Large-Scale Budget Applications of Mathematical Programming in the Forest Service

Malcolm Kirby

Abstract: Mathematical programming applications in the Forest Service, U.S. Department of Agriculture, are growing. They are being used for widely varying problems: budgeting, lane use planning, timber transport, road maintenance and timber harvest planning. Large-scale applications are being mace in budgeting. The model that is described can be used by developing economies.

INTRODUCTION

Two modern techniques of optimization that can be applied to complex resource problems are ADVENT (Kirby and others 1976) and the Eldorado model (Bell and Kirby 1971; Kirby 1971a, 1971b). They are so closely related that it is convenient to refer to both as "the model." the basic premise is that land management requires more than one input (men, money) and usually results in more than one output. The model uses linear programming to handle trade-off relationships and to evaluate the effects of imposing or relaxing levels of inputs, outputs, or both. The management objectives for the model were to prepare a budget request relating outputs to inputs; and once funds are allocated, to select projects that will either meet a set of output goals at minimum cost or will maximize a selected output (Bell and Kirby 1971).

Traditionally, work planning in the National Forests was based on specific resources functions: timber, range, recreation, watershed, etc. Each function used its funds to maximize specific outputs. Through so-called "multiple use" coordination, the effects of one function on another's outputs were considered but seldom explicitly evaluated. But the model does this explicitly, and this is what makes some managers uncomfortable with it. It requires that goals be stated in specific terms: animal unit months (AUM) of forage rather than acres reseeded; cubic feet of timber produced rather than acres planted; specific effects on all outputs as a result of building a rout: rather than miles of road built.

A list of outputs from a typical National Forest include timber, recreation, water, wildlife grazing, and livestock grazing. In addition, there are

miles of spectacular scenery, numerous lakes, miles of fishing streams, wilderness, power houses, summer homes, ski resorts, irrigation canals, roads, trails,
dams, pipe lines, organization camps, and other sundry special uses such as a temporary high altitude training camp for the Olympics.

National Forest planners are faced with three limitations: limited land, limited funds, and pressures for fulfilling the needs of an ever-increasing population. The planning problems are very complex. Goals include meeting the demands for outputs and maintaining the local economies, maintaining a trained work force, and maintaining the productivity of the larva.

Work done on National Forest lands requires multiple inputs--land and money (let money here represent tools, equipment, supplies and manpower). These inputs result in multiple outputs--forage, water (both quantity and quality), soil stability or erosion, camping, picnicking, fishing, hunting, timber growth, and timber cut. There are also more nebulous outputs (or effects) such as aesthetics, fire risk, air quality, and so on. These effects vary depending on the productive capability of the land, the primary purpose of the work being done, the methods used, and the spatial position of the land being treated.

The model is used for preparing proposals either for one or more future fiscal years or for the fiscal year that is about to begin. It is now being used for both budgeting and long-range planning at the local and national levels. We have also used ADVENT for trade-off analyses in land use planning, where long range timber yield considerations are not important.

The model is designed to generate a large number of feasible alternative programs. The design criteria are that the model be multiple-output oriented, able to generate alternative programs that are feasible, able to report the future implications of various alternatives, and able to generate optimal alternative programs on the basis of output-oriented criteria.

PROBLEMS IN INPLEMENTATION

Some of the problems in implementing such a model are these:

People: To begin with, when you say, "here is a better way to prepare a budget request," you have insulted those who have been following another system for a number of years. They have two reactions: "What's wrong with the way we've been doing it?" and "Show me."

Data: The amount of data needed for a complex mathematical model is formidable. Everything must be reduced to numbers.

Goals: They must be specific and quantifiable; narrative statements cannot be used. The manager may have to use hunches in interpreting the results, but the model cannot.

The people problem is very real. There is a generation gap between the top managers and a fast-growing group of mathematicians and economists. Managers are not used to thinking in terms of abstractions. It behooves both the teachers and the practitioners to take the time and effort to strip away the mystery, interpret the jargon into terms that can be understood, forget the theory, and show by actual examples what is meant. If we seem to labor this point, it is because we fear that if young people, exposed to new methods and techniques, do not recognize the problem, they will be frustrated when their ideas are not received with enthusiasm.

The land manager can have faith that these models work with great mathematical accuracy. However, he should scrutinize the figures, make sure they are correct, and test the final answers on the basis of reasonableness.

What about data? After all these years of research, we do not have all the information needed. For example, we have fairly reliable information as to the effect of a specified thinning regime on the volume growth of timber over time, when we know the site class. What we do not always know is the effect of the thinning on the forage output for domestic or wild grazing animals, or the effects on water runoff, or the tons of fuel per, acre resulting from one thinning operation, or whether leaving the slash on the ground is more beneficial for protecting the site than it is detrimental as a fire hazard. During the development of the Eldorado model, we reviewed nearly a thousand research papers and found less than 20 that were helpful in assessing effects on more than one output.

What about goals? Traditionally managers set goals in rather general terms--for example: meet the allowable cut, thin 1,000 acres, eradicate 500 acres of sagebrush, build 5 miles of fence. The model requires goals that are related directly to outputs such as cubic feet of timber growth, AUM's of forage produced, or tons of soil per acre that would remain in place if a protective fence were built. Specific goals such as these are very difficult to set. The output goals that we considered included the following:

Timber Cut	Water Quality
Timber Growth	Soil Stability
Timber Regeneration	Recreation Environment
Livestock Grazing	Recreation Visitor Days
Wildlife Grazing	Fire Hazard Reduction
Water Runoff	Fire Accessibility

The manager who is comparing two alternative forest-wide programs can scan the computer printouts and decide if one program is better or worse than the other and if the increase in output is worth the decrease in some other output. Inasmuch as output information is limited at this time, he cannot make his decision on the basis of actual physical outputs alone.

BASIS FOR DECISIONS

Some managers are uncomfortable with the model because there is no single criterion that indicates the "best" choice. To overcome this drawback some economists suggest converting everything to dollars and selecting projects based on benefit/cost ratio, or present worth, or internal rate of return, etc. This approach would be ideal except for four problems:

Difficulty of measuring all of the desired outputs for each project
Difficulty of assigning dollar values to all of the outputs
The specific statement in the "Multiple Use Sustained Yield Act" that the management of National Forest lands is not to be based upon the highest dollar return
The non-uniqueness of dollar values which give the same answer

There are many kinds of values--for example, market value, consumer value (a willingness to pay), producer value (the cost to produce), increasing gross national product, monopoly revenue value, and expenditure value. Whaley (1968) defines six different value methods. he points out that the value system must be appropriate for the model, must use the same method for achieving values for all outputs and must allow the values to be empirically quantifiable. The point is that since so many different kinds of values exist, the absence of a value system means the choice of method for valuing outputs can be rather arbitrary. To date, such a system has not been adopted for the Forest Service.

What then is the basis for decisions? Again, Whaley (1966) lists four measures of program effectiveness which may be used in public resource management: meet established production goals at least cost, establish the budget level and maximize some outputs, claim that no rational solution exists (we don't make this claim!), and maximize economic development. The Annual Budget Model and ADVENT were designed for using any of these measures. Therefore, when values for outputs are developed, by any value system, they can be easily employed in the model. Regardless of the manager's value systems, he still needs alternative programs from which to choose, and the model makes it easy to generate alternative programs. The models simply process information, bringing into focus the sociological, economic, and organizational consequences of alternative decisions. The final selection rests with the land managers and Congress, who must weight the socio-economic and political impact of their decisions.

The linear programming part of the model can carry out the following steps:

(1) determine whether or not the problem can be solved
(2) if it is solvable, give an optimum solution
(3) allow constraints of outputs, money, manpower, activity types
(4) maximize an output for, a given budget or, provide a specified output level at minimum cost
(5) provide a budget which includes all the costs of the various projects

ADVENT also has a goal programming option to minimize the deviations from a set of goals or "targets".

The model has reporting capabilities to transform the original data into a series of abbreviated reports or complete reports as desired by the manager. Information available for each solution includes manpower, needs by skills, by sub-units; money needed; list of projects selected; and list of total outputs.

One of the drawbacks, in the opinion of some managers, is that using it requires that more work be planned than there will be money to do. This represents extra effort which in times of tight budgets seems useless. Extra projects must be provided or there is no choice. Another drawback is that the time frame of 1 year is too short. This is admittedly a disadvantage, but budgeting, particularly fund allocation, is a year-to-year process. As already pointed out, there is a shortage of estimates of multiple outputs and "relative effects" are an unfamiliar substitute. The model requires that goals be set in quantitative terms. This has proved difficult at first.

Positive advantages of the model are that it considers the joint effect of inputs on outputs; it gives the manager a tool to explore a series of alternatives; and it focuses attention on specific measurable goals rather than broad overall objectives.

NUMERICAL EXAMPLE

To illustrate how the model works, let us consider a small hypothetical numerical example of eight projects, as follows:

Item	1	2	3	4	5	6	7	8
Land management and administration:								
Expenditures (million dollars)	2	3	3	2	4	2	4	4
Manpower (man-years)	100	100	100	50	300	100	100	100
Road construction aria maintenance:								
Expenditures (million dollars)	7	6	3	1	1	3	2	3
Manpower (man-years)	200	100	100	100	100	200	100	100
Timber-, for the next decade:								
Average annual cut (1000 bd. ft.)	8	9	8	7	5	4	5	2
Average annual net growth (1000 bd. ft.)	9	9	8	7	6	5	5	3
Benefits and costs:								
Total value of output (million collars)	28	27	15	6	9	8	8	7
Total expenditures (million dollars)	9	9	6	3	5	5	6	7
Administrative priority rating:	1	1	2	3	5	4	5	5

Suppose we wish to select a project mix that meets the following specifications:

(a) Include project 1 because it is already under contract
(b) Include all projects with priorities 1 and 2
(c) If project 7 is included, project 8 must also be included, and vice versa
(d) Do not permit both projects 5 and 6: one or the other, but not both (they are close substitutes)
(e) Achieve a minimum level of timber growth of 4;
(f) If there is a tie, then choose the combination of projects that minimizes total land management costs

(Note that in addition to constraining the level of individual inputs and outputs, or their combinations, the user can control individual projects or their combinations).

The solution is as follows:

Project No.:	1	2	3	4	5	6	7	8
Percentage:	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

The solution is presented below in the format of one of the 22 reports which can be prepared with ADVENT. Both the input data and the information contained in the LP solution can be displayed in these reports. The user can also employ ADVENT in a pure simulation mode by selecting a set of projects on the basis of experience and intuition, and call for a report detailing the corresponding costs, revenues, outputs, activities, manpower requirements, etc.

ADVENT report corresponding to the LP solution of the numerical example

*** PROJECTS SELECTED ***

AGGREGATE WORK/ACTIVITY DESCRIPTION	AMOUNT
PLANTING & SITE PREPARATION	600 ACRES
SLASH REDUCTION	1,000 ACRES
PRECOMMERCIAL THINNING	400 ACRES
TIMBER SALES PREPARATION	2,000 ACRES
ROAD MAINTENANCE	300 MILES
ROAD CONSTRUCTION	75 MILES

AGGREGATE OUTPUT DESCRIPTION	AMOUNT
DISPERSED RECREATION USE	20,000 VISITS
TIMBER HARVESTED	80,000 MBF
TIMBER SOLD	85,000 MBF
WILDLIFE HABITAT IMPROVEMENT	5,000 ACRES
VALUE OF TIMBER HARVESTED	47,000,000 $

AGGREGATE COST DESCRIPTION	AMOUNT
TOTAL EXPENDITURES	50,000,000 $
TOTAL ROAD CONSTRUCTION & MAINTENANCE	25,000,000 $
TOTAL LAND MANAGEMENT & ADMINISTRATION	25,000,000 $

MATHEMATICAL FORMULATION

For the reader interested in the mathematical formulation we present a simplified version of the linear programming problem.

maximize $\Sigma_j \quad d_j x_j$ subject to:

$$\Sigma_j\, a_{ij}\, x_j \geq f_i, \qquad i = 1, 2, \ldots I,$$

$$\Sigma_j\, c_{kj}\, x_j \leq b_k, \qquad k = 1, 2, \ldots K,$$

where:

x_j = 1 if the project is selected and zero otherwise

a_{ij} = amount of the ith output per unit of x_j

c_{kj} = amount of the kth input per unit of x_j

f_i = constraint on the total amount of the i^{th} output

b_k = constraint on the total amount of the k^{th} input

I is the set of output categories

K is the set of input categories

and where d_j may be chosen as

a_{ij} if the i^{th} output (e.g. timber growth) is to be maximized

or

$-c_{kj}$ if the k^{th} input is to be minimized

or

$-\Sigma_{K \xi K^*}\, c_{kj}$ "here K* is a subset of commensurable inputs such as costs or manpower

The term d_j may also be specified as the discounted or undiscounted total net revenue.

Note that the problem is formulated as an integer program, but it is solved, by means of a linear programming routine. The reason is that the solution generally turns out to be an excellent approximation to the integer solution, and the computer time is very short compared to the time required to solve the corresponding integer program. It is this feature that makes ADVENT a practical tool for widespread use. A discussion of why these approximations work as they do may be found in McConnen and others

CONCLUSION

ADVENT can be used by developing economies for both budgeting and long range planning. It has been tested in many different uses, over more than 4 years, by more than 50 organizations. The model's flexible design permits other planning applications such as road maintenance, capital investment analysis, project selection and other trade-off analyses. It is designed for use by relatively unskilled users of computers. The cost of a typical computer run, for 400 projects, is about $50.

REFERENCES

Bell, F., and M. Kirby. 1971. An example of optimization techniques in land Management: The Eldorado model. Forest Service, U.S. Dep. Agric., Berkeley, Calif.

Kirby, M.W. 1971a. An overview of program budgeting on a National Forest. Forest Service, U.S. Dep. Agric., Berkeley, Calif.

Kirby, M.W. 1971b. The methodology of program budgeting on a National Forest: The Eldorado experience. Forest Service, U.S. Dep. Agric., Berkeley, Calif.

Kirby, M.W. 1974. A model for allocating roar maintenance funds. [Unpublished paper on file, Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.]

Kirby, M.W., D. Wegner, L. Visser. 1976. ADVENT: A user's guide", 2nd Edition, Forest Service, U.S. Dep. Agric., Berkeley, Calif.

NcConnen, R., M. Kirby, D. Navon. 1966. A planning programming budgeting system for National Forest Administration. [Unpublished report on file, Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.]

Whaley, R.S. 1968. Multiple use decision-making: where do we go from here? [Unpublished report on file, Rocky Mountain Forest and Range Exp. Stn., Fort Collins, Colo.] .