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Multiple-use land planning and conflict resolution by multiple objective linear programming

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Abstract: We report a study for the U.S. Bureau of Land Management, spanning several years, to match production objectives with management activities, constrained by resource limits, budget, and policies. To handle the unique problem features, we evolved a new variant of multi-objective optimization. The effort included the development of special solution software, augmented to include interactive and analysis capabilities. Our methodology was applied to planning units comprising approximately 145 000 acres, uncovering potential improvements in the BLM's planning system and demonstrating that the issue of conflict resolution in the agency's planning operations can be effectively handled.

Keywords: Multiobjective optimization, software, interactive, planning, goal programming, vector maximization

1. Introduction

Multiple-use land planning is a problem that constantly confronts the planners and managers of our public land. The problem is essentially one of conflict between different uses for limited land where the conflict is caused by unacceptable interactions between land uses.

The broad objective for a multiple-use plan is to bring about a pattern of land use which maximizes net social benefit. The Federal Land Policy and Management Act of 1976 defines the term multiple use as "the management of the public lands and their various resource values so that they are utilized in the combination that will best meet the present and future needs of the American people".

In more specific terms, multiple-use land planning can be viewed as matching a set of production objectives with a set of management activities, constrained by physical resource capabilities, budget, and policies.

This paper reports a study of this problem that the authors undertook for the Bureau of Land Management (BLM). To carry out this study, which has spanned a number of years, we explored numerous alternative formulations and methodologies to identify an approach that best captured the real world complexities of the BLM problem, and which gave useful and meaningful answers. Although a multi-objective formulation seemed appropriate, we discovered that the standard multi-objective formulations in the literature[1] including goal programming, were not suited to modeling the BLM problem in a truly effective way. Thus, we evolved a new variant of the multi-objective approach and verified its effectiveness in application to a series of practical scenarios. The effort included the development of special solution software which we augmented to include interactive and analysis capabilities. This paper

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[1] Different authors use the term 'multi-objective programming' in different ways. For convenience, we allow it to subsume goal programming as well as vector maximization and related approaches.

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and socio-economic inputs, the decision maker decided on:

1. The resources to be maximized and the weights.
2. The resources to be minimized and their weights.
3. The resources to be constrained, with the desired upper bound for less-than-or-equal type constraints, and the desired lower bound for greater-than-or-equal type constraints.

The multi-objective methodology

Conceptually, multiple-use land planning is a multiple objective problem whose from cannot be adequately expressed by customary formulations. The limitations of preemptive goal programming, for example, are particularly apparent in this setting. Given the policy set of basic guidelines and the set of local and regional goals, the land manager seeks balanced resource maximization and very rarely finds himself in the position of establishing preemptive priorities of goals. Instead, he must carry out the mandate of 'optimizing' all goals at the same level of priority although different weights may be assigned to the goals according to the different emphases imposed by the socio-economic considerations and inputs from the interested publics.

It is, truly, a question of seeking the 'best compromise' solution, and not a question of clear-cut, incommensurable, and preemptive goal priorities. The land manager seeks to reconcile conflicts and is willing to explore the implications of different compromises. Nonpreemptive goal programming models are more relevant, but in the setting we examine do not adequately encompass the *relative* influences of alternative goals in the manner subsequently demonstrated.

Other standard multi-objective methods also have shortcomings. The vector maximization method and its variants produce a set of efficient extreme points from which the decision maker is, in theory, able to select the most desirable one. However, the lack of a simple methodology to whittle the large number of efficient solutions down to manageable size makes the vector maximal approach impractical.

The weighted-sums approach seems attractive at first because of its operational simplicity and the ready availability of commercial LP codes. However, there are aspects in its simplistic approach that are troublesome in the context of the multiple-use land problem, particularly the lack of homogeneity in the units of measurement of the different objective functions. Thus, if the conceptual weights (λ's) assigned by the decision maker to the objectives are used as the mathematical weights in the generation of the composite objective function, the end problem solved may not be the one originally intended. Even if the decision maker's preferences are correctly expressed in terms of the λ's, the use of such λ's in the generation of the single objective function indirectly results in the solution of a different problem, because of the failure to compensate for the dimensional heterogenity of the objective functions.

To improve upon the deficiencies of the straight-forward weighted-sums method, an eclectic MINMAX approach that draws from the weighted sums approach and the Benayoun et. al. stepwise algorithm [8] has been adopted and is presented below: Consider the multi-objective problem:

$$\begin{aligned}
&\text{Max } C^1X,\\
&\text{Max } C^2X,\\
&\quad\vdots\\
&\text{Max } C^qX,\\
&\text{s.t.}\quad AX \leqslant b,\\
&\qquad\; X \geqslant 0.
\end{aligned}$$

Let M_k be the maximum value of C^kX, obtained by solving the LP problem for each objective function individually. then, the problem can be reformulated:

$$\begin{aligned}
&\text{Min } Z,\\
&\text{s.t.}\quad AX \leqslant b,\\
&\qquad C^1X + Z \geqslant M_1,\\
&\qquad C^2X + Z \geqslant M_2,\\
&\qquad\quad\vdots\\
&\qquad C^qX + Z \geqslant M_q,\\
&\qquad X \geqslant 0,\\
&\qquad Z \geqslant 0.
\end{aligned}$$

To compensate for the discrepancies in units of measurement and order of magnitude of the different objective functions, these objective functions can be normalized by reference to the M_k values, and the multi-objective problem now besummarizes the nature of the problem faced, the methodology developed for dealing with it, the interactive software which was tailored to BLM user needs, and the implementation of the system in the real world.

To present our approach, we first characterize the planning environment that provides the background for the problem.

2. The planning area

In order to manage the decision unit called a planning area, the initial step is to collect the following information:

- Planning uses and planning criteria,
- Bio-physical resource inventory data,
- Socio-economic data of the planning area and surrounding region,
- Potential levels of production and/or management intensity for each manageable resource.

The planning issues are the problems, concerns, or opportunities identified by the public or by the planning agency at the outset of the planning process. The planning criteria are the set of guidance statements that direct the resolution of the issues through the planning process. They can be in the form of limits or constraints or can be measurable desiderata stated as goals or standards to be achieved. The planning criteria are intended to focus the planning effort, reduce the collection and analysis of unnecessary information, and facilitate subsequent analysis and decision-making.

The bio-physical resource inventory data characterize the physical environment of the planning area. Information is collected on a wide range of land attributes (air quality, climate, geology, topography, soils, hydrology, vegetation, fauna, and cultural plus visual resources), all of which significantly affect the performance of various land functions. Much of these data are geographically referenced and mappable, and the base data themes are digitized and entered into a Geographic Information System (GIS). The biophysical background furnishes information on the land attributes necessary for defining and delineating functional areas and for evaluating user functional areas for various land functions.

The potential levels of resource production and/or management are determined through analysis of the area's present situation (i.e., uses, production, conditions, trend, problems), its present environmental quality and ecosystem, and the projection of the full potential for each of the resources. The aim is to determine reasonable and potential levels of production, use, and management intensity for each manageable resource. Much of these data are geographically referenced and mappable, and the thematic maps produced are essential to the identification of conflicts later on.

On the basis of this background information, the planning area is subdivided into several homogeneous land units (ecological or functional units) based on geology, land form, soil and vegetative type. Relevant management alternatives are identified, and available resources are identified and mapped. It is at this point that the critical issue of conflict resolution in multiple-use planning arises.

3. Structuring in multiple-use problem as a multiobjective problem

We structure the multiple-use planning problem into a multi-objective format by means of several sequential steps. The result is a multiobjective formulation that departs somewhat from those standardly proposed in the literature (e.g., [5,6,7]), but which proves more appropriate and effective for our purposes. The steps leading to our formulation are examined below. Although stated in abbreviated form, they summarize the stages actually performed for applying our approach to a real world project of public lands management.

Step I. Preparation of a cross-impact matrix

The cross-impact matrix is the major information reference of the system. It links the resources and the management alternatives. The matrix rows are the resources and the matrix columns are the management alternatives. The matrix coefficients represent the quantitative responses of the resources to the management alternatives imposed on them.

The determination of the matrix coefficients is a difficult process which involves experimental field data collection, extrapolation from existing data, and expert opinions of the different resource specialists. Conceptually, each coefficient represents the fractional increase or decrease of a given resource if one acre of that resource-producing land is subjected to a given management alternative. Dimensionally, the coefficients are generally expresssed in terms of resource units/acre.

In some cases, because the quantification of the impacts of management alternatives on certain resources may be almost impossible to formulate, a relative scale is used to express degrees of impact. A five point scale with a +5 indicating the largest positive impact, −5 the largest negative impact, and 0 no impact at all, has proven quite effective.

The advantage of using relative impacts is that the coefficients obtained express a general relationship between resources and management alternatives which is independent of the ecological profile of the unit.

In implementing our approach, the cross-impact matrix, containing both relative and absolute values, was reviewed and amended using judgmental estimates of the area planner and the resource specialists that had prepared the area bio-physical profile. The task occupied three full days and amounted to an informal Delphi process. Because of the criticality of these coefficients in the decision-making process that followed, the methodology for arriving at the coefficient values was given intense attention. Delphi methods or policy capturing methodologies of the kind advocated by Hammond [3] proved appropriate to externalizing the estimate of experts where more direct approaches led to irreconcilable differences of opinion.

Step II. Identification of the cross compatibility of management alternatives

The identification of the cross-compatibility of management alternatives is important because the existence of incompatibilities among the competing management alternatives in a given area generates additional constraints to be imposed on the decision-making process for that area. For example, if two management alternatives MA1 and MA2, cannot utilize the same acre of land, a constraint has to be formulated stating that $MA1 + MA2 < 1$. In a formulation that relaxes the integer restriction on the management alternatives, this is to be interpreted as competition for the same acre that may be resolved by allocating fractions of it to each alternative. On the other hand, if MA1 and MA2 are not competitive, then MA1 and MA2 can jointly use the same acre and the constraints are just expressed as upper bounded variables; that is, $MA1 \leqslant 1$ and $MA2 \leqslant 1$.

Step III. Identification of resources directly applicable to each management alternative

This is not to be confused with the cross-impact matrix of coefficients. The best way to illustrate the difference is via an example. We employ the terminology and notation actually employed in the planning project, taken from the BLM data tables.

Consider one acre of land with natural gas deposits underground and a vegetative cover of pinion-juniper, and let us look at two management alternatives, oil and gas leasing, and two-way chaining and seeding of pinion-juniper. If oil and gas leasing alone is implemented on this acre of land, the resources directly involved are GAS-OIL, the acre containing the natural gas deposits, GASPROD, the potential gas production in thousands of cubic feet, and MANPOWER, the manpower to be consumed in implementing this management alternative. If the second alternative, alone, is implemented on this acre of land, the resources directly involved are: PDLTASE, the potential increase in sediment yield; IDLTASED, the immediate increase in sediment yield: POLTAWATER, the potential increase in water yield; IDLTAWATER, the immediate increase in water yield; and MANPOWER, the manpower consumed in implementing this alternative. However, if the two alternatives are implemented together on this acre, then seven resources are involved: GAS-OIL, PDLTASED, IDLTASED, PDLTAWATER, IDLTAWATER, GASPROD and MANPOWER, and the cross-impacts of each of the two management alternatives of these seven resources will be given by the cross-impact matrix coefficients.

Step III, then, relates each management alternative to the resources directly associated with it. Another way to state this relationship would be to say that the management recommendations associated with specific resources (i.e., mineral, watershed, etc.) relate directly to these specific resources and may or may not cross-impact the nonspecific resources.

Step IV. Identification of objectives and resource constraints

Based on the policy guidelines, public inputs, comes:

$$
\begin{aligned}
&\text{Min } Z,\\
&\text{s.t.}\quad AX \leqslant b,\\
&\qquad C^1X + M_1 Z \geqslant M_1,\\
&\qquad C^2X + M_2 Z \geqslant M_2,\\
&\qquad\quad \vdots\\
&\qquad C^qX + M_q Z \geqslant M_q,\\
&\qquad X \geqslant 0,\\
&\qquad Z \geqslant 0.
\end{aligned}
$$

The solution to the problem above will give the 'best' compromise solution with all the objectives conceptually (and mathematically, because of the normalization) equally weighted.

In the setting we faced, it is desirable to weight the objectives unequally, and this is accomplished by solving the problem:

$$
\begin{aligned}
&\text{Min } Z,\\
&\text{s.t.}\quad AX \leqslant b,\\
&\qquad C^1X + (M_1/W_1) Z \geqslant M_1,\\
&\qquad C^2X + (M_2/W_2) Z \geqslant M_2,\\
&\qquad\quad \vdots\\
&\qquad C^qX + (M_q/W_q) Z \geqslant M_q,\\
&\qquad X \geqslant 0,\\
&\qquad Z \geqslant 0,
\end{aligned}
$$

where W_k is a nonnegative weight assigned to the kth objective function. This is the model used in the treatment of the multiple-use land problem.

The advantages to this MINMAX eclectic approach are several. The use of the maximum value, M_k, of each objective function to achieve standardization, cues the decision maker with a reference point and guarantees that under equal weights one-to-one tradeoffs are modeled between deviations in the various objectives, eliminating the problem of discrepancies between conceptual and algorithmic weights. Additionally, for values of $W_k \geqslant 1$, the value of Z will now indicate the fractional deviation from the individual optimum, M_k, of the least attained objective.

The MINMAX formulation yields a solution point which is on the boundary of the original feasible region but is not a corner point of the original constraint set. Contrary to the MINSUM goal programming approach in which only the original vertices are possible contenders for solutions and slight changes in the W_k cause jumps, often major, in such solutions, the MINMAX formulation makes the solution point a continuous function of both the weights, W_k, and the targets, M_k, and thus effectively eliminates the problem of jumps in the solution points (see, e.g., De Kluyver and Martinson [1], Glover, et al [2], Klingman and Glover [4]).

A practical consequence of the MINMAX approach is that by reducing the multi-objective formulation to the standard LP formulation, the solution to the problem can be obtained using any of the existing commercial LP codes. It also permits postoptimality analysis and tradeoffs which are not possible with preemptive goal programming or the multi-objective vector maximization formulations. The MINMAX formulation generates the 'best' compromise solution according to the conceptual weights imposed on the objective functions and it eliminates the need for the decision maker to scan the set of efficient solutions which, in real-life problems of sizable dimensions, is an enormous, if not impossible, task.

4. The multi-objective solution to the multiple-use land problem

A computer program written in FORTRAN and fragmented into three separate modules was written to handle the tasks of matrix generation, solution, and report writing. The matrix generator takes the data from steps 1 through 4 and structures them in multi-objective format. For a given planning area, data from steps 1, 2, and 3 are invariant and can be stored on disk as a permanent file. Data from step 4 are entered interactively. The multi-objective code solves the multi-objective problem using a linear programming algorithm for bounded variables. The report writer cross-references the solution vector obtained by the multi-objective code to the original variable set and expresses the compromise solution in the vernacular of the planning area management alternatives. It also displays the extent to which the objectives have been achieved.

The generation of the final 'compromise' solution is an iterative process which is accomplished by man-machine interaction. On examination of the initial solution to the problem, the resource weights and the resource constraints can be modified interactively and the solution process repeated. This man-machine interaction is continued until the 'best' compromise solution (in the opinion of the decision maker) is attained.

In reformulating the objective weights and constraints, we have organized our approach as follows. If the initial set of weights fails to give an acceptable solution in the judgment of the user (expert), the approach systematically assignes less weight to the objectives that are being accomplished satisfactorily. If the constraints are tight, the right-hand sides are relaxed and the results observed. If the results obtained are still not satisfactory, it may be because one (or more) of the objectives totally clashes with the others, in which case a step-wise elimination of objectives, according to some intuitive or lexicographical order, will eventually point to the conflicting objective(s).

The relative weights are expressed using a value of 1 for the objective function with the least emphasis. The value of the Z obtained is then indicative of the fractional deviation of the solution vector from the individual optimum of the least attained objective. In particular, rather than lowering the weights below 1.0 for the objectives to be relaxed, increasing the weight of the objectives that have not been attained accomplishes the same results and is algorithmically preferable. If the objective functions maximized are expressions of resources being maximized, a value of Z greater than 1 alerts the decision maker of negative resource utilization (resource depletion or opportunity loss), and of the advisability of readjustment of weights if resource depletion cannot be tolerated.

Computer implementation of our approach for the multiple-use planning problem is thus keyed to be philosophy of allowing different exploratory moves for the decision maker, which leads to the progressive refinement of his choices.

A series of computer outputs for an abridged example are displayed in Tables 1 through 4, and are annotated below, to show the different moves of the decision maker and the progressive narrowing of his choices.

With all objectives equally weighted, resources COAL3, IDLTASTCK, PDLTAWATER and IDLTASED have equal negative percent attainment and the GE resource constraint for MANPOWER is at bound. Before re-allocating weights, the right-hand side for this constraint should be relaxed.

Table 1

Ecological unit no. 1
Z value 1.15

Resources maximized

Resources	Weight	Attained	Desired	Percent
COAL	1.0	−8.71.66	5956.00	−14.64
SALBLMIN	1.0	730.00	730.00	100.00
PDLTASTCK	1.0	5385.26	52260.00	10.30
IDLTASTCK	1.0	−764.83	5226.00	−14.64
PDLTAWATER	1.0	−871.66	5956.00	−14.64
PCLASS2	1.0	644.59	5581.15	11.55
ICLASS2	1.0	776.32	5956.00	13.03
COALPROD	1.0	263.46	2978.00	8.85
STONEPROD	1.0	292.00	292.00	100.00

Resources minimized

Resources	Weight	Attained	Desired	Percent
PDLTASED	1.0	−1554.17	−51443.00	3.02
IDLTASED	1.0	716.06	−4892.80	−14.64

Resources constrained

Resources	INEQ	Attained	Desired
MANPOWER	LE	1000.00	9999.00
MANPOWER	GE	1000.00	1000.00

The percent negative attainment of resources COAL 3, IDLTASTCK, PDLTAWATER and IDLTASED has improved but at the expense of lower percent attainment for the other resources. Since the MANPOWER constraint is still at bound, it is clear that only the trivial solution of zero acres allocated to each management alternative will resolve the conflict. It appears that some objectives are antithetical and cannot be considered simulta-

Table 2

Ecological unit no. 1
Z value 1.01

Resources maximized

Resources	Weight	Attained	Desired	Percent
COAL3	1.0	−68.26	5956.00	−1.15
SALBLMIN	1.0	91.93	730.00	12.59
PDLTASTCK	1.0	277.23	52260.00	0.53
IDLTASTCK	1.0	−59.89	5226.00	−1.15
PDLTAWATER	1.0	−68.26	5956.00	−1.15
PCLASS2	1.0	−18.10	5956.00	−0.30
ICLASS2	1.0	−18.10	5956.00	−0.30
COALPROD	1.0	0.00	2978.00	0.00

Resources minimized

Resources	Weight	Attained	Desired	Percent
PDLTASED	1.0	−76.63	−55910.00	0.14
IDLTASED	1.0	59.89	−5226.00	−1.15

Resources constrained

Resources	INEQ	Attained	Desired
MANPOWER	LE	100.00	9999.00
MANPOWER	GE	100.00	100.00

Table 3

Ecological unit no. 1				
Z value	0.92			
Resources maximized				
Resources	Weight	Attained	Desired	Percent
COAL3	1.0	4120.18	5956.00	69.18
SALBLMIN	1.0	60.86	730.00	8.34
PDLTASTCK	1.0	10685.45	52260.00	20.45
PDLTAWATER	1.0	496.55	5956.00	8.34
PCLASS2	1.0	465.30	5581.15	8.34
COALPROD	1.0	2978.00	2978.00	100.00
STONEPROD	1.0	24.34	292.00	8.34
Resources minimized				
Resources	Weight	Attained	Desired	Percent
PDLTASED	1.0	−4288.77	−51443.00	8.34
Resources constrained				
Resources	INEQ	Attained	Desired	
MANPOWER	LE	1511.67	9999.00	
MANPOWER	GE	1511.67	1000.00	

neously. Given the context of the problem, the resources PDLTASTCK and IDLTASTCK, PDLTASED and IDLTASED and PCLASS2 and ICLSS2 are likely to oppose each other since they represent two different points in time, potential and immediate, of a given resource utilization.

Resources IDLTASTCK, ICLASS2 and IDLTASED are eliminated from consideration and the GE constraint for MANPOWER is restored to its initial value. With only potential resources to be maximized and minimized, a satisfactory solution is attained. Using it as a reference point, the decision maker can now examine the effects of different weights.

Table 4

Ecological unit no. 1				
Z value	0.93			
Resources maximized				
Resources	Weight	Attained	Desired	Percent
COAL3	1.0	3619.20	5956.00	60.77
SALBLMIN	10.0	662.42	730.00	90.74
PDLTASTCK	1.0	10739.47	52260.00	20.55
PDLTAWATER	1.0	442.53	5956.00	7.43
PCLASS2	1.0	414.68	5581.15	7.43
COALPROD	1.0	2978.00	2978.00	100.00
STONEPROD	10.0	264.97	292.00	90.74
Resources minimized				
Resources	Weight	Attained	Desired	Percent
PDLTASED	1.0	−3822.24	−51443.00	7.43
Resources constrained				
Resources	INEQ	Attained	Desired	
MANPOWER	LE	2169.68	9999.00	
MANPOWER	GE	2169.68	1000.00	

Since resources SALBLMIN and STONEPROD are compatible with each other (they express the same resource in different fashion), their weights can be increased simultaneously. Other weight schemes were tried (not shown here) but they seemed to accentuate the differences between the resources and resulted in unsatisfactory solutions. The best compromise solution appears to be either the reference solution with equal weights (Table 1) or this one that emphasizes the maximization of resources SALBLMIN and STONEPROD.

5. Summary and real-world application of the new method

The methodology of our study was applied to a collection of planning units comprising approximately 145 000 acres and exhibiting a wide range of management alternatives and resources. The outcome demonstrated that the issue of conflict resolution in the U.S. Bureau of Land Management's planning system could be effectively handled by the multi-objective approach, as incorporated into the interactive software we developed for the study. The results have pointed to potential improvements in the agency's planning system, and have established the benefits to be derived from a follow-on effort, now underway, to examine the comprehensive use of our approach to guide agency decisions in the preparation of future land plans nationwide. (Computer generated tables and samples of interactive sessions may be obtained from the authors on request.)

The approach to multiple-use land management we have applied is quintessential of the multiple objective linear programming method. As such, it is behaviorally-grounded. It allows the land managers to engage in interactive search until he finds a solution that comes the closest to his ideal. It allows the decision process to be situational and incremental. Unlike goal programming, no precommitment of goal priorities is required. Unlike rational optimization, the solution is not independent of the decision maker's judgments and inputs. It does not take away from the land manager his prerogative to choose, as a rational optimization model would do. It defines the relevant planning alternatives and it leaves the choice under the control of the manager's subjective judgment.

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