LAND USE PLANNING FOR THE SAN TIBURCIO WATERSHED

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ABSTRACT

Land use planning, within the context of socio-economic development, is characterized by many conflicting objectives. This paper defines ojectives for the San Tiburcio watershed in northern Mexico. A mixed multiobjective programming model is developed. The model serves as an aid to a group of decision makers in choosing a "satisficing" feasible set of non-mutually exclusive land use alternatives. The paper concludes with a discussion of possible solution techniques.

INTRODUCTION

Land use planning has been of interest to both practitioners and researchers for many years. Recently, the use of quantitative models has become widespread. Utility theory (Edwards, 1977), simulation (Baur and Wegener, 1975), and optimization methods (Goicoechea, 1977; Nijkamp and Rietveld, 1978, and Bamni and Bamni, 1979) have been used to aid land use planners. Multiobjective models seem particularly appealing since many of the goals of land use planning are incommensurate and conflicting.

This paper discusses a multiobjective mixed-integer programming (MMIP) model that will provide insight for land use planning in the San Tiburcio watershed. This region is located in the state of Zacatecas, Mexico and is a rural area. Currently, the area is not well developed and lacks much of the infrastructure normally assumed to exist in land use planning studies. Therefore, land use planning must be considered within the framework of a total regional development program. While this paper does not explictly discuss the development program for the region, the land use alternatives are compatible with the development goals and in some cases projects considered have impact beyond the specific land use.

The paper contains a description of the San Tiburcio watershed and a discussion of its land use problems, which provides a decision scenario for the study. This is followed by a group assessment procedure, which gives the value structure for the MMIP land use planning model. Preliminary solution results and future plans for the model are discussed.

DECISION SCENARIO

CHARACTERISTICS OF THE SAN TIBURCIO WATERSHED

The characteristics of the region have been well documented (Medina, 1978). This section will summarize those characteristics.

The San Tiburcio Watershed lies in the northeast corner of the state of Zacatecas in the north of Mexico, comprising approximately 1500 square kilometers. It is located in the Chihuahuan Desert with an elevation ranging from 1700 meters above mean sea level in the bottomlands to 2500 meters in the mountains. On the basis of a five-year record, the mean annual temperature is about 12°C; mean annual evaporation is 2100 millimeters and the mean annual precipitation occurs in a few individual rainfall events during the summer season. In addition to this, the area suffers from a short

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drought period in the middle of the summer, known as the August or Intraestival drought. The distinctive feature of this period is a striking decrease in the number of rainy days, which accounts for a drastic diminution in the amount of precipitation. The maximum yearly temperatures occur during this time, which combined with the low moisture conditions, makes this part of the year a critical one for all agricultural activities of the peasants. Erratic rainfall, short growing season, and shallow and saline soils, have resulted in highly uncertain conditions for the entire range of agricultural activities. The net effects are low and unstable crop yields, total loss of crops in three out of five years, abandomnent of farming parcels, highly erodable soils and frequent floodings. The risk inherent in these factors results in a reduction of income, which for the total rural population averages three U.S. dollars per capita per month, with a range between one and five U.S. dollars.

The region suffers from an increasing demographic pressure. This situation tends to persist and is resulting in a highly pernicious phenomenon that is detrimental to the social and economic development of people: the "minifundia" (Manzanilla, 1969). Here small holdings of less than five hectares per family are used for farming and combined with seasonal part-time labor market activities such as the extracting and selling of native fruits, fiber, wax and other natural products.

The labor structure is traditionally of an agricultural-pastoral-native products-gathering nature. About 90% of the economically active population is engaged in primary activities, generally for local consumption. Therefore it is difficult for the tenants to accumulate working capital for husbandry improvements or to finance repairs.

The region's infrastructure exhibits an overall deficiency in such aspects as roads, communications, electricity, health centers, schools, hospitals and potable water. For example, the educational level of the people is as follows: no single householder have attended secondary school; only 5% have finished elementary school and 44% have no formal education at all.

Villages and rural communities are widely scattered and most have small populations. The access to these small communities is through unpave roads that are almost impassable during the rainy season. In 1970 the total population resided in 21 towns or cities with the following distribution: 62% had less than 100 inhabitants, 27% with 100-500 people and 11% with more than 500 people. This situation becomes a factor that limits the introduction of the basic public services within reasonable costs. This factor, coupled with the low productivity of land, accounts to a large degree for the unfavorable commericalization of products, high prices of basic food items, and monopolization of produced goods. Moreover, in most instances the local villages present a internal duality with respect to production. On the one hand, a small number of landholders monopolize most of the local resources, and by exerting economic pressure on the least affluent tenants, control the local economy. On the other hand, most of the people have small choice in farming systems and are customarily engaged in operations that produce low outputs per hectare, such as goat and cattle raising and gathering native plants.

Maize and beans comprise 95% of the crops. To a lesser extent, and dependent on the year's climatic conditions, wheat, barley, and vegetables are planted. Normally, seeds used for planting are "creole" seeds, i.e., seeds harvested and stored from previous years. In general, mineral fertilizers are not used, natural fertilizers are used on only few parcels.

Land tenure is also a problem in the San Tiburcio watershed. The lands in the region are either privately owned or are ejidos. The ejidos, accounting for 87% of the land area, are collectively owned lands which are subdivided and operated on an individual basis. This creates a diversity of land usage within a small area. The work will be directed towards ejido lands with the hope of initiating negotiations for better use of these lands.

INSTITUTIONAL SETTING

There are three major agencies involved with the development, and hence land use planning, of the San Tiburcio watershed. They are Secretaria de Programacion y Presupuesto (SSP), Secretaria de Agricultura y Recursos Hidraulicos (SARH) and the Comision Nacional de Zonas Aridas (CONAZA). Through a specific research and development agreement, the Universidad Antonoma Agraria "Antonio Narro" (UAAAN) has been designated the coordinating institution in the structuring of the San Tiburcio development program. UAAAN has operated an experimental station in the region for the past six years and collected extensive data on potential impact of various land use alternatives.

Due to the complexity of the issues and the multiplicity of the agencies and people involved, it was deemed necessary to explicitly state the underlying basis for any decision making criteria. Thus a multidisciplinary group was formed which will provide a first-level value structure. Using this value structure in conjunction with the MMIP land use model, UAAAN will develop a set of potential land use alternatives to present to a second-level decision body. This body, composed of government officials, will then choose the course of action to be pursued in the development of the San Tiburcio watershed.

DECISION REQUIREMENTS

The preceding discussion of the characteristics of the region and the institutional setting highlight certain requirements and/or restrictions placed on the decision framework. They can be summarized as follows:

1. both factual and subjective information must be considered,
2. several levels of decision making exits,
3. high natural uncertainty exists,
4. existing conditions limit the range of alternatives,
5. community participation is desirable, but difficult due to educational levels, location, etc.,
6. ecological interdependence among units within the watershed is high.

DEFINITION OF TERMS

In the development of following sections it will be necessary to define the following terms:

Objective - In general, it will indicate a "direction" which results in "improvement" (Keeney and Raiffa, 1976).

Goal - A specific point in the "direction" of an objective; its achievement is binary, either it is or it is not achieved.

Attribute - Given by the physical or physiological characteristics identifiable with the alternatives under consideration. The attributes can be viewed as means or information sources available to the decision maker for formulating and achieving desired objectives (Starr and Zeleny, 1977).

Criterion - Standard upon which a judgment is based; it implies some measurement and/or scale.

Project - Indivisible element that compirses the alternative set for the decision making task. Note that the projects are not necessarily mutually exclusive.

Program - A subset of the set of projects that satisfies the set of constraints and contributes in the largest extent to the fulfillment of some overt objectives.

In the context of land use planning a project represents a land use alternative. For example, a project might be to plant maize. In this case the decision would entail not only whether or not to undertake the activity, but also at what level it will be operated. Other projects, such as constructing a water catchment, may only involve a go-no-go decision. A program then would be a particular land use plan for the region.

GROUP DECISION MAKING

The structuring of a development program is viewed as a closed loop procedure requiring the selection of projects which emphasize a particular area of concern. A group of experts is responsible for ascertaining a set of objectives, establishing the project relationships, and providing the value structure on which the selection procedure is based. In this sense, the present work strives to set up a framework in which land use planning becomes one aspect in the process of structuring a development plan for a rural community in Mexico. The next sections deal mostly with the group organization, task, and assessment procedure under this general framework.

CHARACTERISTICS OF THE GROUP

Within the context of the overall problem, the actual decision making transactions constitute only one activity among several others which are required of the group. Hence, it is more appropriate to speak of a multidisciplinary group whose aim is to define objectives, resolve conflicting viewpoints and confront technical problems. The presence of mutual influence between group members through open and direct communication distinguishes this approach from other procedures used to extract factual or subjective information.

Current research is yielding support for the assertion that cooperative task group processes generate a greater collective and member performance, than their competitive counterpart (Dailey, 1978). Among the factors which contribute more notably to the group's behavior, the literature mentions group size, cohesiveness, task certainty, and task interdependence (O'Keefe, et al, 1975: Wallmark, et al, 1973). Since group size has been shown to be negatively related to satisfaction, level of agreement, and personal involvement (Hackman, et al, 1970; Daily, 1978), it is consistent with the stated requirements to contemplate the structuring of this group with no more than fifteen members. However, care must be taken in the structuring process to include the necessary skills and expertise demanded by the problem.

The importance of the task characteristic and its impact on the group process has been pointed out by several researchers (Frank, 1971: Dailey, 1978). In addition, task interdepencence pertains to the dependencies among group members to perform their individual jobs. It should be pointed out that task interdependence is related to the organization and structuring of the group transactions, hence it is an integral part of the planning stage.

Basically, the tasks assigned to the group can be grouped into two categories: problem definition activities and decision making transactions. In the first case, the specific output sought is a hierarchy of objectives along with a set of measures of effectiveness. The set of measures of effectiveness (or attributes) will be required to satisfy certain conditions that would insure the existence of an assessable utility function (Keeney and Raiffa, 1976). The culmination of the decision making transaction is the statement of a group utility function for the set of attributes defined previously. A period of feedback between the model's output and the actual group preference is also desirable.

A preliminary inquire into the hierarchy of objectives applicable to the San Tiburcio Watershed have provided a tentative structure which is being applied to the land use alternative case (Figure 1).

GROUP VALUE STRUCTURE ASSESSMENT

Group decision making has neither a well developed theory, nor enough applications to enable the extraction of guidelines regarding implementability of utility models (Sheridan & Sicherman, 1976· Keeney & Raiffa, 1976). The main thrust lies in the inadequacy of utility aggregation models which are reliant on interpersonal comparison of utilities. Although it is evident that such comparisons are often made as Horsanyj (1974) points out, their subtleness is difficult to quantify. Edwards (1977) stresses that any utility assessment scheme must consider the actual behavior observed in the decision making process. Hence, if the assessment framework is too unlike that which decision maker is accustomed, it will introduce unnecessary bias into the group response.

In order to avoid the utility aggregation problem, Kryzsztofowicz (1978) has proposed an alternative scheme which as proven successful in dealing with real time reservoir control problems. Although it is premature to claim real life success, the proposed procedure does seem to circumvent some of the shortcomings of other schemes. It is interesting to note that the requirements imposed by the complex nature of the present problem make it the ideal proving ground for such an assessment scheme. The assessment process proceeds as follows:

Step 1: The group makes a decision in relation to regrouping its members into subgroups or committees.

Step 2: Each subgroup assesses its own utility function and determines its own decision role.

Step 3: The whole group must establish its tradeoff coefficients among the attributes.

Two assumptions are critical in the above procedure:

a. the group acceptance of the subgroup utility functions as their own, and

b. each group member accepts the Von Newman-Morgenstern (1947) utility axioms (or any other equivalent set of axioms that insure a weak order on a set).

Each group and subgroup must determine its own decision rules. An arbitrary but desirable decision rule has been adopted as part of the group structure. In the case of a dichotomous situation a majority voting rule is adopted and a median rule is used when the situations are related to the value of a continuous variable. The entire group transactions include a predecision stage, an interchange of points of views stage, and a final decision.

LAND USE PLANNING MODEL

The approach taken in this paper is to develop a multiobjective optimization model for land use planning. This approach is quite common in the literature (Bamni and Bamni, 1979; Barber, 1976; Etushenko and Mackinnon, 1976 Nijkamp and Rietveld, 1978.) The model developed in this paper differs from most previous models in that integer valued variables are included. These variables must be included since certain infrastructural projects are prerequisites for carrying out particular land use alternatives.

Mathematically, the problem can be stated as follows:

$$\text{v.max} \quad \sum_{j=1}^{n} f_i(x_j) + \sum_{j=1}^{m} c_{ig} y_j \qquad i=1,2,\ldots,p \qquad (1)$$

$$\text{s.t.} \quad \sum_{j=1}^{n} a_{ij} x_j + \sum_{j=1}^{n} a^1_{ij} y_j \leq b_i \qquad i=1,2,\ldots,q \qquad (2)$$

$$\sum_{j \varepsilon} y_j \leq 1 \qquad \forall_{i \varepsilon} T \qquad (3)$$

$$y_i - y_j \leq 0 \qquad \forall (i,j) \varepsilon \bar{C} \qquad (4)$$

$$y_i - y_j = 0 \qquad \forall (i,j) \varepsilon SC \qquad (5)$$

$$y_i + y_j + y_k \leq 1 \quad \forall (i,j,k) \varepsilon \bar{C} \qquad (6)$$

$$L_i y_j \leq x_j \leq M_i y_j \qquad \forall j \varepsilon E \qquad (7)$$

$$x_j \geq 0 \qquad j=1,2,\ldots,n \qquad (8)$$

$$y_j \varepsilon \{0,1\} \qquad j=1,2,\ldots,m \qquad (9)$$

The variables, objectives and constraints for this formulation will now be discussed in some detail.

VARIABLES

There are two types of variables considered in this model, continuous variables (x_i) and integer variables (y_i). Each variable is associated with a project. Projects are either land use alternatives or infrastructural industrial projects which must be done before certain land use alternatives are feasible or economically viable. A list of variables used in the model is given in Table 1.

OBJECTIVES

The land use planning model has three proxy objectives, economic return, social benefit and environmental impact.

The proxy objectives can be derived by use of a subset of the attributes of Figure 1. The attributes actually used for the land use olanning objectives are

α_1 - total cost, oroperly discounted ($).

α_2 - total revenue, properly discounted ($).

α_3 - employment level (man-days)

α_4 - community acceptance (per cent)

α_5 - ecological impact (change in carrying capacity).

Calculation of α_1, α_2 and α_3 are striaghtforward for a given project. The values for α_4 may be obtained from questionnaires or interviews. Finally, values of α_5 can be found by using regression techniques or available empirical data.

The proxy objectives can then be derived from the attributes. Economic return can be expressed as the difference of return and cost. In order to determine social benefit, a utility function assessment over α_3 and α_4 using the group utility procedure previously outlined must be carried out. For the purposes of this study, ecological impact will be represented exclusively by the change in carrying capacity of the land. With the possible exception of the portion of the social benefit objective associated with the continuous variables, all objectives are linear in the decision variables. The social benefit utility function will be linear if the subgroups have linear utility functions and the entire group is risk-neutral. If not, additiona zero-one variables can be added and a piecewise-linear aoproximation can be used.

CONSTRAINTS

The constraints of the land use planning model can be considered to be either resource constraints or logical constraints. Examples of resource constraints (constraints (2) in the model formulation) include a limited budqet and limitations of certain tyoes of land suited for oarticular land use alternatives. Logical constraints ((3)-(9)) insure that certain logical conditions must be met. Constraints (3) represent mutually exclusive projects, for example projects for water delivery to the greenhouse from wells or from a run-off catchment are mutually exclusive. Constraints (4) and (5) represent (strict) contingency relations between projects. An example of this would be wells and water distribution. It would be useless to build a watering distribution system without first drilling a well. Other constraints may represent complementary relations: that is doing two projects together may have an effect different than if the projects were done separately. Constraints (6) handle this case. An example might be road construction and processing of goat cheese. Each project has certain characteristics independently of the other, but if both are implemental, new markets are opened up and the impact is greater. Constraints (7) have several purposes. They enforce thresholds, account for economies of scale, and provide the mechanism for handling piecewise linear objectives. An example of this case would be that yucca fiber transformation can take olace only if a processing plant is to be built. Finally, the constraints (8) and (9) required levels to be non-negative and certain projects to be done or not done.

For the sake of brevity the entire formulation is not presented in this paper. The prototype problem has more than fifty variables (including slacks and artificials), seventy constraints, and three objectives.

SOLUTION APPROACH

There are three approaches normally taken in solving multiobjective optimization models such as the one discussed in this paper. They are goal oroqramming, utility approaches, and vector maximization. Goal programming has been widely used (Lee, 1972; Lee and Moore, 1977; Daver and Krueger, 1977; and Bussey, 1978) but has certain drawbacks. For objectives expressed as utilities, such as social benefit, it is very hard to set meaningful goals. In addition, weights must be chosen a priori for the different objectives, which may also prove a difficult task. Utility approaches suffer from a similar difficulty: determining a utility function over the different objectives. Explicitly determining such a utility function requires much time and effort on the decision maker (Edward 1977; Farquhar, 1977) and when decisions are made by a group, as in this case, the problem is magnified. Imolicit derivations of the utility function are also possible through interactive solution procedures. Vector maximization (Geoffrion, 1967; Kornbluth, 1972; Zeleny, 1974) is an attempt to generate all non-dominated (or efficient) solutions, and is usually computationally intractable.

Initial attempts to solve the prototype problem by use of an explicit utility function have not been promising. The particular decision structure seems to necessitate explicit tradeoffs at the second level. Thus, the solution approach will be to generate some subset of the efficient solutions. Previous work (Bitran, 1978; Zionts, 1978; Villarreal and Darwin, 1978; Banker et al., 1978) indicates that generating the entire efficient set for multiobjective mixed integer problems of reasonable size may be beyond the capabilities of existing algorithms and computers. For example, the largest problem solved by Banker et al. (1978) has nine variables, seven constraints and four objectives. The algorithm used was, for this problem only twice as efficient as total enumeration.

The authors are currently working on an heuristic for this problem, which will generate a subset of the efficient set. Controlled enumeration over the feasible region examining all objectives simultaneously will form the basis of the algorithm. Of course, the quality of fathoming rules will determine how well the solutions generated appeal to the second level decision makers.

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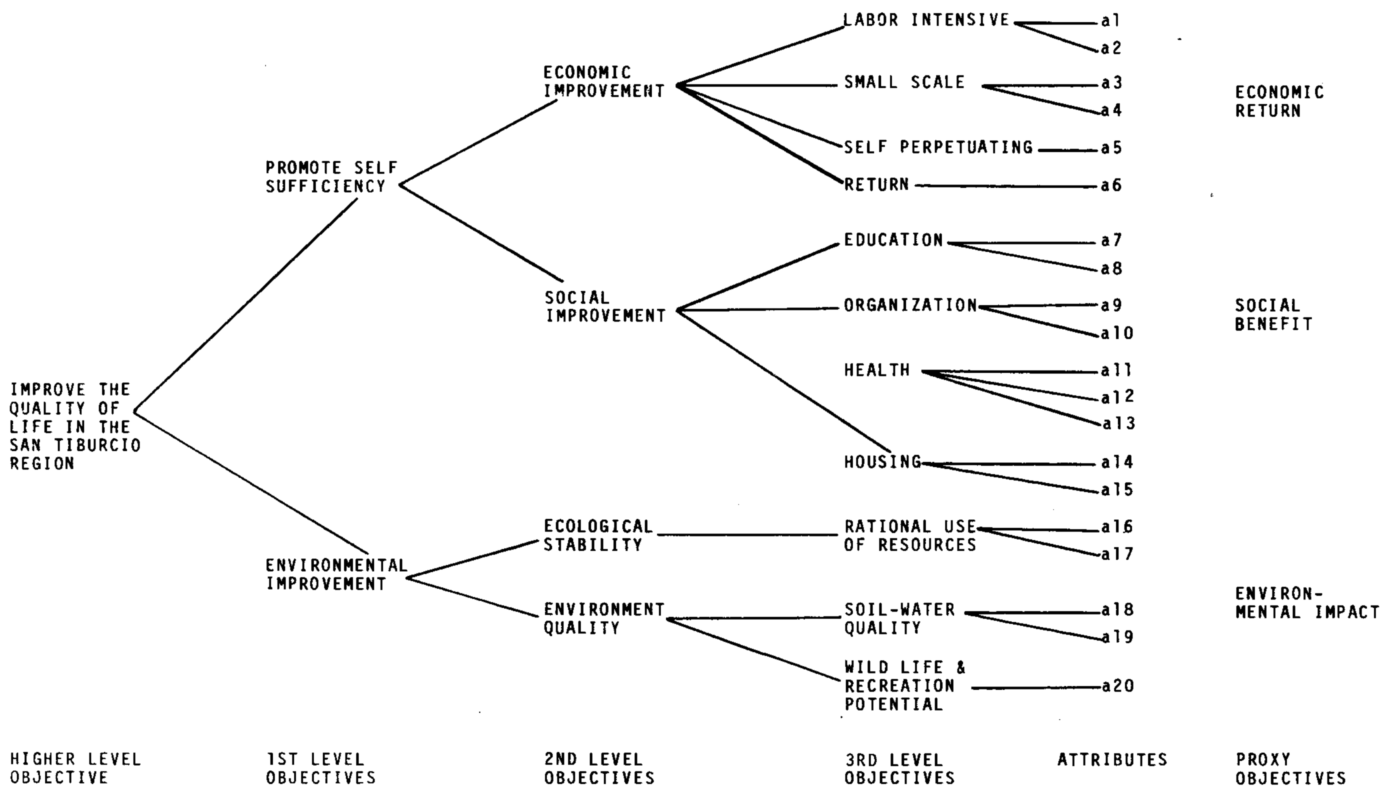

FIGURE 1. HIERARCHY OF OBJECTIVES

DECISION VARIABLE		DECISION VARIABLE	
x_1	Agricultural-NRM: Rest and shrub control the halophyte shrubland.	x_{20}	Industrial-Guayole production level (kgs of rubber).
x_2	Agricultural-NRM: Rest only the Halophyte shrubland (H.S.)	x_{21}	Industrial-Goat milk benefiting (Lts).
x_3	Agricultural-NRM: Rest only the Halophyte grassland (H.G.)	x_{22}	Industrial-Yucca fiber transformation.
x_4	Agricultural-NRM: Do nothing new to the H.G. unit.	x_{23}	Industrial-Agave fiber.
x_5	Agricultural-EC: Rainfed cropland of corn.	x_{24}	Industrial-Opuntia food distribution level.
x_6	Agricultural-EC: Run-off/supplemented corn cropland	y_1	Agricultural-C: Greenhouse
x_7	Agricultural-EC: Rainfed bean cropland.	y_{1w}	Infrastructural-W: Water-run-off structure for watering points.
x_8	Agricultural-EC: Run-off/supplemented bean cropland.	y_{2g}	Infrastructural-W: Well perforation for greenhouse and community consumption.
x_9	Agricultural-EC: Opuntia plantation in L-F unit 1.	y_{2w}	Infrastructural-W: Well perforation and extracting units for watering points.
x_{10}	Agricultural-NRM: Manual shrub control to the L-F unit.	y_2	Infrastructural-L-W: Watering units.
x_{11}	Agricultural-NRM: Range reseeding the L-F unit.	y_{3b}	Industrial-Goal milk by-products.
x_{12}	Agricultural-NRM: Selective shrub control Y-O unit	y_4	Industrial-small scale guayole plant.
x_{13}	Agricultural-NRM: Rest only the Y-O unit.	y_5	Industrial-Yucca and agave textile facility
x_{14}	Agricultural-NRM: Semimechanical shrub control y-O unit (selective)	y_6	Industrial-Opuntia food and candy
x_{15}	Agricultural-NRM: Mechanical shrub control Y-O unit (selective).	y_7	Infrastructural - Roak construction to industrial installations.
x_{16}	Agricultrual-NRM: Total shrub control y-O unit.	y_8	Infrastructural-Fencing
x_{17}	Agricultural-NRM: Range reseeding & water suoplemented the L-F unit.		
x_{18}	Agricultural-P: Animal units year of goats (AUYG)		
x_{19}	Agricultural-P: Animal units year of cows (AUYC)		

Table 1. Decision Variables under consideration for the land-use planning preliminary phase.