision makers to generate several good options that meet multiple objectives in land distributing, before arriving at the best option that most satisfied the decision makers.

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