A MULTIOBJECTIVE DECISION SUPPORT SYSTEM FOR WATER PROJECT PORTFOLIO SELECTIONS

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by

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ABSTRACT

A MULTIOBJECTIVE DECISION SUPPORT SYSTEM
FOR WATER PROJECT PORTFOLIO SELECTIONS

Recent rapid growth in the development and use of multiobjective decision-aiding methods has bypassed a class of decision problems common to at least three important federal water resources development programs. The reasons for this situation are revealed by an examination of these programs in the context of the evolution of federal water project planning procedures from a single objective to a multiple objective orientation. The study then selects one program for detailed analysis, examines the characteristics of the decision problem to determine the best solution approach, develops a multiobjective decision support system to overcome the problem, tests the decision support system by trial implementation using actual agency facilities, data and personnel, and evaluates the results. The new decision support system is not limited to the development of a mathematical decision-aiding algorithm, but also includes all other components necessary for effective decision making, including the development of an operational objectives set, implementing software, data collection system, and implementation plan.

Four additional contributions to multiobjective decision making are contained in the study:

1. An up-to-date and comprehensive survey of the use of multiobjective decision-aiding techniques in water resources planning, design and management is presented in the framework of a new taxonomy that promotes an understanding of the relationships among the various techniques and the conditions under which each may be used most advantageously.

2. A new multiobjective decision-aiding model selection paradigm is developed and presented.

3. A new approach to the difficult problem of objective set specification is developed and described.

4. A new interactive multiobjective decision-aiding algorithm that overcomes several disadvantages of previously developed procedures is developed and presented.

APPROVAL SHEET

This dissertation is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Systems Engineering).

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$\underline{A}$	matrix of objective contribution coefficients
a_{ij}	individual objective contribution coefficient
b	capital budget limit
$\underline{C}$	vector of capital requirements
$C_{O\&M}$	present value of future appropriated O&M costs
c_i	individual project capital cost
d	deviation from target or aspiration level
$\underline{d}^k$	most promising steepest ascent direction at iteration k
$f_j(\underline{x})$	objective function j
$f_j^{min}(\underline{x})$	minimum attainable value for objective j
$f_j^*(\underline{x})$	maximum attainable value for objective j
$f_{\hat{j}}(\underline{x})$	objective function selected for change by decision maker
$f_j(\underline{x}^k)$	contribution to objective j of solution vector (portfolio) $\underline{x}^k$
$f_k^{\,i}$	accumulated return function for objective k through stage i
$\underline{f}(\underline{x})$	vector of objective functions
$\underline{f}(\underline{x}^k)$	vector of objective attainment levels resulting from solution vector (portfolio) $\underline{x}^k$
$\underline{f}^*(\underline{x})$	ideal unattainable solution vector
$\underline{G}(\underline{x})$	vector of goal attainment percentages
$\underline{g}(\underline{x})$	vector of constraint functions
I	discount rate
J	set of unsatisfactory objectives
k	iteration counter
$\underline{L}$	vector of aspiration levels

l	number of acres of new land to be irrigated by a water project investment
m	number of construction project candidates
n	number of objectives or planning horizon in years
$\underline{P}$	vector of objective attainment percentages
p	percentage of O&M costs borne by appropriations
r	immediate return function
S	surrogate objective function
s	structural state variable
T	target level
$T_k{}^i$	state transformation function for the k^{th} state variable
t	parameter varying between 0 and 1
$U(\underline{x}^k)$	utility of decision maker for solution $\underline{x}^k$
w	objective or deviation weights
$w(f(\underline{x}))$	surrogate worth function
$\underline{x}$	vector of decision variables
Y	feasible set of decision variable values
Z	feasible set of objective function values
α	weighting coefficient
Δf_{js}	change in the level of a satisfied objective
Δf_{ju}	change in the level of an unsatisfied objective
Δf_j	change in the level of objective function j
$\Delta f_{\hat{j}}$	decision maker-specified change in objective $\hat{j}$
ε	parametrically varied parameter
λ_{ij}	Lagrange multiplier representing trade-offs between objectives i and j
$\nabla_{\underline{x}} f_j(\underline{x}^k)$	gradient of $f_j(\underline{x})$ evaluated at $\underline{x}^k$

EXECUTIVE SUMMARY

Introduction

This study describes recent work to develop, implement and evaluate a multiobjective decision support system for an important class of problems in water resources decision making. This class of problems is characterized by the need to select a preferred portfolio of projects from a finite, but very large, set of discrete feasible solutions. Throughout the study, emphasis was placed on demonstration of the value of multiobjective methods in assisting with actual public investment decisions in water resources development. To accomplish this, a real decision problem was used as a vehicle for conducting a large portion of the study. This decision-making environment provided a context within which the newly developed decision support system was evaluated and which enabled successful use of the decision support system to be demonstrated.

Problem Statement

Since the U. S. Congress first appropriated money for the construction of an irrigation canal on the Colorado River Indian Reservation, Arizona in 1867, federal involvement in Indian water development has increased steadily. By 1981, the Bureau of Indian Affairs had in operation 91 irrigation projects serving 676,784 acres of land. Most of these projects provide economic returns far less than would be necessary to justify such investments solely on economic grounds. Thus it is clear that the Congress established and continues to fund the Indian irrigation program to serve multiple objectives.

Many authors have demonstrated the complexities involved in solving problems with multiple noncommensurable and conflicting objectives. Historically, decision makers in the Bureau of Indian Affairs have dealt heuristically with the problem of allocating limited financial resources among competing water projects to serve multiple objectives. During each appropriations cycle, narrative justifications for construction activities were developed at the local level and submitted through the organizational hierarchy to the Bureau headquarters in Washington, D. C. There the narratives were reviewed and priorities assigned by staff specialists.

This approach may have been adequate when the program was small and the number of competing projects were few. However, in the past few years, the irrigation construction budget experienced a very rapid growth. The average annual appropriation for the program was $9.6 million in the years 1964-1973, as compared to an average of $38.5 million annually for the years 1974-1983. In the five year period 1979-1983, the average annual appropriation was $47.2 million.

In the fiscal year 1984 budget cycle, 133 narrative justifications were received for review in the headquarters office. The number of portfolio combinations theoretically possible with 133 project candidates is equal to 2^{133} or $1x10^{40}$. Although the size of the feasible region in a given budget cycle normally would be smaller than this (it is a function of the cost of each project candidate and the capital budget constraint), it is always an extremely large number, well beyond the capability of human cognition to deal with. Because of this situation, the Appropriations Committee (Subcommittee on Interior) of the House of Representatives directed the Bureau in 1978 to develop a better way of making project funding decisions, which led to this study.

Research Approach

Subsequent to problem formulation, the study was conducted in four phases: design of an appropriate multiobjective decision-aiding algorithm, development of other components necessary for an effective decision support system, implementation of the decision support system, and evaluation. The term "decision support system" as used in this study refers to a complete, systematic procedure that is fully developed for the support of complex decisions. It is not limited to the development of a mathematical decision-aiding algorithm, but also includes all other components necessary for effective decision making, such as the specification of objectives, algorithm programming, and data collection system.

Design of a Multiobjective Decision-Aiding Algorithm

This phase of the study was conducted in three steps: comprehensive literature review of existing multiobjective decision-aiding techniques to determine the conditions under which each may be used most advantageously, development of a model selection paradigm to match methodological capabilities with decision problem characteristics, and use of paradigm output to design a tailored decision-aiding algorithm.

In the first step, a new classification framework (Table 1) was developed to structure a focused, comprehensive and up-to-date review of existing multiobjective decision-aiding methods used in water resources planning, design and management. Emphasis was placed on identification of decision situation characteristics under which each method is particularly effective. The results of this review, combined with several additional models having potential applicability to water resources problems, provided a basis for the development of a new multiobjective decision-aiding model selection paradigm. The purpose of the paradigm is to enable analysts to tailor models to fit problem situations and avoid the common practice of attempting to restructure decision problems to fit fixed solution methodologies.

The following decision problem characteristics and desirable model attributes were used as input into the model selection paradigm to identify the most appropriate approach to the water project portfolio selection problem:

1. Finite set of discrete alternatives
2. Multi-stage decision problem with changing decision maker preferences
3. Large number of objectives, decision variables and alternatives
4. Reluctance of decision maker to express tradeoff preferences explicitly
5. Need to communicate solution methodology persuasively to other parties
6. Use of real instead of hypothetical alternatives to assess decision maker preferences

Table 1

Multiobjective Decision-Aiding Techniques

A. Nondominated solution generating techniques
   1. Constraint method
   2. Weighting method
   3. Multiobjective dynamic programming
   4. Multiobjective simplex method
   5. Noninferior set estimation method

B. Techniques involving a priori complete elicitation of preferences
   1. Optimal weights
   2. Utility theory
   3. Policy capture
   4. Techcom method

C. Techniques involving a priori partial elicitation of preferences
   1. Lexicographic approach
   2. Goal programming
   3. ELECTRE method
   4. Compromise programming
   5. Surrogate worth trade-off method
   6. Iterative Lagrange multiplier method

D. Techniques involving progressive elicitation of preferences
   1. Step method
   2. Semops method
   3. Trade method
   4. Pairwise comparisons
   5. Tradeoff cutting plane method

E. Visual attribute level displays
   1. Objective achievement matrix displays
   2. Graphical displays
   3. Mapping

7. Use of absolute levels of objective attainment instead of marginal rates of substitution to assess decision maker preferences

8. Implementation simplicity

Application of the paradigm resulted in identification of the interactive approach as the best solution procedure for the decision problem. However, none of the existing interactive multiobjective decision-aiding methods were computationally tractible with decision problems involving the search for an optimal portfolio of discrete alternatives from a very large set of feasible solutions. Therefore, a new interactive multiobjective decision-aiding algorithm was developed that combined desirable features of several existing interactive methods with new capabilities.

The new algorithm is an interactive linear multiobjective algorithm based on zero-one integer programming. The new algorithm requires as input three types of data: the impact of the construction of each candidate project on each objective, cost of each project (combined construction cost and net present value of operation, maintenance and replacement costs), and a capital budget constraint. The algorithm sequentially calculates optimal contributions to each objective in isolation (without regard to the other objectives) to obtain an "ideal unattainable vector" of objective achievements. It then minimizes the sum of the relative distances (absolute distances divided by the optimal value of each respective objective) from the optimal level of each objective to obtain an initial solution. This objective space solution is presented to the decision maker who may vary the level of one or more objectives to obtain a second solution. The decision maker selects his favored solution from this paired choice using a special decision-aiding display. This sequence continues until the algorithm converges to the decision maker's preferred solution.

A flowchart of the new algorithm is provided in Figure 1 using the following notation:

$\underline{A}$	m x n matrix of objective contributions
a_{ij}	contribution of project candidate i to objective j
b	capital budget limit
$\underline{C}$	m x 1 vector of project construction capital requirements
c_i	capital requirement for the construction of project candidate i
$\Delta f_{\hat{j}}$	decision maker-specified change in objective $\hat{j}$
$f_j{}^*(\underline{x})$	maximum level attainable by objective j
$f_j(\underline{x}^k)$	contribution to objective j of project candidate vector (portfolio) $\underline{x}^k$
$\underline{f}^*(\underline{x})$	vector of maximum values of all objectives displayed simultaneously. Referred to as the "ideal unattainable solution" vector
$\underline{f}(\underline{x}^k)$	vector of objective attainment levels resulting from project candidate vector (portfolio) $\underline{x}^k$
k	cycle counter
m	number of construction project candidates
n	number of objectives
$\underline{p}^k$	vector of objective attainment percentages resulting from project candidate vector (portfolio) $\underline{x}^k$
$\underline{x}^k$	vector of project candidates $\underline{x} = (x_1,\ldots,x_i,\ldots,x_m)$ at iteration k
x_i	integer decision variable that takes on a value of 1 if project candidate i is included in the portfolio, 0 otherwise

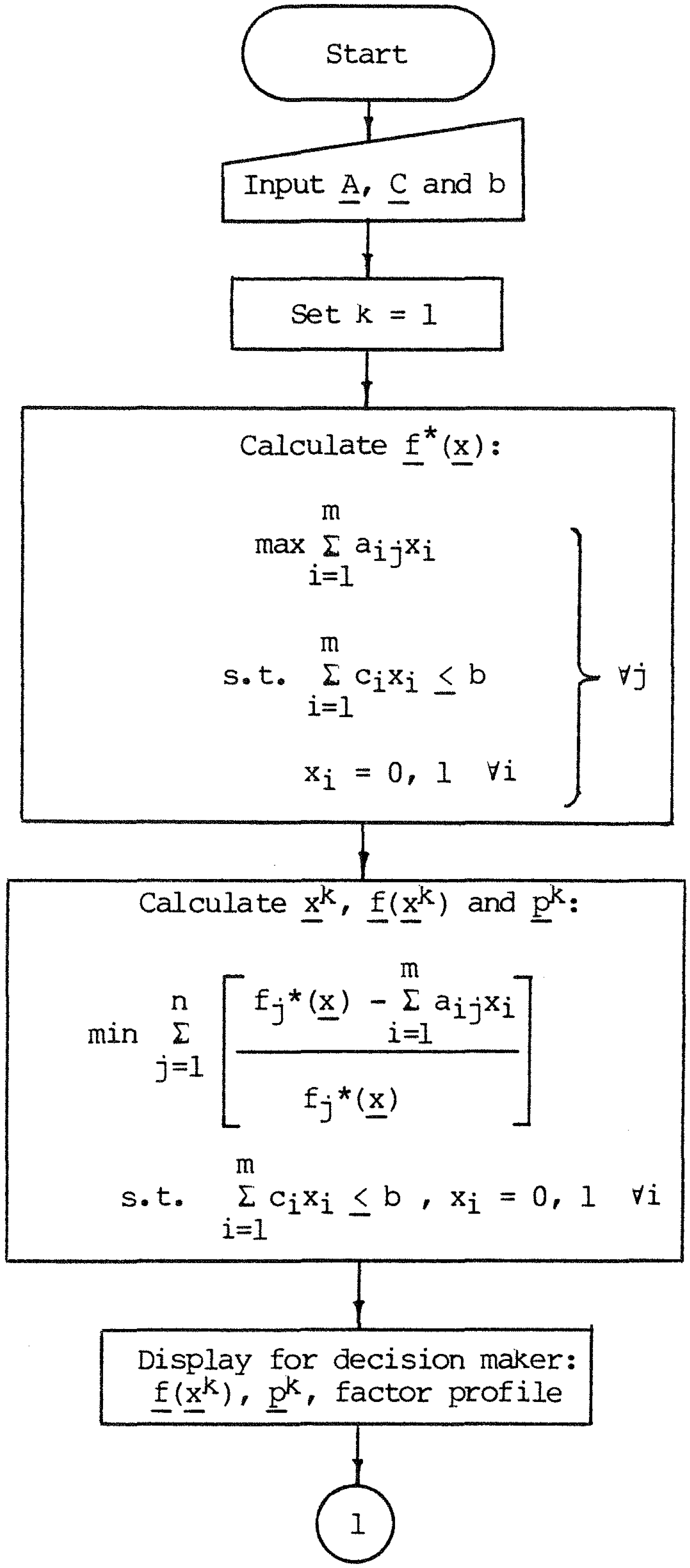


Figure 1

Flowchart of Interactive Algorithm

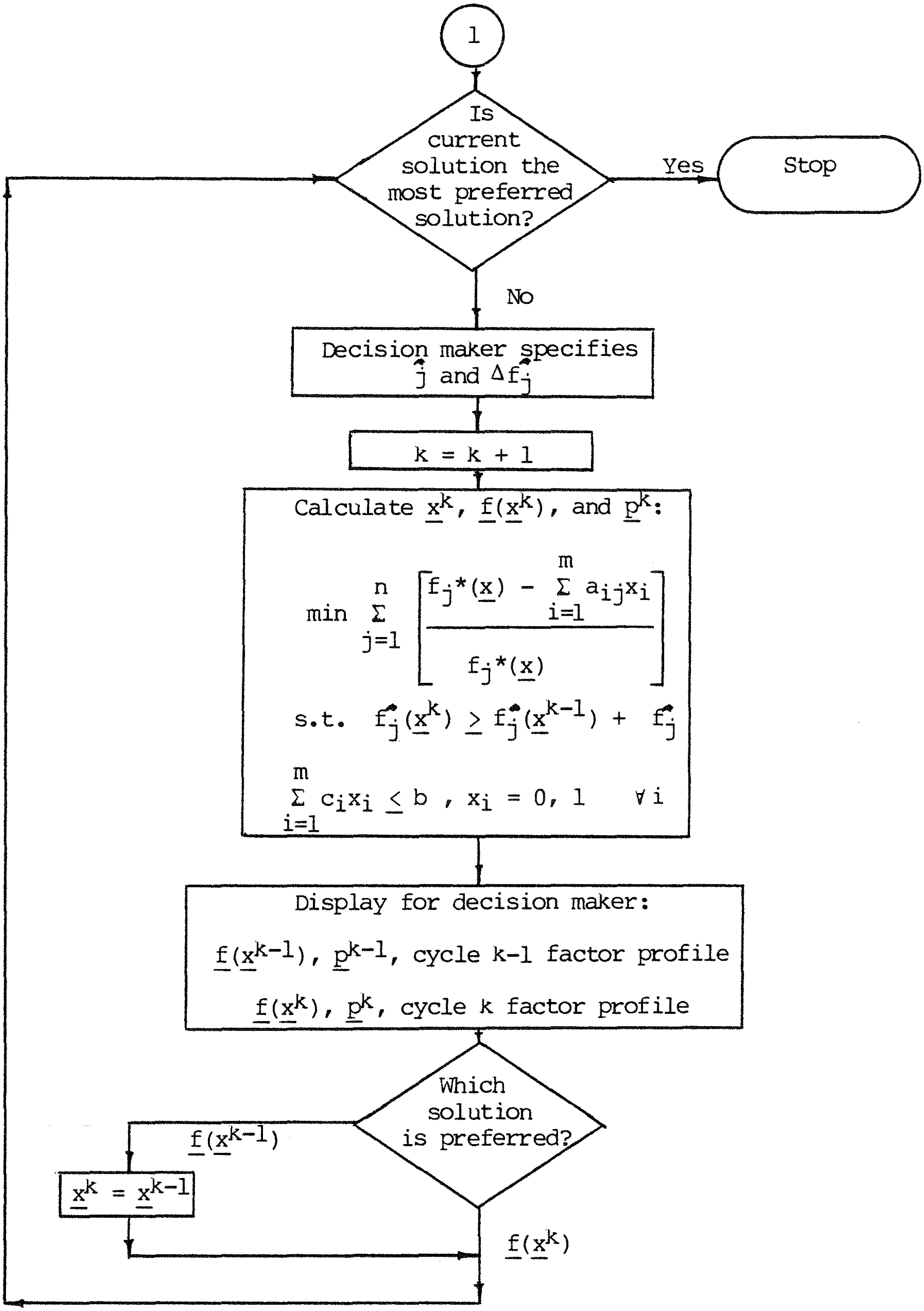


Figure 1 (continued)

Flowchart of Interactive Algorithm

Development of a Decision Support System

This phase of the study was also conducted in three steps: algorithm programming, development of an operational objectives set, and collection of input data. The IBM program product MPSX/MIP 370 was chosen for use in implementing the algorithm of Figure 1 because of its capability in solving large integer programming problems and its ready availability on the Amdahl V7 computer at the U. S. Geological Survey headquarters in Reston, Virginia. The software consists of a master program and 16 subroutines, all contained in Appendix D. Three languages are used: FORTRAN, CLIST (IBM Command List Language) and MPSCL (IBM Mathematical Programming System Control language).

The specification of objectives effort used recent research results from the disciplines of management and psychology in the design and implementation of a group idea generation and structuring process. Sequential use of the Nominal Group Technique and Interpretive Structural Modeling led to the development of the objectives hierarchy displayed in Figure 2. The objectives set used in subsequent implementation of the decision support system was composed of the lowest level of objectives in Figure 2.

The data collection step was conducted in four increments: determination of the most appropriate level of aggregation of project features for data collection purposes, identification of separable project features, development of a valid data set describing the impacts of the construction of each project division on each objective, and design of a plan for future data refinement.

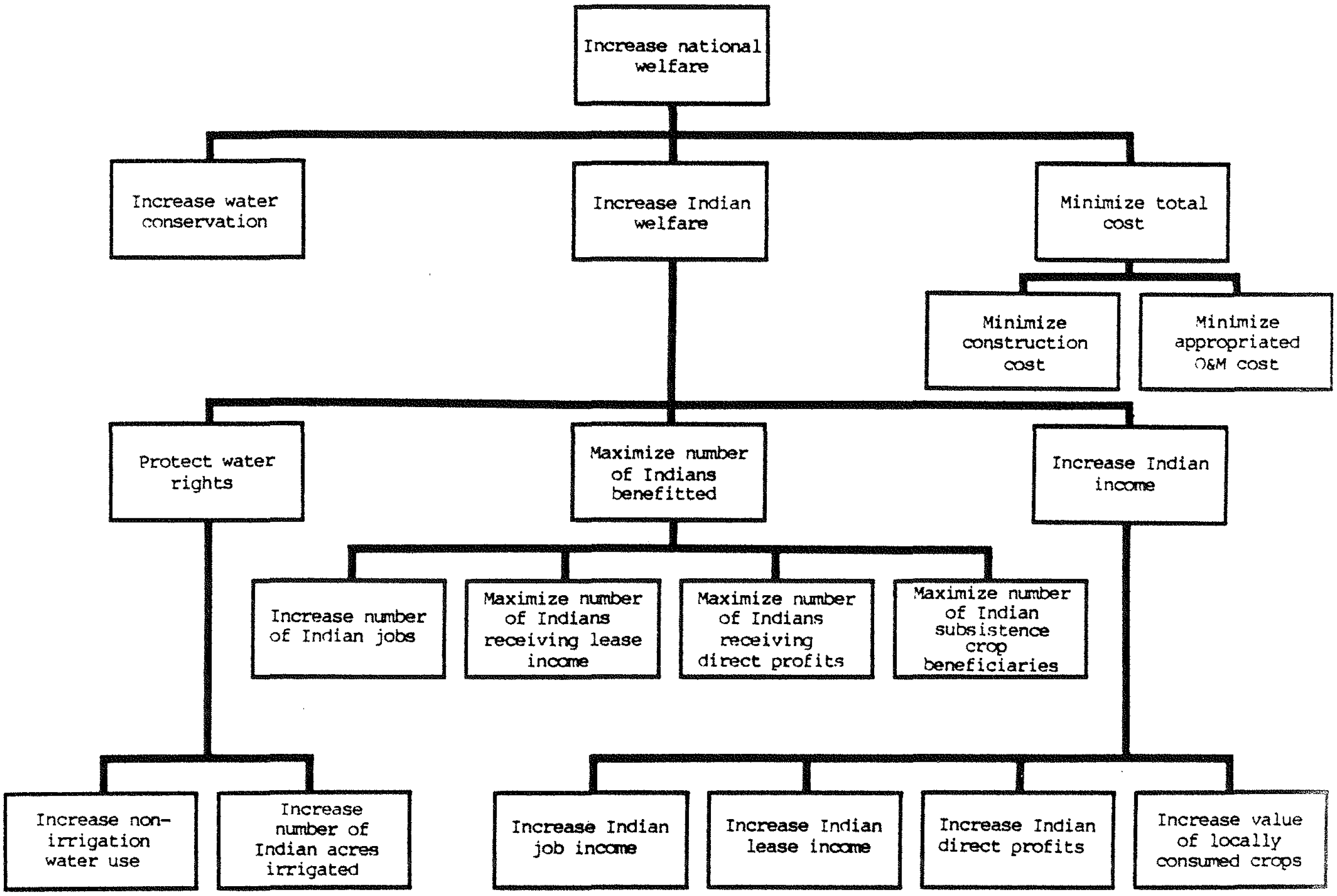


Figure 2

Objectives Hierarchy for the BIA Irrigation Program

In the first increment, five levels of aggregation were identified upon which to base the data collection effort. The top level involved collection of data to describe impacts of construction or rehabilitation of each of 91 project candidates on each of the identified program objectives. At the lowest level of aggregation, the data would describe impacts of construction or rehabilitation of individual work plan elements (such as installment of pumps, construction of individual diversion dams, or lining of canals) on each objective. Selection of the most appropriate level of aggregation involved a trade-off between political attractiveness and the availability of valid data. The highest level of aggregation would have the lowest level of political attractiveness but the greatest availability of data, and the reverse would be true of the lowest level of aggregation. The selected approach involved collection of data describing impacts of the construction or rehabilitation of separable project divisions on each program objective, and represented a compromise between political attractiveness and data availability.

The second increment resulted in the identification of 152 separable project divisions having significant new construction needs and 170 divisions having significant rehabilitation needs, for a total of 322 separable project divisions. These are listed in Appendix E.

The third increment made extensive use of secondary data sources, including several hundred project and watershed planning reports, budget documents, and two existing management information systems in the Bureau of Indian Affairs. A detailed description of data sources, assumptions made, sources of data imprecision, and procedures used to fill data gaps is provided. The complete data set is contained in Appendix F.

The fourth increment resulted in the design of a logical framework to improve the data set by the collection of primary field data. It envisions a three-part procedure to be conducted on each project candidate: development of a written statement of the size, condition and ultimate ownership of each project upon completion, development of a comprehensive construciton plan leading to attainment of the stated completion goal, and determination of the impacts on each of the program objectives of project construction.

Decision Support System Implementation

The test implementation phase resulted in one of the few existing examples of successful application of a multiobjective decision support system to an actual decision problem in water resources planning. The test was conducted in a real decision environment in that it:

- involved interactions with an actual agency decision maker,
- was conducted using the same agency facilities that will be used for future applications,
- used real input data as described above, and
- used the operational objectives set developed earlier.

Initially, common barriers to the effective implementation of decision support systems were examined and related to the decision environment in an attempt to identify and mitigate the severity of potential problems. Only two potentially significant implementation problems were identified, perceived problem urgency and data availability, neither of which adversely affected implementation.

The implementation phase of decision support system development did not involve an abrupt change in the involvement of user organization members. Since the decision maker and other members had been involved in previous stages of the research, progression from model development to test implementation involved no user participation discontinuities. Instead, it was treated as another stage of decision support system growth. Because of this continuous user involvement, requirements for the education of the decision maker at the time of initial solution availability were very small.

In the first application of the decision support system, the decision maker was able to converge on his preferred solution in only four iterations. Figure 3 and Table 2 provide the decision-aiding display used by the decision maker on one of the four iterations, including decision space information added during the implementation process. Computational experience for the test application is presented in Table 3.

Evaluation

Results of the test application were used to conduct an evaluation of the decision support system in terms of effectiveness (i.e., development of portfolios of projects that yield more desirable contributions to the program objectives, under equivalent constraints, than did the previous portfolio selection procedure), efficiency (i.e., consumption of no more resources than its output justifies), and acceptability (measures of effectiveness and efficiency are irrelevant if the using organization fails to accept it). Nine design specifications developed in the initial portion of the research project were used as evaluation criteria. Three of the nine criteria were applied to the portfolio selected with the assistance of the decision support system:

- contributions to program objectives,

	OBJ 1 (Indian land irrig)	OBJ 2 (Indian farm benef)	OBJ 3 (Indian jobs)	OBJ 4 (Indian lease benef)	OBJ 5 (Indian subsis benef)	OBJ 6 (Indian farm profits)	OBJ 7 (Indian job income)	OBJ 8 (Indian lease income)	OBJ 9 (Value of subs crops)	OBJ 10 (Non-irr water use)	OBJ 11 (Water con-served)
Alternative D											
Objective attainment	43,766 a	2,665	458	302	1,377	$4,756M/yr	$4,580M/yr	$402M/yr	$950M/yr	6,593 AF	190,800 AF
Percent of maximum attainable	66%	72%	83%	15%	30%	70%	83%	5%	31%	68%	27%
Alternative C											
Objective attainment	49,468 a	2,158	462	300	1,827	$4,683M/yr	$4,620M/yr	$405M/yr	$1,013M/yr	7,155 AF	176,700
Percent of maximum attainable	75%	58%	83%	15%	40%	68%	83%	5%	33%	74%	25%

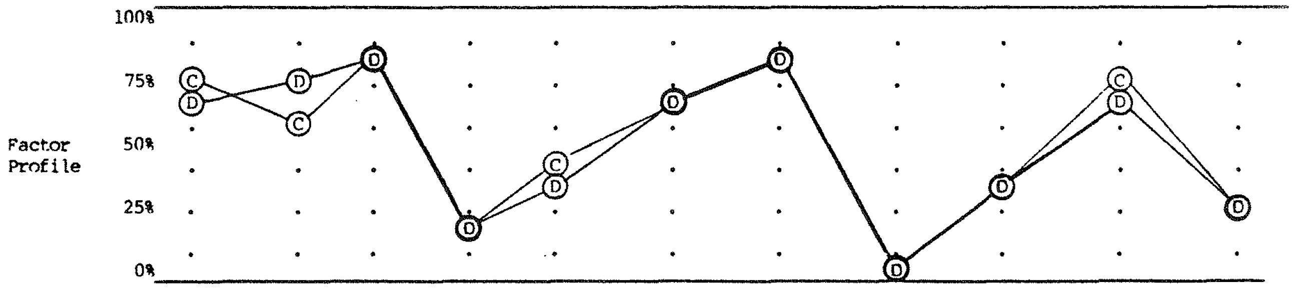


Figure 3

Decision-Aiding Display (Objective Space), Fourth Iteration

Table 2

Decision-Aiding Display (Decision Space), Alternative D

Area	Construction Projects	Construction $(mill)	R&B Projects	R&B $(mill)	Total Projects	Total $(mill)
Albuquerque	3	$ 4.498	3	$1.367	6	$ 5.865
Billings	4	7.051	2	1.700	6	8.751
Navajo	0	0.000	1	0.807	1	0.807
Phoenix	4	10.289	11	3.741	15	14.030
Portland	1	12.408	0	0.000	1	12.408
Sacramento	11	7.096	9	1.043	20	8.139
Total	23	$41.342	26	$8.658	49	$50.000

Table 3

Decision-Aiding Algorithm Computational Experience

Run	CPU time	Total time	Cost	Class*	Integer solutions found	Branches abandoned while computing	Number of constraints
1	2.6s	1.98m	$26.83	A	4	121	1
2	6.5s	1.05 m	12.77	B	2	31	1
3	5.4s	1.17m	11.96	B	2	32	1
4	5.5s	1.22m	7.03	D	2	21	1
5	3.4s	1.48m	5.70	D	1	1	1
6	11.3s	1.91m	18.18	B	2	159	1
7	5.4s	1.44m	6.89	D	2	31	1
8	5.0s	1.23m	11.35	B	2	23	1
9	8.9s	4.34m	15.25	B	3	120	1
10	17.9s	4.59m	25.68	B	3	216	1
11	3.9s	1.09m	5.90	D	1	1	1
Alt A	16s	2.61m	17.74	D	1	195	1
Alt B	41s	2.94m	33.80	D	2	**	2
Alt C	2m 16s	10.22m	98.92	D	9	1526	3
Alt D	1m 47s	12.32m	77.13	D	4	**	5

* A = interactive
B = batch, daytime processing
D = batch, overnight processing

** Data for Alternatives B and D are for non-optimal solutions.

- compatibility with existing construction capabilities of the using organization, and
- political feasibility.

Six criteria were applied to the decision support model itself:

- cost of data collection,
- cost of computer support,
- time of decision maker required,
- compatibility with available data,
- compatibility with using organization expertise, and
- compatibility with decision style of the decision maker.

Application of these criteria demonstrated that the decision support system can improve dramatically the effectiveness of decision making by increasing the level of contributions to program objectives within existing budgetary constraints. Using actual total program expenditures for the past five years as a budget constraint, the decision support system produced an initial portfolio that dominated actual project selections made during the FY 1979-1983 time frame on all objectives, and which provided a more equitable distribution of funding among regions. This result is viewed as a lower bound on the effectiveness of the decision support system since incorporation of the decision maker's preferences would lead to an even more attractive portfolio.

To test for efficiency, a reasonable lower bound on monetary benefits was obtained by finding the lowest cost portfolio that produced at least as great a contribution for each program objective as did the portfolios actually selected during FY 1979-1983 and subtracting the cost of the least cost portfolio from actual expenditures to yield cost savings potential. Not only did this result in a cost savings potential of $90.175 million, but the least cost portfolio also provided an improved distribution of funding in the decision space. Use of the cost savings potential and the total estimated cost of full decision support system implementation ($1.5 million) yielded a decision support system benefit-cost ration of 60.1 to one.

Evaluation of the decision support system with respect to acceptability yielded findings that it has a satisfactory level of compatibility with the existing expertise of the using agency, the cognitive decision style of the decision maker and, given the prescribed level of resources, available input data. The test application also resulted in the identification of a preferred portfolio that was determined to be both compatible with existing construction capabilities of the using organization and politically feasible.

Conclusion

Major contributions of this study to the existing body of knowledge may be summarized by five statements:

1. A new survey of multiobjective decision-aiding methods useful in water resources planning, design and management was developed. This survey is more up-to-date and comprehensive that any other existing survey. In addition, the results of the survey have been presented in the framework of a new taxonomy that promotes an understanding of relation-

ships among multiobjective methods and the conditions under which each may used most advantageously.

2. A new multiobjective decision-aiding model selection paradigm was developed and demonstrated.
3. A new multiobjective decision-aiding algorithm was developed for deterministic decision problems in which the decision variables exhibit binary characteristics and in which optimal portfolios from finite sets of feasible candidates are sought.
4. A new procedure for the identification of an operational set of objectives using group idea generation and structuring processes was developed and demonstrated.
5. A major demonstration of the successful application of a multiobjective decision-aiding method to solve an actual problem in water resources planning was provided by building a fully developed decision support system around a theoretically valid multiobjective algorithm and applying it to a real decision problem of high complexity.

A number of less significant accomplishments were also achieved in the course of study. These included a survey of all major federal water resources programs to identify existing problems of the class under consideration, an investigation into the reasons why recent advances in multiobjective decision-aiding techniques had not been used previously to assist with such problems, development of the software necessary to implement the new interactive algorithm, collection of data necessary to undertake trial implementation of the decision support system, development of a data collection plan to increase the effectiveness of the decision support system, examination of barriers to the effective implementation of the multiobjective decision support system, and development of a useful evaluation framework for multiobjective decision-aiding methods, including the establishment of evaluation criteria. Finally, nine promising directions for future research were identified to increase the effectiveness and efficiency of the decision support system developed in the course of study and to extend it into other areas.

I would not, if I could, attempt to substitute analytical techniques for judgment based on experience. The very development and use of those techniques have placed an even greater premium on that experience and judgment, as issues have been clarified and basic problems exposed to dispassionate examination. The better the factual basis for reflective judgment, the better the judgment is likely to be. The need to provide the factual basis is the reason for emphasizing the analytical approach.

Robert S. McNamara
quoted from Technological Forecasting in Perspective, Erich Jantsch, Organisation for Economic Co-operation and Development, Paris, 1967, p. 273.

Chapter 1

INTRODUCTION

In recent years the profession of water resources planning has experienced explosive growth in the development and application of techniques to assist decision makers in evaluating project and program alternatives in terms of the contributions of these alternatives to more than one objective. Such techniques have been referred to in the literature variously as multiple objective optimization, multiobjective analysis, multiple criteria decision making, multiattribute planning, and vector optimization methods. These methods have been applied to a wide variety of water resources problems, such as river basin planning, individual project planning, multiple reservoir operation, and water quality management. In addition, they have been applied to problems with either deterministic or stochastic characteristics, have taken both theoretical and empirical approaches, have used both continuous and discrete variables, and have used both linear and non-linear formulations. Collectively, these decision-aiding techniques have been applied widely to the planning of major federal water development projects; to the evaluation of of federal, state and local government programs and smaller projects; and, to a lesser extent, to the planning and evaluation of water project investments in less developed countries.

At the federal level, many multiobjective decision-aiding techniques have been developed to support the project evaluation guidelines of water project development agencies. These techniques represent attempts to operationalize the project evaluation guidelines of the federal government. Federal guidelines have undergone a distinct evolution in the last 20 years from single objective to multiple objective evaluation, and the analytical techniques used by planners to implement these procedures have followed suit.

However, multiobjective decision-aiding techniques have not been applied by federal water development agencies to certain portfolio selection decisions that do not fall under the purview of federal water project evaluation guidelines. This is true despite a rather obvious need for decision support systems utilizing such techniques. There are at least two possible explanations for this situation. First, the primary focus of analysts in the water resources field over the last decade has been to develop techniques to assist planners in implementing federal water project guidelines. Those programs not covered by such guidelines have been ignored. The close relationship between the development of multiobjective decision-aiding techniques for the application to water resources problems and the evolution of federal water project guidelines from a single to a multiple objective orientation is examined in Chapter 3. Second, since most of the techniques have been developed to assist in major water project planning, design and management decisions, they have tended to be too expensive and time-consuming to be useful for water project decision situations that are too small to fall under the purview of federal water project evaluation guidelines. However, some of these decision situations have a great need for multiobjective decision support systems and the impacts of such decisions are sufficiently important to warrant the development of decision-aiding methodologies for them.

It is this particular problem that this study addresses. The study investigates the reasons why the problem exists, selects the water project portfolio selection problem of one federal agency for detailed analysis, examines the characteristics of the decision problem to determine the best solution approach, develops an individually tailored decision support system to solve the problem, applies the decision support system to the problem within the actual decision making environment, and evaluates the results.

It should be understood that the term "decision support system" as used in this study refers to a complete, systematic procedure that is fully developed for the support of complex decisions. It is not limited to the development of a mathematical decision-aiding algorithm, but also includes all other components necessary for effective decision making, such as the specification of objectives, algorithm programming, data collection system, and planning for effective implementation.

Although one result of this study is the potential improvement of decision making in a major federal water project construction program, perhaps the major result is the demonstration of the workability of multiobjective decision support methods within the constraints of an actual decision making environment. It is hoped that this demonstration will contribute to more rapid exploitation of the value of these methods in solving complex planning problems.

In addition to these two contributions, the study presented herein provides the following four contributions to the state of the art in multiobjective decision making:

- an up-to-date and comprehensive survey of the use of multiobjective decision-aiding techniques in water resources planning, design and management is presented in the framework of a new taxonomy that promotes an understanding of the relationships among the various techniques and the conditions under which each may be used most advantageously;

- a new multiobjective decision-aiding model selection paradigm is developed and presented:

- a new approach to the difficult problem of objective set specification is developed and described; and

- a new interactive multiobjective decision-aiding algorithm that overcomes several disadvantages of previously produced techniques is developed and presented.

The study is organized such that a statement of the problem addressed by the research effort is provided initially. This problem description is contained in Chapter 2. It identifies three federal water programs that have a need for multiobjective decision support systems and describes the nature of a problem that is common to all of them. In addition, Chapter 2 contains data to indicate the magnitude of annual expenditures of these programs in order to impart an appreciation of the impacts of the multiobjective decisions made in them.

Chapter 3 briefly traces the recent history of the evolution of federal water project planning guidelines and demonstrates how this evolution from a single objective to a multiple objective orientation has led to the development of multiobjective decision-aiding techniques for application to water resources problems. In addition to helping gain an understanding of the problems that many of the multiobjective decision-aiding techniques were designed to address, Chapter 3 is helpful in gaining an appreciation of why analysts in the water resources field have focused most of their attention over the last decade on problems covered by the federal water project planning guidelines and have largely ignored other smaller but equally complex problems. Chapter 3 also provides a foundation for the research effort by presenting a short mathematical description of the general multiobjective optimization problem. This description also establishes the mathematical notation used in the remainder of the study.

Chapter 4 examines previous multiobjective decision-aiding techniques that have been developed for, or applied to, water resources planning, design and management problems. Over the last decade, the evolution of federal water project planning procedures described in Chapter 3 has led to a proliferation of such techniques. The establishment of categories of techniques based on common characteristics is helpful in understanding the techniques and in gaining an appreciation of the differences among them. Chapter 4 presents an overview of the categories established by six previous surveys of these methods which provides a basis for the development of a classification scheme used to structure a focused, comprehensive and up-to-date review of multiobjective decision-aiding techniques.

The development of a decision-aiding algorithm that is responsive to the decision problem described in Chapter 2 is presented in Chapter 5. This includes the description of a new multiobjective model selection paradigm, an application of the paradigm to the decision problem characteristics to determine the best approach to the solution of the problem, and the development of a new decision-aiding algorithm within the selected approach.

Chapter 6 describes the development of the ancillary components necessary to convert the algorithm described in Chapter 5 into a fully developed decision support system. These components include the specification of objectives, algorithm programming and data collection.

Chapter 7 recounts a test application of the decision support system that was conducted in the actual decision making environment using real program input data, actual agency computing facilities, an operational objectives set, and the actual program decision maker. Evaluation results from the test application using the original research design specifications as evaluation criteria are presented in Chapter 8.

Chapter 9 reviews the research methodology and findings of the study, draws conclusions and presents recommendations for further research.

Chapter 2

STATEMENT OF THE PROBLEM

An examination of 36 water resources programs of the federal government revealed that three of these programs involve very similar types of portfolio selection decision problems. Each of these programs involves a single annual decision in which a portfolio of competing construction projects or project components must be formulated, which then becomes the basis for construction funding in the program. These decision situations contrast with those of programs which provide funding on an incremental basis throughout the fiscal year, such as the Public Works Development Program of the Economic Development Administration (EDA) in the Department of Commerce. Those such as the EDA program generally evaluate candidate construction projects in terms of a set of minimum threshold criteria, rather than attempt to structure a portfolio of projects that maximize contributions to a set of specified objectives.

Each of the three programs with similar types of portfolio selection problems shares the commonality that the agency administrators have a substantial amount of discretion in allocating the funding to competing projects. These programs are:

- the Construction Grants Program for Wastewater Facilities of the Environmental Protection Agency (portfolio decisions in this program are made primarily by state agencies),
- the Irrigation Construction Program of the Bureau of Indian Affairs in the Department of the Interior, and

- the Sanitation Facilities Constuction Program of the Indian Health Service in the Department of Health and Human Services.

In each of these programs, the total cost of the projects competing for funding greatly exceeds the budget for that program in any given year. In addition, each of the programs has at least two clearly identifiable objectives that have been articulated by their respective agencies. Currently, funding allocation decisions within the programs are based almost entirely on subjective judgement. No consistent and objective methodology has been developed to assist the portfolio selection decisions of the programs and, in each program, agency officials have expressed both dissatisfaction with current allocation procedures as well as the need for improved decision making procedures (Brady, 1982; Hartz, 1982; Ragsdale, 1982). A short description of the portfolio selection decision problem contained in each of these programs follows.

The Construction Grants Program for Wastewater Facilities of the Environmental Protection Agency (EPA) was authorized by Section 201 of the Federal Water Pollution Control Act Amendments of 1972 (U. S. Congress, 1972). It provides for federal grants for the planning, design and construction of wastewater treatment facilities. Appropriations for this program averaged $3.45 billion annually for the years 1973-1983 (Council on Environmental Quality, 1982, p. 83). Grants are usually made from EPA to the applicant (normally a municipality). However, priorities for the various candidate projects within a state are set by a state agency within broad guidelines set by EPA. These guidelines establish four objectives for the Construction Grants

Program (U. S. Code of Federal Regulations, 1981). These are:

- the severity of pollution problems,
- existing population affected,
- the need for preservation of high quality waters, and
- the category of need that is addressed.

Each state is free to establish priorities for its wastewater treatment facilities within this broad framework. A number of methods to establish these priorities have been developed by the states. These vary widely in quality and objectivity. An overview of the method currently used by the State of New Jersey is presented here. New Jersey was chosen for illustrative purposes because its priority ranking system clearly identifies State objectives for wastewater treatment facility construction and because it uses a common multiobjective decision-aiding technique: linear weighting.

In New Jersey, priorities for wastewater facility construction grants are established by the Division of Water Resources of the Department of Environmental Protection. The New Jersey system contains four equally weighted objectives (New Jersey Department of Environmental Protection, 1980). Three of the objectives are related to the geographical area in which the proposed project is to be located, and the fourth concerns existing discharge conditions at the proposed site of the project. Each potential project is scored on each objective and the scores are summed. Then the projects are ranked according to total scores. The objectives and the range of possible scores on each objective are displayed below:

Objectives	Ranges
Population	1 - 200 (more points for high populations)
Attainable Water Uses (potable water supply, swimming, fishing and shellfish industry)	0 - 200 (more points for more water uses)
Existing Water Quality	0 - 200 (more points for poor water quality)
Existing Discharge Conditions	1 - 500 (more points for less sophisticated existing facilities)

The Irrigation Construction Program of the Bureau of Indian Affairs (BIA) was authorized by the Snyder Act of 1921 (Water Policy Implementation Interagency Task Force, 1979, p. 14-15). It provides funding for the rehabilitation and extension of existing irrigation and hydroelectric power projects and the construction of new projects on and near federally-recognized Indian reservations. Total identified construction needs in excess of $400 million far exceed the current average annual budget authority of $50 million for this program. Priorities for the candidate construction projects are established, with rare exceptions, by the BIA in its annual budget request to the Congress. The BIA has identified 14 major objectives of the Irrigation Construction Program (U. S. Bureau of Indian Affairs, 1979).

The Sanitation Facilities Construction Program of the Indian Health Service was authorized by the Indian Sanitation Facilities Act of 1959 (U. S. Indian Health Service, 1969). Projects constructed by this program provide safe domestic surface and ground water supplies, water treatment, distribution systems, and facilities for wastewater disposal on federally-recognized Indian reservations. Construction appropriations for this program averaged about $66 million annually in recent years (Water Policy Implementation Task Force, 1979, p. 61). Annual portfolios of construction projects to serve existing homes and communities are established subjectively and are based on narrative justifications developed at the field offices of the organization. Four objectives are used by the agency decision makers in developing the portfolios. These are:

- tribal contributions,
- existing health conditions,
- economic feasibility,
- type of service required (e.g., initial service, rehabilitation etc.).

Total construction needs have far exceeded the funding levels available in recent years.

The problem addressed in this research effort involves the development of an effective, efficient and acceptable decision support system to assist federal decision makers with the portfolio selection problems identified above. In order to focus the research effort and to provide a means of testing the effectiveness, efficiency and acceptability of such a decision support system, the Irrigation Construction Program of the Bureau of Indian Affairs was chosen as a vehicle in which the research was carried out. This program was chosen instead of the others discussed above for six reasons.

First, a clear mandate exists to develop a decision support system for the Irrigation Construction Program of the Bureau of Indian Affairs.

During the appropriations hearings for the fiscal year 1979 budget of the Bureau, the Subcommittee on Interior and Related Agencies of the House Appropriations Committee directed the Bureau to (U. S. Congress, 1978, p. 53):

> establish a funding priority system which takes into account when each irrigation or power system will be self-sustaining, the total estimated cost of the system, the number of people affected, the availability of an adequate water supply, current condition of the system, ultimate annual maintenance and operating costs, and whether the system should be continued.

In the time since this directive was issued, the Bureau had expanded the above list of seven criteria to 14, and had attempted to use a scoring method to rank competing irrigation construction budget elements. However, the effort encountered some difficulties, and the Bureau system had not been used by the time of this study to assist in the development of project portfolios for the annual appropriation request of the Bureau.

Second, the short-term need for a decision support system is great in the BIA irrigation program. In the past few years, the irrigation construction budget has experienced a very rapid growth. The average annual appropriation for this program was $9.6 million for the years 1964 - 1973, as compared to an average annual appropriation of $38.5 million for the years 1974 - 1983. In the five year period 1979 - 1983, the average annual appropriation was $47.2 million (U. S. Bureau of Indian Affairs). However, the method used by the Bureau to develop project portfolios for the annual budget requests had remained unchanged for decades. Narrative justifications for construction activities were developed at the local level and submitted through the organizational hierarchy to the Bureau headquarters in Washington, D. C. There the narratives were reviewed and priorities assigned by staff members of the Division of Water and Land Resources. In the 1984 budget cycle, 133 such narratives were reviewed (U. S. Bureau of Indian Affairs). Obviously, high levels of objectivity and consistency cannot be attained under such a system.

Third, the potential for well-defined specification of the objectives of the irrigation program of the BIA was present at the beginning of the research effort. As stated above, the Bureau had developed a preliminary list of 14 objectives of Indian water development prior to the initiation of the research effort.

Fourth, the existing data base of the BIA irrigation program appeared to be more appropriate, extensive and accessable than those of the other programs. In addition, data gaps seemed to be easier to fill in the BIA irrigation program than in the others. The Bureau had an extremely experienced cadre of field professionals in this program and the potential for use of professional estimates to fill data gaps appeared to be high. Many of these individuals had worked with the Indian irrigation projects for substantially all of their professional careers.

Fifth, the introduction of an appropriate decision support system into the annual project portfolio selection problem of the Bureau appeared to contain the potential to have a major impact on the actual projects selected for funding. As indicated above, at the initiation of this research effort both the Bureau and the Congress were actively looking for a methodology to establish funding priorities for Indian irrigation projects. Chances for the adoption of an appropriate decision support system and its successful application to an actual decision problem appeared to be high.

Sixth, and perhaps most important, the federal agency involved offered its full cooperation in the research effort. A number of key officials in the Bureau of Indian Affairs were enthusiastic about the project because of its apparent potential benefit to the agency. Because of this situation, problems related to the procurement of data, and access to necessary documentation and key personnel were not expected to occur.

The Irrigation Construction Program of the BIA is clearly of sufficient magnitude to warrant the development of a decision support system to assist with the annual portfolio selection decision. In calender year 1981, the 91 irrigation projects operated by the Bureau of Indian Affairs served 676,784 acres of land with water, which in turn produced crops valued at $178,062,616. These projects also served 27,163 customers with electrical power and returned $29,300,000 to the U.S. Treasury from irrigation and power collections. In addition to extensive rehabilitation needs of these projects, the Bureau has existing plans for the irrigation of an additional 274,000 acres of land, and a large potential for future mineral and energy development and other purposes exists (Deason, 1982a, p. 15-17).

This, then, describes the problem that has been addressed in the research effort presented in this study. Throughout the study, the usability of the decision support system to assist in actually solving the stated problem and the ultimate acceptance of the methodology by the using agency were kept foremost in mind.

Chapter 3

BACKGROUND

Evolution of Federal Water Project Evaluation Guidelines

The traditional approach to the analysis of multipurpose water resources development proposals has been to determine the combination of project or program components that will maximize the net contributions of the project or program to a single objective: national economic development. Only in recent years has the concept of multiobjective optimization been recognized explicitly in the planning guidelines of the federal government. A brief look at the history of federal water development policies provides a revealing insight into the major force behind the recent interest in multiobjective optimization within the water resources planning community.

Although the complete history of federal involvement in water resources development begins when the first Congress enacted the first water development act on August 7, 1789, our purpose here will be served by confining this historical summary to the recent period beginning with the Flood Control Act of 1936, which can be considered the beginning of modern water resources planning theory. Table 3-1 presents a summary of the milestones in federal water project planning since that Act. A concise history of Congressional expressions of desired objectives of water resources development before that Act may be found in Werner (1968, p. 7-15), and an examination of Congressional and Executive Branch expressions of desired objectives in two major

Table 3-1

Milestones in the Evolution of Federal Water Project Planning
From a Single to a Multiple Objective Orientation

1936	Flood Control Act specifies, for the first time, that the federal government should pursue water projects if "benefits to whomsoever they accrue are in excess of the estimated costs."
1950	Subcommittee on Benefits and Costs, Federal Inter-Agency River Basin Committee issues the Green Book, which required that water projects be sized according to their incremental effects on national income.
1952	U. S. Bureau of the Budget Circular A-47 requires benefits of a project purpose to exceed economic costs attributable to that purpose.
1962	Senate Document 97 lists three objectives for water projects: development, preservation, and well-being of people, but provides guidance heavily weighted toward national economic analysis.
1970	Rivers and Harbors and Flood Control Act expresses Congressional preference for four objectives in water project development: regional development, environmental quality, well-being of people and national economic development.
1973	President approves Principles and Standards, which require that water project plans be formulated toward two objectives: national economic development and environmental quality, and that impacts of such plans be calculated on two other "accounts": regional development and social well-being.
1978	President's Water Policy Message reiterates the two objectives of the Principles and Standards.
1983	President approves Principles and Guidelines, which return to a single objective (national economic development) with freedom to formulate other cost effective alternatives that contribute to social, regional and environmental goals.

federal water resources programs prior to World War II may be found in Major, et al. (1977).

The Flood Control Act of 1936 provided a milestone in the evolution of federal water project planning activities when it specified, for the first time, that the federal government should pursue water development projects if "benefits to whomsoever they accrue are in excess of the estimated costs" (U.S. Congress, 1936, Section 1). This recognition of economic efficiency from a national perspective continues to this day as a major criterion of project merit.

The first major document developed by the Executive Branch of the government to guide water planning activities was a report by the Subcommittee on Benefits and Costs, Federal Inter-Agency River Basin Committee, composed of the Corps of Engineers, the Departments of Interior, Agriculture, and Commerce, and the Federal Power Commission. The report, originally issued in 1950 and revised and reissued in 1958, became popularly known as the Green Book. The Green Book required that projects be sized according to their incremental effects on national income and became a major influence in institutionalizing efficiency benefit-cost analysis in federal water project planning.

The concept of national economic efficiency as the single objective of water development projects was strengthened by the issuance of U.S. Bureau of the Budget Circular A-47 in 1952. Since this document established criteria used by the Bureau of the Budget to review all water resources programs, projects and budget estimates prior to submission to the Congress, it had a major impact on federal water planning.

The nature of BOB Circular A-47 (p. 6) is captured by the following key passage:

> one essential criterion in justifying any program or project will, except in unusual cases where adequate justification is presented, be that its estimated benefits to whomsoever they may accrue exceed its estimated costs. Inclusion in a multiple-purpose program or project plan of any purpose of resource development will, except in unusual cases where adequate justification is presented, be considered only if the benefits attributable to that particular purpose are greater than the economic costs of including that purpose in the program or project.

BOB Circular A-47 was rescinded in 1962 and replaced in that year by an agreement between the Departments of Interior, Agriculture, Army, and Health, Education and Welfare (HEW). This agreement was approved by President Kennedy and printed by the U.S. Senate as Document No. 97. Senate Document 97 (U. S. Senate, 1962, p. 1-2) represented a marked change from the single objective orientation of the Green Book and BOB Circular A-47, as it explicitly listed three objectives toward which plans were to be formulated. These were: (1) development (national economic development and development of each region within the country), (2) preservation (stewardship of natural resources), and (3) well-being of people (basic needs of particular groups of people). Despite the multiple objective philosophy expressed in the directive, however, the detailed guidance on standards for the formulation and evaluation of plans were heavily weighted toward national economic analysis. As a result, Senate Document 97 did not significantly reorient the planning activities of the federal water planning establishment.

In general, the development of analytical models to support water resources planning activities prior to 1973 was focused on those models with single objective functions. Cohon and Marks (1973, p. 826) briefly discuss the work of five authors who introduced models based only on the economic efficiency objective during this time frame. These models represent attempts to make noncommensurable items commensurable in order to serve a single objective function. The limited work concerned with multiple objective analysis conducted during this time frame apparently did not contribute significantly to a move toward multiobjective planning. Werner (1968, p. 145) wrote that works in the then "current literature for use of a multiple-term objective function (are) not obviously practical for present use," but felt that multiobjective analysis could improve the basis for decision making in water resources planning. Other authors were more optimistic. Dorfman (1965, p. 336), for example, was referring to the growth of multi-objective analysis in water resources planning when he wrote that "We are only at the inception of this revolution...." The National Water Commission (1973, p. 383) referred to the change toward multiobjective planning as a pioneering phase that was proving to be difficult because such change entails "significant changes in planning procedures and in present levels of expertise."

Eight years after the appearance of Senate Document 97, Congress provided a clear expression of predilection toward multi-objective planning in the Rivers and Harbors and Flood Control Act of 1970. Section 209 declared that:

> It is the intent of Congress that the objectives of enhancing regional development, the quality of the total environment,

> including its protection and improvement, the well-being of the people of the United States, and the national economic development are the objectives to be included in federally financed water resource projects, and in the evaluation of benefits and costs attributable thereto.

A major reorientation of federal water planning activities toward multiobjective analysis was induced by the next major planning document developed by the Executive Branch. This was the *Principles and Standards for Planning Water and Related Land Resources* (U.S. Water Resources Council, 1973). The *Principles and Standards* required plans to be formulated in the context of contributions to the objectives of national economic development and environmental quality. In addition, consideration of the effects of plans on regional development and social well-being "accounts" was allowed in selecting a recommended plan. The extent to which this document affected federal water development planning is disclosed in a 1975 collection of 10 papers, each describing the implementation of multiobjective planning in a different federal water development agency (Michalson, *et al.*, 1975).

Congress gave further impetus to multiobjective water resources planning in the *Water Resources Development Act of 1974* (Section 80c) when it again expressed a preference for:

> consideration of enhancing regional development, the quality of the total environment including its protection and improvement, the well-being of the people of the United States, and the national economic development, as objectives to be included in federally-funded water and related land resources projects and in the evaluation of costs and benefits attributable to such projects.

The dual objectives of national economic development and environmental quality contained in the *Principles and Standards* of 1973 were reiterated by President Carter in his 1978 Water Policy Message (Office of the White House Press Secretary, 1978, p. 3) and were retained in the revised Principles and Standards issued in 1980 (U.S. Water Resources Council, 1980, p. 64391).

In March 1983, the U. S. Water Resources Council issued a new planning document entitled Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies, which replaced the Principles and Standards. Although the new document reduces the number of water project planning objectives to one (national economic development), it also contains the following provisions (p. 7):

> In addition to a plan which reasonably maximizes contributions to NED, other plans may be formulated which reduce NED benefits in order to further address other Federal, State, local and international concerns not fully addressed by the NED plan. These additional plans should be formulated in order to allow the decisionmaker the opportunity to judge whether these beneficial effects outweigh the corresponding NED losses.

In addition, the new planning framework is intended to be in the form of flexible guidelines, as opposed to the Principles and Standards, which were promulgated as regulations. This should give water resource planners more flexibility to address simultaneously additional objectives that are warranted by the planning setting. The major role of multiobjective analysis in implementing the new Principles and Guidelines is discussed by Deason (1982b).

The need for flexibility to address multiple objectives, and the subsequent need for multiobjective decision-aiding techniques, is apparent in many of the documents produced under federal planning guidelines. One recent example was provided by the Central Arizona

Water Control Study, which was concerned with an analysis of flood control alternatives in central Arizona. A 1980 report (U. S. Water and Power Resources Service, p. 15) described how alternatives were subjected to a "screening process" and how the remaining alternatives were subjected to a "trade-off analysis":

> An analysis was made of the cost, performance characteristics, and environmental and social effects of each of these systems (e.g., alternatives). Each of these systems will work (e.g., is feasible), but some will provide more flood control than others, some more regulatory storage than others, while others have fewer environmental and social impacts. To assist in the decision, these values will have to be "traded". In mid-November the decision makers from each of the agencies held a "Trade-off Meeting". They were presented economic, performance, environmental, and social data. (parenthetical comments added)

The usefulness of a multiobjective analytical technique to assist in this decision making process is obvious. The traditional benefit-cost approach to multiobjective optimization problems such as the above has been to reduce all attributes to a common basis of comparison (monetary units) so that a single objective can be optimized. This approach is in some ways more difficult and inherently inaccurate than the multiobjective approach. That is, the benefit-cost approach requires that the benefits and costs be measured in monetary units, which is often difficult or impossible when no markets exist for project outputs. This problem is avoided by multiobjective analysis because noncommensurable benefits and costs are treated as such (Cohon and Marks, 1973, p. 828).

Although the recent rapid growth in the development and application of analytical multiobjective modeling techniques to water resources problems seems to have been motivated largely by the reorientation of federal water planning guidelines toward the simultaneous consideration of multiple objectives, there also exists within the water planning establishment a number of planning functions that are not subject to such guidelines, but which are clearly multiobjective in nature. Goicoechea, Duckstein and Fogel (1976, 1979) address one such application in a study to determine the optimal policies for land treatment with respect to five objectives within the Charleston River watershed in Arizona. Other examples are provided by Dean and Shih (1973, 1975), Reid and Leung (1979), the U.S. House of Representatives (1978) and Ashton, et al. (1980).

The rapid evolution of multiobjective analysis that has characterized domestic water resources planning in recent years has not been paralleled in less developed countries. However, recognition of the value of multiobjective analysis in making water development initiatives responsive to the special needs of such countries appears in the works of the United Nations Economic Commission for Asia and the Far East (1972, p. 58), Biswas (1976, p. 11-12), Major (1977, p. 52-53), and Loucks (1977 and 1978). In addition, the notion that maximizing net national income is the only appropriate objective for less developed countries is apparently beginning to give way to the acceptance of multiple objectives by such organizations as the United Nations Industrial Development Organization and the World Bank (1976, p. 53-65 and Stone, 1981, p. 1).

General Multiobjective Optimization Problem

Now that the relationship between water resources planning guidelines of the federal government and the multiobjective decision-aiding techniques that have been developed to serve those procedures has been traced, the nature of the general problem that these techniques address will be desbribed.

A description of the general multiobjective optimization problem in two dimensions facilitates understanding and has intuitive meaning, whereas a description in greater than two dimensions is more complex and a description in greater than three dimensions cannot be depicted graphically. Therefore, the following discussion is conducted in two dimensions. However, it can be easily generalized into n dimensions.

Assume that a project or program has two noncommensurable and conflicting objectives, A and B. For a large river basin plan, such objectives could be national income and environmental quality, or national income and regional income. For a design problem, the objectives could be the quantity of water stored in a reservoir and the amount of water lost to evaporation.

Assume further that we have identified six alternative solutions to the problem, a - f, all of which are feasible. These are depicted graphically in Figure 3-1. It can be seen that alternative b is preferred to alternative f in terms of objective A, but that the reverse is true in terms of objective B. Therefore, it is not possible, at this stage, to make a statement concerning the relative desirability

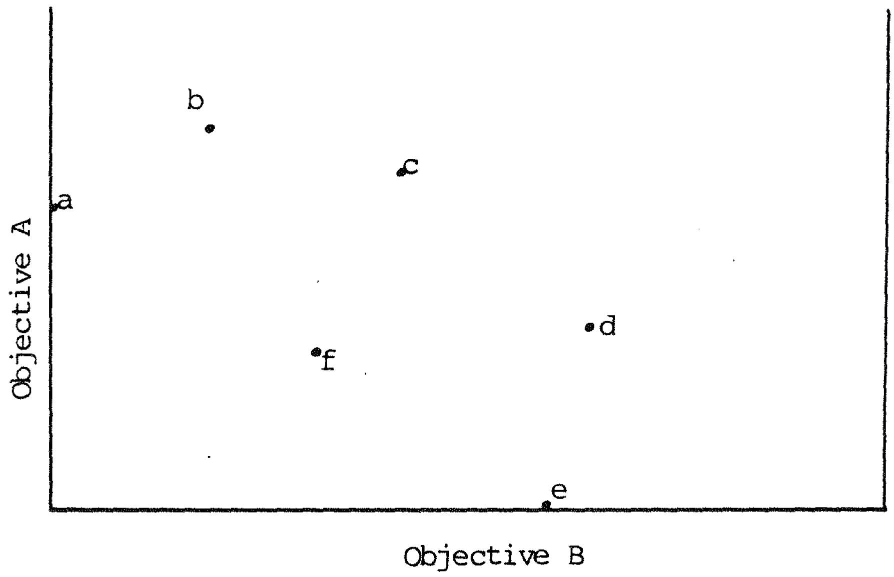


Figure 3-1

Alternative Solutions to Hypothetical Multiobjective Problem

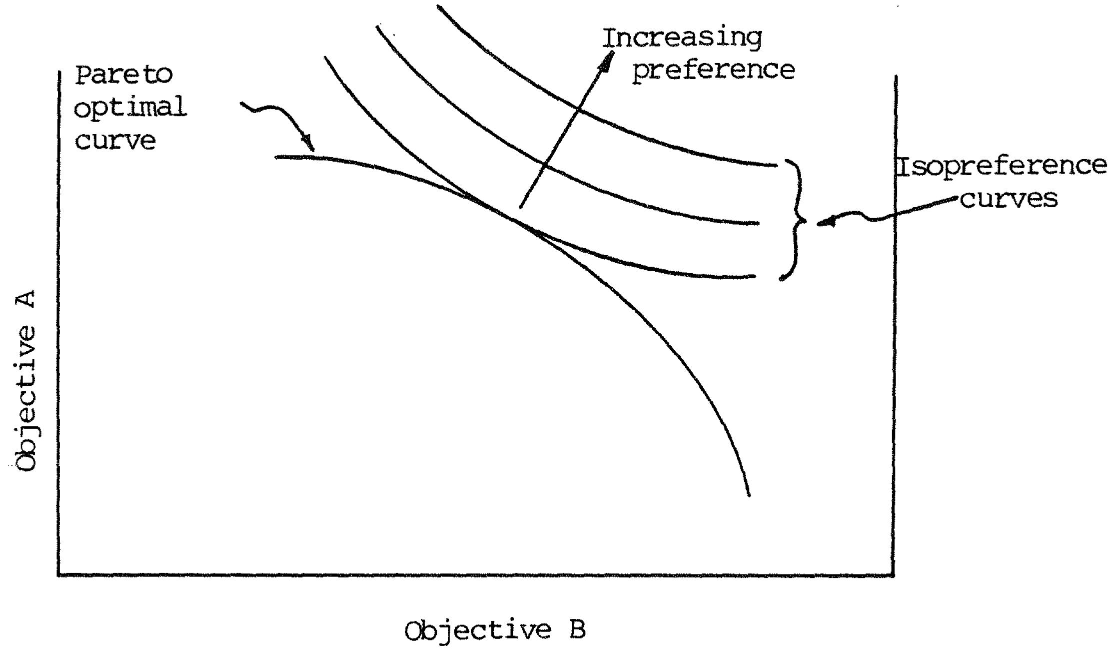


Figure 3-2

Pareto Optimal Curve and Isopreference Curves of alternatives b and f.

However, it can be seen that alternative d is preferred to alternative f in terms of both objectives A and B. Alternative d therefore dominates alternative f, and f should be deleted from further consideration (assuming that only one alternative is to be chosen). Likewise, alternative b dominates alternative a, and d dominates e. Alternatives b, c and d are nondominated, in that no other feasible solutions exist that are superior to any of these alternatives in terms of all objectives. In general, the set of all nondominated feasible solution points forms a Pareto optimal curve, also called a transformation curve or efficient frontier. This concept of Pareto optimality serves as the basis for much of modern welfare economics (Sage, to be published, p. 5.1) upon which multiobjective analysis is based.

For an unconstrained problem, further ordering of the alternatives cannot be conducted without the introduction of value judgments. If exact preference information could somehow be elicited from the decision maker, then a family of isopreference curves could be superimposed over the Pareto optimal curve as illustrated in Figure 3-2. Isopreference curves are a family of curves with the property that any two points on the same curve are equally desirable (Sage, 1977, p. 340-341). The preferred alternative is that which results in the greatest utility, which occurs, for continuous decision variables, at the point of tangency of the highest isopreference curve with the Pareto optimal curve (alternative c).

A simple example will illustrate the usefulness of these concepts in clarifying problems with noncommensurable objectives, and will establish mathematical notation for the remainder of the study. Consider the case of an irrigation construction program which is intended to promote economic development and social well-being of people on Indian reservations. Two noncommensurable objectives of this program might be to maximize the economic return to Indians (measured in dollars) and to maximize the number of Indian beneficiaries (measured in number of people) of the program.

In this simple example, assume that there is only one decision variable, the geographic concentration of investments in Indian irrigation projects. If, at one extreme, it were decided to invest all available funds in the most economically efficient alternative (in terms of dollar returns to Indians), then the former objective would be well served at the potential expense of the latter. For example, if one particular Indian reservation were situated with easy access to high quality water, large expanses of level, highly arable land, a year-round growing season, easy access to markets, and similar attributes, then it is possible that maximum economic return would be acheived by the decision to invest all available funding for irrigation construction on that reservation alone. The total number of Indian people benefitting from the investment would be relatively small.

If, at the other extreme, it were decided to invest all available funds in the most widely dispersed fashion, then the latter objective would be well served at the potential expense of the former. This is likely to occur because the investment of irrigation funding on many Indian reservations provides no economic return, as all of the crops are consumed locally. Many Indian irrigation projects, particularly those on smaller reservations, provide only subsistence units, from which all of the crops are consumed directly by the farmer or bartered locally.

This hypothetical situation is depicted graphically in Figure 3-3. It can be seen that the number of people served increases monotonically with increasing geographic dilution of investments only to a certain point, beyond which it decreases. An explanation of this decrease might be that there exists a point beyond which further geographic dilution of a fixed investment would benefit smaller numbers of people, as some of the expenditures became so small within a given geographic area that they benefit no one. Conversely, it is observed that economic return increases monotonically with decreasing geographic dilution of investments only to a certain point, beyond which it decreases. An explanation of this decrease might be that there exists an optimal size for a fixed investment in irrigation construction, beyond which net economic return decreases.

The problem facing the decision maker in this situation is what quantity to assign to the decision variable such that the most desirable mix of objective accomplishments is attained. The trade-offs between objectives that the decision maker must face in arriving at a decision is illustrated in Figure 3-4.

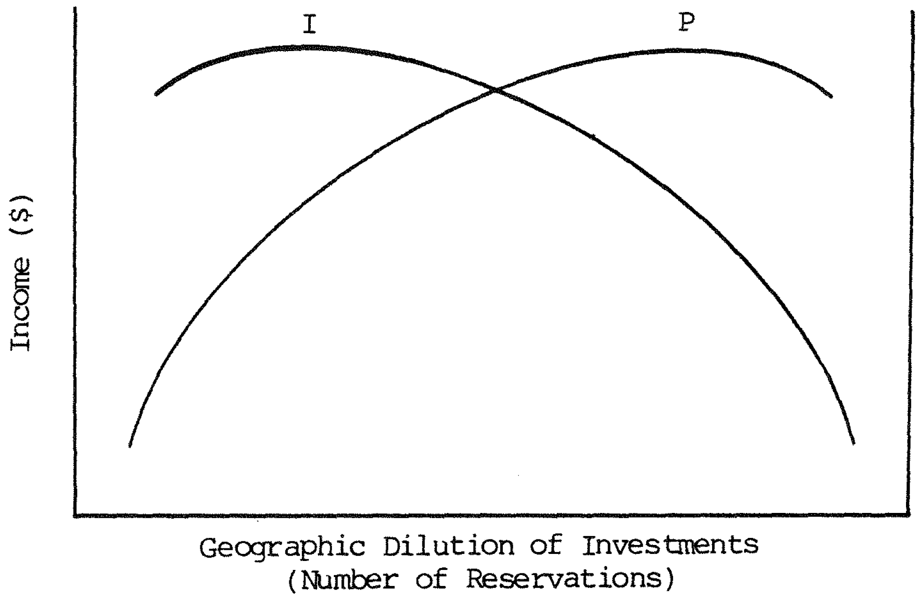


Figure 3-3

Income and People Objectives in the Decision Space

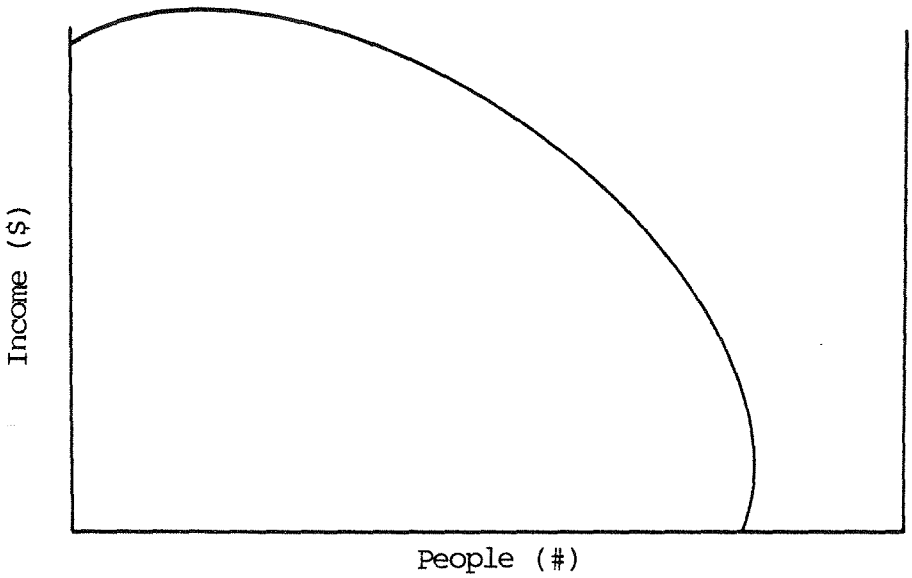


Figure 3-4

Income and People Objectives in the Objective Space

This problem can be described mathematically as:

$$\max_{x} \{f_1(x),\ f_2(x)\} \tag{3-1}$$

subject to

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \tag{3-2}$$

$$x \geq 0 \tag{3-3}$$

where $f_1(x)$ and $f_2(x)$ are the two objective functions, x is the single decision variable and the $g_j(x)$ represent n constraints imposed on the problem (such as the largest or smallest number of reservations on which a fixed investment level can be spent within a given fiscal year).

Of course, an initial screening of all possible values of x and the objective function vector $\underline{f}(x)$ can be obtained by examining feasibility. The constraints $g_j(x)$, $j = 1, 2, \ldots, n$ define the feasible set of values for the decision variable x. If we denote this feasible set as Y, then Y is defined in vector notation as $Y = (x | \underline{g}(x) \leq 0)$. Further, each feasible value of x, or each $x \in Y$, determines a unique value of $\underline{f}(x)$. If we denote this feasible set as Z, then Z is defined as $Z = (\underline{f}(x) | x \in Y)$. Infeasible regions in our hypothetical example are illustrated in Figures 3-5 and 3-6.

Further screening of the set of all feasible solutions can be obtained by applying the concept of noninferiority. In this example, a noninferior solution is a feasible solution $x \in Y$, such that no other feasible solution $x' \in Y$ exists such that $\underline{f}(x') \geq \underline{f}(x)$, with $f_i(x') > f_i(x)$ for at least some i. That is, a noninferior solution

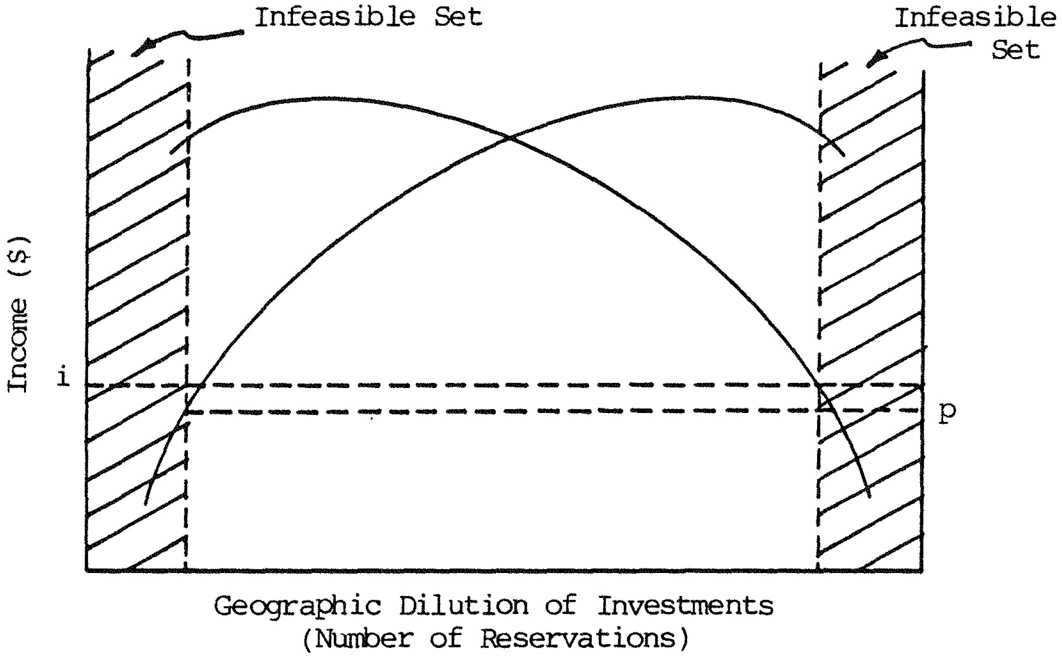


Figure 3-5

Feasible Solution Set in the Decision Space

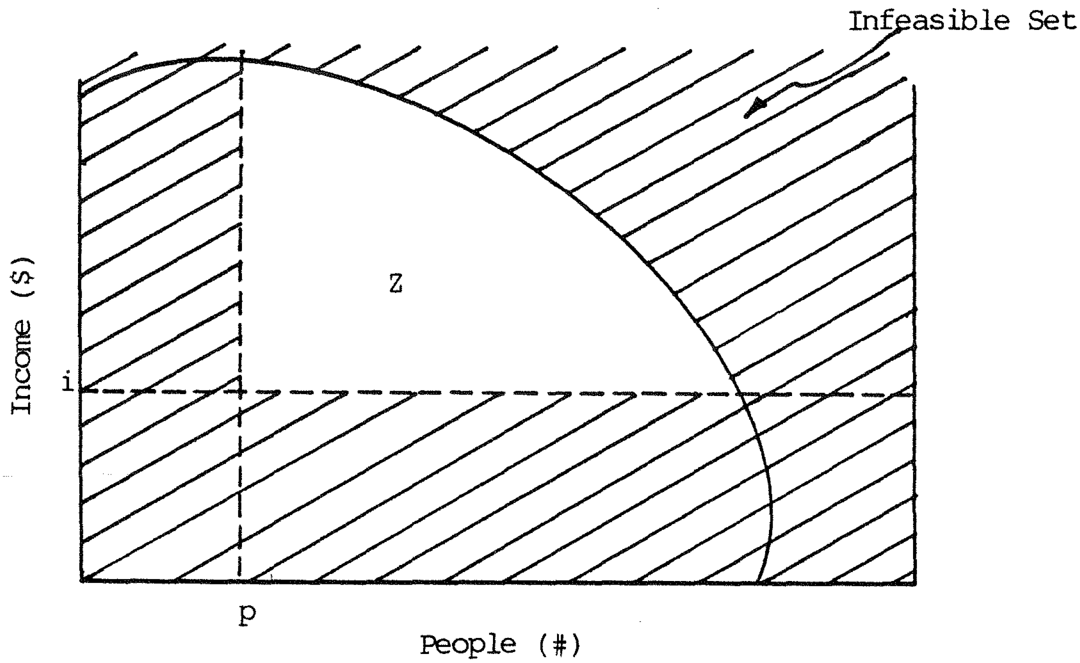


Figure 3-6

Feasible Solution Set in the Objective Space is one in which no improvement can be made in terms of either of the two objectives without a simultaneous decrease in the value of the other objective. In Figures 3-7 and 3-8, it can be seen that every point in the interval between those solution points defining $f_1^*(x)$ and $f_2^*(x)$ is a noninferior point.

Further ordering of the feasible solution set requires the introduction of value judgments. Theoretically, the preferences of the decision maker for various combinations of economic return ($f_1(x)$) and numbers of people served ($f_2(x)$) at a fixed investment level can be represented by a family of isopreference curves. Since we have assumed that the joint utility of $f_1(x)$ and $f_2(x)$ is monotonically increasing in both $f_1(x)$ and $f_2(x)$, this family of curves might typically appear as illustrated in Figure 3-2. These isopreference curves have the property that any two points $(f_1(x_1), f_2(x_1))$ and $(f_1(x_2), f_2(x_2))$ are equally desirable if and only if they are on the same isopreference curve (Sage, 1977, p. 340). The greatest satisfaction is attained at the point of tangency between the Pareto optimal frontier and the highest isopreference curve, or $(f_1(x^*), f_2(x^*))$ in Figure 3-9.

The essence of the decision making process is to choose the alternative that provides that point of greatest satisfaction. All of the multiobjective decision-aiding techniques that are reviewed in this study represent attempts to assist the decision maker (or, in some cases, a number of decision makers) in finding an alternative that approaches the point of greatest satisfaction, referred to herein as the "most preferred solution."

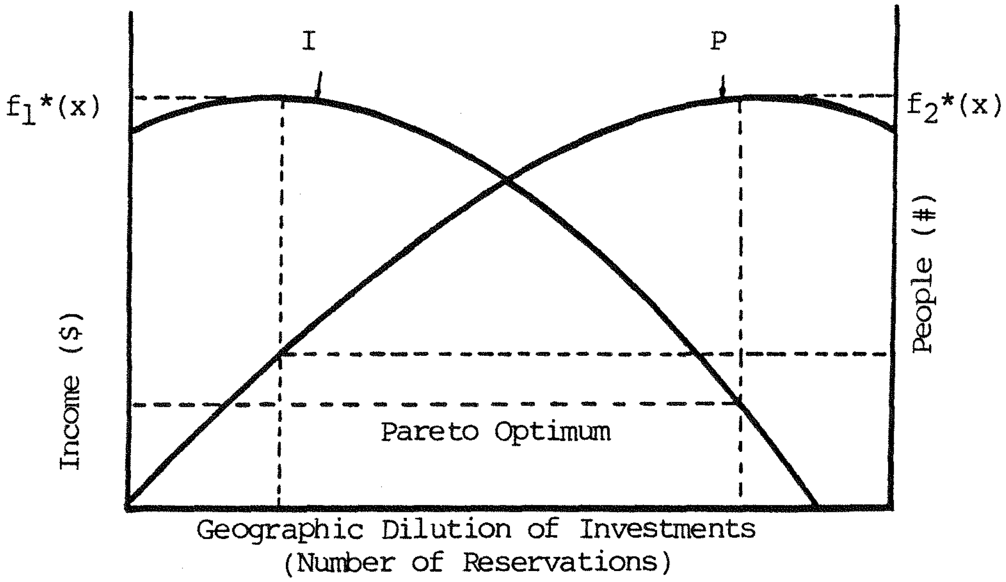


Figure 3-7

Pareto Optimal Solution in the Decision Space

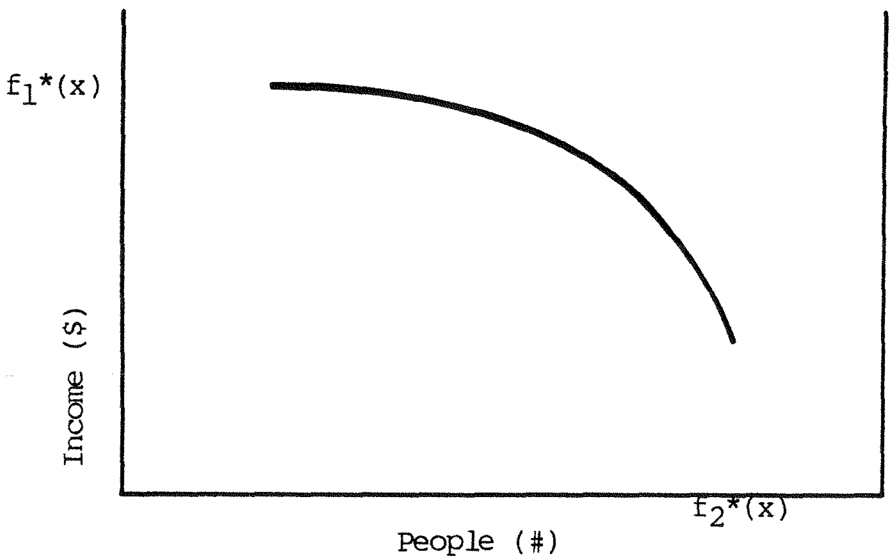


Figure 3-8

Pareto Optimal Solution in the Objective Space

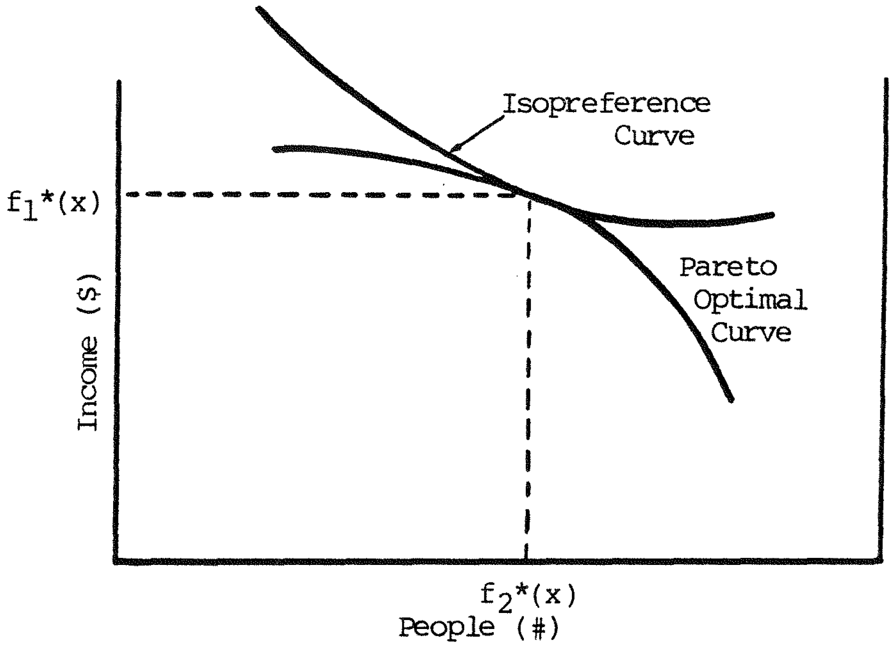


Figure 3-9

Most Preferred Solution

Chapter 4

LITERATURE REVIEW

Previous Surveys of Multiobjective Decision-Aiding Methods in Water Resources Planning and Management

In the past ten years, there have been at least six attempts to bring some order to the proliferation of multiobjective decision-aiding techniques that have been developed for, or applied to, water resources planning problems. Although this may seem to indicate that considerable duplicative work has been undertaken, such is not the case. These six literature reviews have had widely varied purposes, scopes, degrees of exhaustiveness, and perspectives. Such differences are manifested by the fact that each established different categories into which the multiobjective decision-aiding techniques are grouped, and, for those that performed an evaluation function, each used different evaluation criteria.

The fact that each of the six reviews established different categories and evaluation criteria is not surprising, since the problems of grouping and evaluating multiobjective decision-aiding techniques are themselves multiobjective in nature. No category is fully appropriate or exclusive, because most of the techniques have attributes which could place them in more than one category, regardless of the categories that are established. Evaluation criteria can be used to assess the utility of the various multiobjective decision-aiding techniques only with respect to specific problems. For different problems, for example, our relative concerns for accuracy, computational efficiency, the amount of information provided to the decision maker, the explicitness of trade-offs, the amount of data needed, the level of resources required, and the amount of time demanded of the decision maker could vary considerably. Cohon and Marks (1977, p. 693) wrote that the use of different sets of criteria to evaluate multiobjective optimization techniques is not inconsistent, but in fact is desirable because it is helpful in gaining "insight into the relevance of different techniques in different situations."

A compendium of the six previous survey efforts is presented in Table 4-1 and in Appendix A. Table 4-1 contains a listing of the multiobjective decision-aiding categories that were used in the six surveys and Appendix A contains a display of the categories into which the works of various authors were placed in each survey. A note of explanation concerning Appendix A is in order. Matrix entries appear only where the authors of the respective surveys have associated the various works with one or more of their categories. In some instances, the survey authors have referenced works that they did not associate with any particular category. In such cases, no entry appears.

The findings of each of these six surveys are summarized in this section. This summary provides a basis for the development of a classification scheme used in the next section to structure a focused, conprehensive and up-to-date review of multiobjective decision-aiding techniques that have been used to assist in solving water resources problems.

<u>Cohon</u> (1973)

The first significant review of multiobjective decision-aiding techniques used in a water resources planning context was provided by the graduate research work of Jared L. Cohon. In his doctoral dissertation (1973), Cohon sought to compare and evaluate multiobjective decision-aiding techniques in terms of their applicability to river basin planning problems. His work is broad in scope and, at the time it was written, was comprehensive in the sense that it addressed the major multiobjective decision-aiding techniques in existence with potential applicability to river basin planning. However, it made little effort to discover the extent to which researchers and practitioners had achieved success in applying the various techniques to actual river basin planning problems. This latter approach may not have been appropriate, however, as multiobjective decision-aiding techniques had not been widely applied to water resources planning problems prior to 1973, as we have seen.

Cohon's 1973 work was concerned largely with the manner in which the various techniques elicit value judgments of decision makers and how they incorporate these value judgments into the solution process. This included the appropriate respective roles of analysts and decision makers and the extent to which the opinions or biases of the analyst were allowed to influence the decision. Cohon also examined the practicability of the various techniques with respect to computer budget constraints.

These perspectives provided the foundations for the evaluation

Table 4-1

Categories Established by Previous Surveys of Multiobjective Decision-Aiding Techniques

Cohon (1973)	A. Black box decision making 1. Choice techniques a. Weighting method b. Constraint method c. Adaptive search method d. Approximation of the noninferior set by curve fitting e. Derivation of a functional relationship for noninferior sets 2. Value techniques a. Utility functions b. Estimation of optimal weights c. Goal programming d. Surrogate worth tradeoff method e. Generation of stronger partial orderings B. Explicit decision making 1. Interactive techniques a. Step method b. Interactive weighting method c. Interactive goal programming 2. Multiple decision maker techniques a. Restricted bargaining method b. Paretian analysis c. Vote-trading algorithms
Cohon and Marks (1975)	A. Generating techniques 1. Weighting method 2. Constraint method 3. Derivation of a functional relationship for noninferior sets 4. Adaptive search B. Techniques which rely on prior articulation of preferences 1. Goal programming 2. Assessing utility functions 3. Estimation of optimal weights 4. Electre method 5. Surrogate worth trade off method C. Techniques which rely on progressive articulation of preferences 1. Step method 2. Iterative weighting method 3. Sequential multiobjective problem solving

Table 4-1 (continued)

Haimes, Hall and Freedman (1975)	A. Utility functions B. Indifference functions C. Lexicographic approach D. Parametric approach E. Epsilon-constraint approach F. Goal programming G. Goal attainment method H. Adaptive search approach I. Interactive approaches J. Other approaches

Bishop, McKee, Morgan, and Narayanan (1976)	A. Visual techniques
	B. Rating and ranking methods
	C. Matrix and linear scoring
	D. Tradeoff displays and analysis
	E. Multiobjective programming
	  1. Lexicographic ordering
	  2. Parametric
	  3. Constraint
	  4. Goal programming
	  5. Marginal value tradeoffs
	  F. Goals evaluation methods
	  G. Iterative methods

Cohon (1978)	A. Discrete multiobjective problems
	B. Continuous multiobjective problems
	  1. Generating techniques
	    a. Weighting method
	    b. Constraint method
	    c. Noninferior set estimation
	    d. Multiobjective simplex method
	  2. Techniques that incorporate preferences
	    a. Multiattribute utility functions
	    b. Prior assessment of weights
	    c. Methods based on geometrical definitions of best
	    d. Surrogate worth tradeoff method
	    e. Iterative techniques
	  3. Multiple decision-maker techniques
	    a. Techniques for the aggregation of individual preferences
	    b. Methods used to counsel a single DM
	    c. Techniques for the prediction of political outcomes

Mades and Tauxe (1980)	A. River basin planning models B. Water quality management models C. Reservoir management models

criteria Cohon employed, as well as the categories of multiobjective optimization techniques that he established. The evaluation criteria were divided into two groups: decision making criteria, which he used to evaluate how consistent the techniques were with his model of the political decision making process; and computational criteria, which he used to determine how practical the techniques were in light of limited budgets. The specific evaluation criteria (pp. 89-100) were:

Decision making criteria.

- the number of models of the decision making process to which the techniques are compatible
- the extent to which the decision making process is explicitly considered by the techniques
- the number of value judgments required by the techniques
- the sensitivity of the techniques to the number and accessibility of decision makers

Computational criteria.

- the size of models to which the techniques are applicable (number of constraints and decision variables)
- the sensitivity of the techniques to the number of objectives
- the sensitivity of the techniques to the number of solutions which are necessary to obtain an adequate representation of the problem

The categories that Cohon established for grouping the techniques are listed in Table 4-1. The "black box" techniques are those that do not model the decision process, whereas the "explicit decision making" techniques are those that model explicitly the decision process. The "choice" techniques are those that simply supply information to the decision maker (a decision maker's choice of a solution using these techniques would imply his value structure), whereas the "value" techniques require value judgments from the decision maker prior to the solution process (the value structure of the decision maker explicitly determines his choice of a solution). In "interactive" techniques, the decision maker's preferences guide the decision process, whereas the "multiple decision maker" techniques attempt to predict the outcome of the decision process. Cohon drew a number of conclusions regarding conditions under which the various categories could be most advantageously used and made numerous interesting observations about the relative advantages and disadvantages of the techniques within each category.

Cohon and Marks (1975)

In 1975, Cohon and Marks summarized and extended much of Cohon's previous work. The purpose of Cohon and Marks' work (p. 208) was to evaluate "proposed multiobjective solution techniques," to draw "conclusions on the applicability of vector optimization techniques to water resource planning problems," and to identify "useful directions for future research in multiobjective problems."

As can be seen in Appendix A, Cohon and Marks' review is not comprehensive, but the works that are included in that review are representative of a broad scope of multiobjective optimization techniques. The categories (Table 4-1) that were used by Cohon and Marks to group the various techniques are based on the relative roles of the decision maker and analyst. This set of categories is especially appropriate for the range of techniques examined and is similar to the classification scheme used later in this paper.

The Cohon and Marks paper reflects a primary interest in the mathematical characteristics of the various approaches, rather than in an investigation of the demonstrated utility of the methods. The three evaluation criteria applied by the authors are: computational feasibility and efficiency, explicitness of quantification of the trade-offs among objectives, and the quantity of information generated for decision making (portions of the noninferior solution sets and portions of the sets of all trade-offs among objectives corresponding to the noninferior sets that are generated).

Cohon and Marks applied these three evaluation criteria and concluded that techniques such as the weighting or constraint methods are most advantageously used when there are fewer than four objectives, and that techniques that restrict the size of the feasible region, such as the surrogate worth trade-off method, are most appropriate when there are four or more objectives. They also concluded that several techniques are not generally applicable to multiobjective water resource problems, but that every technique is applicable in at least some situations (p. 219).

Haimes, Hall, and Freedman (1975)

Also in 1975, Haimes, Hall and Freedman published a text that contained a survey of existing multiobjective decision-aiding techniques (p. 15-33). The purpose of this survey (p. 15) was to review "solution methodologies for multiple objective problems." Again, no attempt was made by the authors to undertake a comprehensive review of existing works, although the works that are referenced do constitute a good representation of a variety of approaches to multiobjective decision-aiding. The scope of this review is indicated in Appendix A. The emphasis of the Haimes, Hall and Freedman review is primarily on a description of the characteristics of the techniques, and little effort is devoted to explanations of the circumstances in which the methods can be most advantageously used.

The authors did not attempt to evaluate the various techniques and therefore did not establish evaluation criteria. The categories used by Haimes, Hall and Freedman were based on the characteristics of the methods, as can be seen in Table 4-1. Although such a classification contributes to an understanding of the types of techniques that have been developed, it would result in a significantly greater number of categories than the 10 that the authors used if a more comprehensive review were undertaken.

Bishop, McKee, Morgan, and Narayanan (1976)

The next survey of multiobjective optimization methods had a significantly different scope and perspective than the three previous ones. The work of Bishop, et al. (1976) is oriented more toward the practical application of the techniques that are reviewed, and includes a very broad range of techniques, including a review of non-mathematical techniques for evaluating alternatives to problems with multiple objectives. The purpose of the paper (p. 24) was to review

> the characteristics and capabilities of various multiobjective methods as to their usefulness in generating the information required by (the set of technically feasible noninferior alternatives and the social preferences for alternative outputs) as well as their appropriateness to the various activities and phases of the planning and decision-making process.

As implied by the statement of purpose, the evaluation conducted by Bishop, et al. is oriented toward practical application. The authors used three types of evaluation criteria: "implementation characteristics" (such as quantity of data or level of resources required), "technical content attributes" (attributes related to the development of the noninferior set, such as the portion of the noninferior set that is generated or the explicitness of the trade-offs that are generated), and "value content attributes" (attributes related to elicitation of the value structure of the decision maker).

The authors concluded that three of the six categories that they used (Table 4-1) -- visual techniques, rating and ranking methods, and matrix and linear scoring methods -- can lead to faulty decision making because these tend to aggregate information and obscure trade-offs. These methods were found to be useful, however, in a screening role early in the planning process. They further concluded that two other categories, multiobjective programming and goals evaluation methods, are effective in generating the noninferior solution set and in describing trade-offs.

Cohon (1978)

In 1978, Cohon published an excellent text on multiobjective programming and planning. This work amplifies and extends Cohon's previous efforts and includes multiobjective decision-aiding techniques that are applicable to problems with multiple decision makers and to problems concerning the predictions of political outcomes. The text does not examine techniques that are applicable primarily to problems with a finite number of discrete alternatives or techniques that attempt to assist the cognition of the decision maker directly (such as visual attribute displays).

The purpose of Cohon's text is to provide a reference and a textbook on a wide range of multiobjective programming and planning methodologies. The perspective of the text involves an examination of the applicability of multiobjective decision-aiding techniques to public decision making problems. The author makes an effort to stress the pragmatic aspects of such techniques.

The categories that Cohon established were based on the "characteristics of the decision-making process" in which a problem is addressed (p. 85). According to this concept, in situations involving a single decision maker with a "bottom-up" information flow (from analyst to decision maker), generating techniques are appropriate. Where a single decision maker and a "top-down" information flow (from decision maker to analyst) exists, techniques that incorporate preferences are appropriate. For conflict resolution situations, multiple decision maker methods are appropriate. A full listing of Cohon's categories appears in Table 4-1.

Unlike his previous works, Cohon's text does not attempt to evaluate the various multiobjective decision-aiding methods and therefore does not establish evaluation criteria. The reason given for this is that an evaluation cannot be undertaken unless it is conducted with respect to a specific problem and decision making context.

In his conclusions, Cohon tends to favor generating techniques because they are felt to be the most widely applicable and because they introduce lesser amounts of the bias of the analyst into the decision making process than do other methods. He also indicates that interactive techniques are an exciting area of future analysis, which is a distinct change from the opinions of these techniques that he expressed in his 1975 work with Marks. Finally, he expressed an opinion that multiple decision maker methods and increased emphasis on practical applications were the most promising directions of endeavor in future years.

Mades and Tauxe (1980)

In 1980, Mades and Tauxe conducted a study of multiobjective decision-aiding techniques for the Office of Water Research and Technology in the U. S. Department of the Interior that took a different approach than did any of the previous surveys. Mades and Tauxe examined the applicability of various multiobjective decision-aiding methods to different types of water resource problems. Accordingly, the categories established represent three broad classes of water resources problems: general river basin planning, water quality management, and reservoir management models. The authors also presented a very brief and general review of vector optimization algorithms, which they categorized along the lines of the 1975 Cohon and Marks work: trade-off function generating techniques, techniques requiring prior articulation of preferences, and techniques requiring progressive articulation of preferences.

Although the Mades and Tauxe study is not comprehensive, as indicated by Appendix A, it does provide an interesting overview of the demonstrated utilities of various approaches toward solving real multiobjective problems. In addition, the authors attempted to evaluate the performances of various multiobjective decision-aiding techniques under the number and types of constraints, decision variables and objectives that were established by other investigators in applying the techniques to real problems. Mades and Tauxe concluded only that multiobjective decision-aiding techniques can be applied effectively to complex, large-scale water resources planning problems.

A New Taxonomy of Multiobjective Decision-Aiding Methods in Water Resources Planning and Management

Although each of the six surveys of multiobjective decision-aiding techniques that have been reviewed herein have contributed to the body of knowledge that exists in this field, none are restricted to those techniques that have been developed for, or applied to, problems concerned with the optimal development, management, control and use of water resources, and none are thoroughly comprehensive in that sense. In addition, because of the rapid advances that are being made in the application of multiobjective decision-aiding techniques to water resources problems, none are fully up to date currently.

Presented here are the results of a comprehensive study of multiobjective decision-aiding techniques that is intended to extend the previous work in this area and to contribute to the existing body of knowledge by providing a summary review that is:

- clearly focused on those techniques that have been developed for, or applied to, water resources problems, or which appear to have the potential for being applied to such problems in the future;

- thoroughly comprehensive within the above stated scope of the review;

- ordered in a rational manner so that it promotes effectively an understanding of the relationships among the various approaches and the conditions under which each may be most appropriately used; and

- an accurate reflection of the current state of the art.

Since this review is focused on normative decision-aiding techniques within a water resources context, models which are descriptive in nature generally are excluded, with several exceptions. Examples of such models are those that attempt to predict the political outcomes of decision situations. Such models are described in the works of Cohon (1973 and 1978) and Keith, et al. (1977).

In order to facilitate an understanding of the various decision-aiding techniques and to promote efficiency and effectiveness in their use, it is helpful to establish categories based on common characteristics of the techniques. The characteristics used in this review to establish such categories involve the ways in which the different techniques elicit preference information from the decision maker. For the purposes of establishing such categories, the decision maker is assumed to be a known single individual. Although several of the techniques that are summarized herein could be or have been applied to decision situations in which there are multiple decision makers, all except the Techcom method are applicable to the single decision maker situation. Although the assumption of a single decision maker is not a realistic one for every decision situation (although it is for some), such an assumption is useful for clarifying the nature and uses of the various techniques.

The categories that are used for this review are presented in Table 4-2. In addition, Appendix A provides a summary overview of the categories into which the works of various authors that have developed multiobjective decision-aiding techniques for, or applied them to, water resource problems, are grouped. Appendix A also includes the categories into which various works were grouped in the previous survey efforts. Such a comparison reveals how the current study is related to those conducted in past years. The ensuing discussion follows the order of Table 4-2.

Category A - Nondominated Solution Generating Techniques

The techniques of Category A, referred to as "generating" techniques, make no attempt to incorporate the preferences of the decision maker into the decision-aiding process. These techniques simply generate the set of nondominated solutions and tradeoffs between objectives at various levels of objective accomplishment. In other words, they assist the decision maker by reducing the set of all possible alternatives to the set of Pareto optimal solutions illustrated in Figures 3-7 and 3-8.

The categories below are ordered in terms of decreasing frequency

Table 4-2

Multiobjective Decision-Aiding Techniques

A. Nondominated solution generating techniques
   1. Constraint method
   2. Weighting method
   3. Multiobjective dynamic programming
   4. Multiobjective simplex method
   5. Noninferior set estimation method

B. Techniques involving a priori complete elicitation of preferences
   1. Optimal weights
   2. Utility theory
   3. Policy capture
   4. Techcom method

C. Techniques involving a priori partial elicitation of preferences
   1. Lexicographic approach
   2. Goal programming
   3. ELECTRE method
   4. Compromise programming
   5. Surrogate worth trade-off method
   6. Iterative Lagrange multiplier method

D. Techniques involving progressive elicitation of preferences
   1. Step method
   2. Semops method
   3. Trade method
   4. Pairwise comparisons
   5. Tradeoff cutting plane method

E. Visual attribute level displays
   1. Objective achievement matrix displays
   2. Graphical displays
   3. Mapping

of use in water resources problems.

Constraint method. Perhaps the most widely used generating technique, and one that is used in conjunction with a number of other techniques, is the constraint method. In this approach, one objective is optimized while the remaining objectives are constrained to some specified value. This generates one point on the Pareti optimal curve. Then, the constraint values are varied sequentially in conjunction with repetitions of the optimization process, thus producing other nondominated solutions. This process continues until the entire nondominated solution set is generated. Using our previous example, the problem defined by equations (3-1), (3-2) and (3-3) becomes

$$\max_{x} f_1(x) \tag{4-1}$$

subject to

$$f_2(x) \geq \varepsilon \tag{4-2}$$

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \tag{4-3}$$

$$x \geq 0 \tag{4-4}$$

where ε is chosen such that a feasible solution to the single objective optimization problem exists, and is parametrically varied to obtain the nondominated solution set. A systematic way to carry out this procedure is to choose for the initial value of ε, that value of x that satisfies

$$\max_{x} f_2(x) \tag{4-5}$$

subject to

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \tag{4-6}$$

$$x \geq 0 \tag{4-7}$$

and then to reduce sequentially the value of ε until it reaches the value of x that satisfies

$$\max_{x} f_1(x) \qquad (4\text{-}8)$$

subject to

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \qquad (4\text{-}9)$$

$$x \geq 0 \quad . \qquad (4\text{-}10)$$

For n objectives, one would select one objective to optimize, subject to (n - 1) additional constraints.

The theoretical basis of the constraint method for generating the nondominated solution set has been discussed by a number of authors, including Cohon (1973, p. 134-143), Loucks and Haith (1973, p. 43-44), Haimes and Hall (1974, p. 617-618), Cohon and Marks (1975, p. 211-212), Haimes, Hall and Freedman (1975, p. 19-23), Haimes (1977, p. 225), Haimes, Das and Sung (1977, p. 38-40), Tauxe, Inman and Mades (1979a, p. 1398) and Mades and Tauxe (1980, p. 40).

Three major areas of water resources problems are planning, design and operation. Of these, planning is the one to which the constraint method has been the most frequently applied.

Perhaps the first use of the constraint method was by Marglin (1966, p. 77-78, first published in 1964). Marglin introduced the concept of representing objectives by constraints in a hypothetical two-objective planning problem. Although he stopped short of generating the entire nondominated set, he did address the possibility of varying the level of the constrained objective to generate several alternatives to be presented to the decision makers. In his 1967 work, Marglin (p. 24-25 and 29-32) more explicitly illustrated how the constraint method could be used to generate a variety of nondominated solutions.

Rogers similarly used a constraint method approach in 1969 in an international river basin planning problem. Rogers created a two-objective problem by reducing six objectives within each of two countries to a single objective in each country, using the common attribute of net monetary benefits. He then generated two nondominated alternatives in terms of net benefits to each country and suggested that the countries would negotiate a compromise solution between them.

A partial constraint method approach was again used in 1973 by Andrews and Weyrick, who examined the effects of various policies in a river basin planning problem. The authors postulated a large number of objectives, and then generated alternatives in which each objective was optimized in turn, while the other objectives were left unconstrained. This procedure, in effect, located the set of extreme points on the nondominated surface. Andrews and Weyrick then calculated shadow prices (trade-off ratios) at these extreme points to assist them in developing qualitative predictions of the effects of various policy approaches.

A major study of water resource development potential in the Rio Colorado basin in Argentina, carried out in 1970-1973 by a group of faculty and students from the Massachusetts Institute of Technology in conjunction with members of the Argentinian State Secretariat for Water Resources, also utilized a partial constraint method approach. As summarized by Major and Lenton (1979, p. 74-75 and 179-192), the multiobjective formulations developed by the group were most often optimized with all but one objective treated as constraints.

Miller and Byers (1973) and Byers and Miller (1975) used the constraint method to generate nondominated solutions for a series of two-objective problems, trading off a national economic objective against each of 11 environmental objectives (such as the level of phosphorus loads in the water) for a Soil Conservation Service small watershed project in Indiana. As formulated by the authors, the problem contained nine structural design alternatives and 10 land management practices (which could be combined into many land management alternatives). Initially, an economic objective was optimized, unconstrained by environmental considerations. Then the authors developed trade-off curves between the economic objective and each of the environmental objectives by holding 10 of the 11 environmental objectives fixed at their levels in the optimal economic alternative, and maximizing net economic benefits subject to parametrically varied levels of the non-fixed environmental objective. These trade-off curves were then to be presented to the decision maker to aid in the decision process. Since the decision maker would be faced with a set of such trade-off curves (each displaying the trade-offs between the economic objective and one of the environmental objectives), the authors concluded that it would be desirable to aggregate the environmental objectives whenever they are large in number. In their 1973 work, the environmental objectives were aggregated by averaging the percentage reductions in environmental pollutants at various levels of the economic objective to produce a two-dimensional trade-off curve, which would then be used by the decision maker.

Major, et al. (1974) generated transformation curves among the three objectives of national income, environmental quality and income redistribution in the Lehigh River Basin, Pennsylvania. The model was developed to provide a project alternative screening mechanism for planners at the district level in the Corps of Engineers or the regional level in the Bureau of Reclamation.

In 1976, Brill, et al. used the constraint method to assist in an analysis of potential water quality management policies for the Delaware Estuary. The authors postulated the two objectives of total investment costs and equity, where equity was defined as the sum of the deviations from the most equitable situation (e.g., requiring all polluters to obtain the same removal efficiencies). They then minimized the equity deviations, subject to a parametrically varied cost constraint, to obtain the nondominated solution set, but did not address the issue of obtaining the preferred solution from the nondominated set.

Croley and Rao (1977) incorporated the stochastic nature of reservoir inflows in analyzing the tradeoffs between flood control and recreational benefits. These authors synthetically generated 10 inflow patterns for the Coralville Reservoir near Iowa City, Iowa and calculated benefit trade-off curves for each inflow pattern. No specific reservoir operating policy was identified from this exercise. Instead, the trade-off curves were provided to the reservoir managing agency as a convenient display which could be used to improve operating decisions.

In 1982, Louie, Yeh and Hsu used the constraint method to develop a test set of nondominated river basin management plans in terms of three objectives: minimization of water supply and wastewater disposal, minimization of water quality degradations, and minimization of groundwater table declines.

In recent years, a frequent use of the constraint method has been as part of the application of the surrogate worth trade-off method, commonly referred to in the literature by the acronym of SWT. The SWT method generally involves two phases: generation of the nondominated set and elicitation of the preferences of the decision maker, using information contained in the nondominated set. The second phase of the SWT method will be addressed later.

In 1975, Haimes and Hall used the constraint method in a demonstration of the application of the SWT method to a hypothetical three-objective water quality planning problem. In 1978, Lindsay also used it to generate the nondominated solution set as part of an application of the SWT method to a two-objective model of policy options for wastewater sludge disposal in Boston.

Perhaps the most rigorous test to date of a multiobjective decision-aiding technique within an actual water resources planning situation was provided by the application of the SWT method to the planning of the Maumee River Basin. The Maumee River Basin planning study, which will be summarized later in the discussion of the SWT method, involved extensive use of the constraint method for generating nondominated solutions in models with up to six objective functions. These applications of the constraint method are discussed in Haimes, Das and Sung (1977, p. 106-109), Haimes (1977, p. 314-317), Haimes, Das and Sung (1979,

p. 58-59) and Das and Haimes (1979, p. 1318-1320).

Although the primary use of the constraint method to date has been for planning, its usefulness for design studies has been demonstrated in at least three works. Haimes and Hall (1974) demonstrated how the constraint method can be useful for design decisions when they applied the SWT method to obtain a preferred solution to the Reid-Vemuri reservoir sizing problem (1971), using a hypothetical decision maker. The Reid-Vemuri problem contains three objectives (minimize cost, minimize the annual volume of water lost to evaporation, and maximize reservoir volume) and two decision variables (man-hours of construction labor and mean radius of the reservoir). Also in 1974, Croley used the constraint method to generate nondominated alternatives in a cooling-tower design problem. Croley's problem contained two objectives: minimize excess costs over the least-cost design and minimize the incidence of fogging caused by the cooling tower. In the same work, Croley also demonstrated the use of the constraint method in a reservoir problem. In this demonstration, he generated alternative reservoir operations plans that maximized both flood control benefits and the number of recreational user-days spent at the reservoir.

In 1975, Miller and Erickson used the constraint method to generate nondominated solutions to a five-objective model (minimize cost and minimize each of four water quality parameters) of an urban storm drain design problem in West Lafayette, Indiana.

Weighting method. In the weighting method, the objective function becomes a weighted sum of the objectives in the problem formulation. To illustrate, our example problem becomes:

$$\max_{x} \sum_{k=1}^{2} w_k f_k(x) \qquad (4\text{-}11)$$

subject to

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots , n \qquad (4\text{-}12)$$

$$x \geq 0 \; . \qquad (4\text{-}13)$$

In order to generate the nondominated solution using the weighting method, the objective weights w_k are varied parametrically as the optimizations are carried out. Usually, the objective weights are normalized such that $\sum_{k=1}^{2} w_k = 1$.

The weighting method has a drawback that is not true of the constraint method in that it cannot find all nondominated solutions when the feasible region in the objective space is not convex.

Like the constraint method, the theory of the weighting method has been discussed by a number of authors. These include Cohon (1973, p. 122-134), Haith and Loucks (1973, p. 46), Haimes and Hall (1974, p. 617), Cohon and Marks (1975, p. 211), Haimes, Hall and Freedman (1975, p. 17-19), Haimes (1977, p. 220), Tauxe, Inman and Mades (1979a, p. 1398) and Mades and Tauxe (1980, p. 39-40).

Although conceptually similar to the constraint approach, the weighting method has not been used as often. One of the first uses was by Marglin (1967, p. 23-37), who demonstrated how the assignment of various values to the objective weights could be used to generate nondominated solutions. In 1970 Dorfman and Jacoby used the weighting method in a descriptive political decision making prediction model. Dorfman and Jacoby varied the weights assigned to the objective functions of each of a number of constituent groups to see how the weights affected the set of efficient solutions.

Reid (1971) and Reid and Vemuri (1974) used a weighting approach in the development of a functional relationship between the objectives and the objective weights in a problem with Cobb-Douglas type objective functions; that is, those of the form

$$f_i(\underline{x}) = \prod_{j=1}^{n} x_j^{a_{ij}} \quad i = 1, 2, \ldots, q \quad . \qquad (4\text{-}14)$$

The motivation was to produce a generating technique in which a nondominated point in the objective space could be generated by the substitution of a set of weights into the functional relationship. However, Cohon (1973, p. 149-150) and Cohon and Marks (1975, p. 212-213) found the application of Reid and Vemuri's approach to be extremely limited due to the necessity of having the objectives expressed in the Cobb-Douglas form, the fact that it is limited to unconstrained problems, and the computational intractability that results when more than a few decision variables are involved. In 1978, Passey investigated the Reid-Vemuri approach and showed that, if the objective functions are of the Cobb-Douglas type, then either all solutions are dominated or all solutions are nondominated. In the case of the Reid-Vemuri example, all solutions are nondominated.

In 1979, Thampapillai and Sinden used the weighting method to develop the Pareto optimal curve in a two-objective (maximization of income and environmental quality) problem. The authors then used the results to examine alternative water development plans for New South Wales, Australia.

Perhaps the best use of the weighting method is to use it to provide decision makers with a feel for the effects of various weights on the objectives. Such an approach was included in the Rio Colorado river basin study previously mentioned (Major and Lenton, 1979, p. 74, 143-145 and 186-189; and Major, 1973, p. 237) when a range of weights was assigned to a six-objective formulation. The objectives in this formulation were national income, and regional income for each of five provinces.

Multiobjective dynamic programming. Although dynamic programming is normally associated with problems involving temporal variations, Tauxe, Inman and Mades (1979a and 1979b) have demonstrated that Bellman's principle of optimality can be used to generate the nondominated solution set for a multiobjective formulation when the objective functions are separable and few in number.

In a multiobjective dynamic programming formulation, one objective is chosen arbitrarily as the primary objective and the other objectives are treated as constraints, which necessitates the establishment of one additional state variable for each additional objective. The presence of additional objectives can have severe computational implications as Bellman's "curse of dimensionality" (Bertsekas, 1976, p. 179-180) takes its toll. For this reason, the multiobjective dynamic programming approach is useful only for problems in which the number of objectives is small, generally three or less.

To illustrate this approach, our example problem is put into a dynamic programming formulation. The level of attainment of the primary objective, $f_1(x)$, through stage i is expressed by the recursive equation

$$f_1^i(s^i, f_2^i) = \max_x r^i(x^i, s^i, f_2^i) + f_1^{i-1}(s^{i-1}, f_2^{i-1}) \quad (4\text{-}15)$$

subject to

$$s^{i-1} = T_1^i(x^i, s^i, f_2^i) \quad (4\text{-}16)$$

$$f_2^{i-1} = T_2^i(x^i, s^i, f_2^i) \quad (4\text{-}17)$$

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \quad (4\text{-}18)$$

$$x \geq 0 \quad (4\text{-}19)$$

where

f_k^i is the accumulated return function for objective k through stage i;

s^i is a structural state variable;

x^i is the decision variable for stage i;

r^i is the immediate return function for stage i; and

T_k^i is the state transformation function for the k^{th} state variable.

Multiobjective simplex method. An algorithm utilizing the simplex method to generate the noninferior set when all objective functions and constraints are linear has been summarized by Cohon (1978). The method uses a simplex tableau augmented with an additional objective row for each additional objective, along with a corresponding additional reduced cost row for each additional objective. The multiobjective simplex algorithm moves from one noninferior extreme point to another in a finite number of pivots until all such points have been located.

Noninferior set estimation method. Cohon (1978, p. 127-140) and Cohon, et al. (1979) presented an algorithm for generating an approximation of the nondominated set which can overcome some of the computational burdens of the constraint and weighting methods. However, it is limited to problems in which the feasible region is a convex set (as is the weighting method) and in which the objective functions are linear.

The algorithm starts by optimizing each objective separately. Then the maximum possible error between the line connecting the two optima (assuming a two objective problem in this explanation) and the two linear indifference curves corresponding to the weighted objective functions used in the generation of the two optimal solutions is calculated and compared to the maximum allowable error (preset by the analyst). If the maximum possible error is less than the allowable error, the algorithm exits. Otherwise, a new weighted objective function with the ratio of the objective weights equal to the negative slope of the line connecting the optima is optimized. This yields a new point in the objective space, which is the solution that is farthest out in the direction perpendicular to the line segment between the original optima. This process is repeated until the allowable error exceeds the maximum possible error. The maximum possible error will get smaller at each iteration and the algorithm is guaranteed to converge.

Category B - Techniques Involving A Priori Complete Elicitation of Preferences

The techniques of Category B, like those of Categories C and D, involve an explicit elicitation of the preference structure of the decision maker such that the preferred solution is attained as part of the analysis. However, unlike the techniques of Categories C and D, these generally develop a mathematical approximation of the complete preference structure of the decision maker.

Optimal weights. Of those techniques in Category B, the assessment of optimal weights is both the simplest and the most frequently used in the literature. The optimal weighting approach assumes that the isopreference curves illustrated in Figure 3-2 are linear. That is, it assumes that the marginal rates of substitution between the objectives are independent of the absolute levels of the objectives. In addition, it is well known that the slopes of the linear isopreferences curves are equal to the negative of the ratios of the objective weights. Using our example, this means that, once the optimal weights w_k^* are found, then the preferred solution can be obtained by solving the problem:

$$\max_{x} \sum_{k=1}^{2} w_k^* f_k(x) \qquad (4\text{-}20)$$

subject to

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \qquad (4\text{-}21)$$

$$x \geq 0 \qquad . \qquad (4\text{-}22)$$

An early suggestion concerning the application of the optimal weighting approach was provided by Haveman (1965). Haveman conducted an empirical analysis of Corps of Engineers projects in 10 southern states and showed that a number of objectives were served by the projects, even though the projects were planned only to maximize economic efficiency. He suggested that past allocations of funds for water projects be observed in order to derive weights to guide future investments. He further suggested that the inverse of the effective marginal tax rates be used as a Congressional expression of a social welfare function. Steiner (1969, p. 33) cited the works of other economists who suggested that optimal weights can be inferred from past Congressional actions.

Marglin (1966, p. 79) also suggested the use of the optimal weighting approach to obtain the preferred solutions to a problem in water resources decision making when he hypothesized a problem in which planners would develop plans to maximize a weighted sum of the two objectives of income redistribution to American Indians and national economic efficiency. In his 1967 work (p. 37), Marglin further suggested that such optimal weights, once found, be revised periodically, such as every five years, as information from past decisions is used to refine the preferences of society.

In 1969, Major showed that the slope of the line that is tangent to both the Pareto optimal set and the greatest isopreference curve is equal to the negative of the ratio of the optimal objective weights. Major advocated using these optimal weights to obtain a multiobjective benefit-cost ratio in which the numerator contains a weighted sum of national income and regional income benefits and the denominator contains a weighted summation of national and regional costs.

Freeman and Haveman (1970), in a paper that reflected different views from those expressed in Haveman's 1965 work, were critical of Major's approach, pointing out that the establishment of regional weighting factors is impossible politically, and, even if it were not, the real equity concern should be with differences in individual income levels, not regional income levels. Therefore, any equity objective should focus on the effects of the income levels of low-income people, regardless of the regions in which they live. Freeman and Haveman were also critical of Major's assertion that the optimal weights can be approximated from past decisions reached by the Congress. They wrote that social preferences are not stable over time, and that even if they were, the properties of a social welfare function cannot be inferred from the Congressional process. Freeman (1969, p. 673) explained that inferring weights from past Congressional decisions is inappropriate in any case since members of Congress obviously do not have full knowledge of all consequences when they make their decisions.

In 1970, Dorfman and Jacoby took a different approach to the estimation of optimal weights. In an attempt to model the political process in order to predict the outcome of political decision making, Dorfman and Jacoby tried to estimate weights based on the influence of each of the various groups in the political process. The authors felt that such a model could be useful as a tool in understanding and facilitating the political decision process.

A number of authors have applied weighting methods to the problem of assessing the impacts of water resource development projects on multiple environmental criteria. The Batelle Columbus Laboratories developed such a method for the Bureau of Reclamation (Dee, et al., 1972 and 1973; and Seader, 1975). The method converted the predicted impacts of each proposed project on each of 78 "environmental impact units" by the formula

$$EIU = \sum_{i=1}^{78} w_i EQ_{i(\text{with project})} - \sum_{i=1}^{78} w_i EQ_{i(\text{without project})} \qquad (4\text{-}23)$$

where

i = environmental criteria index,

w_i = weight of environmental criterion i, and

EQ_i = environmental quality measure of criterion i.

The environmental quality measures (EQ_i) were normalized by equating the greatest conceivable impact to an environmental quality level of 1 and the least conceivable impact measure to an environmental quality level of 0 for each of the 78 criteria, and then developing a functional relationship between the extremes (not all were assumed to be linear). Of course, once this process was completed for all alternative project proposals, the projects could be evaluated with respect to the 78 criteria simply by using the commensurable environmental impact units.

The Tulsa District of the Corps of Engineers developed a similar method for the assessment of environmental impacts of water projects in 1972. The major differences between the method of the Tulsa District and that of the Bureau of Reclamation involved the manner of assessing the raw scores for each environmental criterion (the EQ in the Reclamation method) and the fact that the Tulsa District approach resulted in a separate score for each of three major objectives for each project alternative. With the exception of the deletion of dominated alternatives, the method gave no guidance on assisting the decision maker from that point. A practically identical method was applied by O'Riordan (1972) in developing a river basin plan for the Okanagan Valley, British Columbia.

Brown and Valenti presented another interesting application of linear weighting in a procedure entitled Multi-Attribute Tradeoff System (MATS). The MATS procedure (1983) was designed to assist Bureau of Reclamation planners in evaluating and comparing the effects of alternative water project plans. It is composed of three parts: development of a value function for each element of an objectives set, specification of weights for each objective, and calculation of a value score for each alternative plan.

The MATS procedure provides two ways of specifying the value function for each objective: direct specification by the decision maker or by use of an interactive interrogation process. Both approaches yield a graphical display of objective attainment value (on a scale of zero to one) versus objective attainment (on a scale of minimum to maximum achievable objective levels). In the interrogation process, the decision maker is presented with a series of tradeoff questions concerning preferences for different levels of the same objective. His responses determine the shape of the value function.

As with the specification of value functional forms, the

MATS technique provides two ways of specifying objective weights: direct specification by the decision maker or by use of an interactive interrogation process. In the interrogation mode, the decision maker is again presented with a series of tradeoff questions, but these involve preference decisions for tradeoffs between objectives. These pairwise prompts continue for four iterations or until indifference is reached. If indifference has not been reached at the conclusion of four iterations, the algorithm selects the midpoint between the last two responses as an estimate of the indifference point.

Calculation of the value score for each discrete alternative is carried out by multiplying the value score on each objective by the objective weight, summed over all objectives. The alternatives are then ranked according to score.

In 1978, the Bureaus of Reclamation and Indian Affairs used a different set of weights in each of four different future scenerios in attempting to identify the most promising opportunities for water conservation in the western states (U. S. Department of the Interior). Seaver, et al. (1979) used a linear weighting value function in a simplified utility theory approach to multiobjective water resources problems. The linear weighting approach has also been applied commonly in other disciplines (Edwards, 1977).

Utility theory. In general, utility theory assumes that the utility structure of the decision maker can be derived, and it, in turn, can be used to make different objectives commensurable so that a preferred alternative can be identified from a set of alternatives, each of which contributes some amount toward each of the objectives. At the fundamental level, utility theory is based on six assumptions which are described by Sage (1977, p. 329-331). When more than one objective is involved, utility theory is commonly referred to as multiple attribute utility theory.

Some authors make a distinction between utility functions and value functions, which serves to indicate whether or not risk is involved in the elicitation of the preference structure. In this short discussion of the use of utility theory to assist in water resources decision problems, such a distinction is not made. In the applications of utility theory to water resources decision problems that have been made to date, almost no consideration has been given to risk. Perhaps this is one of the reasons that utility theory has not enjoyed wide use in the resolution of water resources problems. Many water resources problems involve stochastic phenomena which, in turn, involve risk. Examples include problems concerned with the reliability of water supplies or the amount of exposure to flood damages. Certainly the attitudes of the decision maker or the public toward risk aversion or risk proneness could be significant factors in such problems. However, despite the fact that utility theory is well suited to address such factors, it has not yet been used extensively in that way.

The assessment of optimal weights, discussed in the section above, is actually just a special case of utility theory. A linear weighting approach implies that the preferences of the decision maker for various levels of a given objective are independent of the absolute levels of the other objectives, which, of course, is not always valid. A discussion of various other forms of the utility function is contained in Sage (1977, p. 346-353) and in Keeney and Raiffa (1976, p. 288-297).

One of the earliest applications of utility theory to a water resources decision problem was conducted by Dean and Shih, who assumed that additive utility functions were valid in two water development planning problems in Texas. The first problem that they addressed (1973) involved choosing the best source of augmentation water supplies for the city of San Angelo, Texas from 10 alternatives. In this four objective problem, the authors used the delphi method to elicit the preferences of the public in order to establish scaling constants, which were substituted into an additive utility function to ascertain the preferred solution. In 1975, Dean and Shih used a similar approach in a problem involving the expansion of a "River Walk" development project along the San Antonio River in San Antonio, Texas. This problem had eight discrete alternatives and five objectives. Again, the authors used an additive utility function to identify the preferred alternative.

Sinden (1974) used utility theory to estimate the benefits accruing from water-based recreational opportunities in an attempt to improve on the standard travel-cost method for evaluating recreational benefits of water projects. Sinden elicited the utilities of users of water-based recreational facilities for various recreational and aesthetic experiences and used this information to develop a family of indifference curves. Using these curves, data on the marginal costs of consuming the various recreational activities, and estimates of consumer recreational budgets, he then developed demand curves for the various recreational alternatives. The demand curves were used, in turn, to estimate the benefits accruing from the various recreational facilities.

In 1974, Major used indifference curves to in a descriptive sense to illustrate the compromise that took place between the Corps of Engineers and the Izaak Walton League (a conservationist group) concerning two objectives of a proposed dam and reservoir in Indiana.

Perhaps the most complete application of utility theory to a problem in water resources planning was provided by Keeney and Wood (1977) when they evaluated five water resource development plans for the Tisza River Basin in Hungary. In this twelve objective problem, they carried out the steps of investigating the independence properties of the attributes, determining the appropriate form of the utility function, assessing the component utility functions, assessing the scaling factors, and calculating the total utilities of each alternative using the composite utility function. This same problem was examined by David and Duckstein (1976) using the ELECTRE method and by Duckstein and Opricovic (1980) using compromise programming. The results of the three studies were similar. Keeney and Wood (p. 705) found that the use of utility theory had the following advantages over the other approaches in the problem that they addressed:

- it does not require that the preferences of the decision maker for various levels of one objective be independent of the levels of the other objectives, as does the assessment of optimal weights;

- it avoids awarding undue weight to an objective that varies over a small range over the noninferior set; and
- it can handle systems with a large number of decision variables and constraints without excessive confusion.

In 1978, Reid and Leung presented a utility theory approach to the problem of establishing water resource development priorities within the State of Oklahoma and demonstrated an application in 1979. The authors developed two indices of project merit, a "single index" and a "double index". The single index was simply an additive utility function. The double index consisted of a "demand index" and a "desirability index", both of which used additive utility functions. The demand index included only certain objectives, deemed "need and deficiency parameters". The demand index was used to cluster the alternatives into a hierarchy of desirability. The alternatives were further ranked within each cluster by the desirability index, which used an additive utility function that included only the remaining objectives. The authors provided no information concerning the derivation of the component utility functions or the scaling constants, or of any tests for additive independence of the attributes.

Policy capture. In 1975, Crews and Johnson presented an adaptation of the social judgment theory of Kenneth R. Hammond (Balke, et al., 1973; Hammond, et al., 1975; Hammond and Adelman, 1978; Hammond, et al., 1977) to water resources planning and applied the name policy capture to the procedure. The policy capture method provides a means of estimating the utility functions of decision makers using regression analysis. The authors generated 30 hypothetical future scenerios which contained various levels of two objectives. Two decision makers expressed their preferences for these scenerios by placing them on scales, which were then normalized to facilitate comparisons. The authors then used a nonlinear multivariate regression model to derive utility functions for each decision maker. In an attempt to aggregate the two utility functions, the authors developed marginal rates of substitution (MRS) curves for each decision maker and found that they had a common point. Crews and Johnson then concluded that the slope of the line from the origin to the intersection of the MRS curves represented a common trade-off, and that any alternative involving such a trade-off would be acceptable to both decision makers. Although the conclusion is erroneous, the method of policy capture could be a useful approach for approximating utility functions.

In a manner similar to that of Crews and Johnson, Moreau, et al. (1981, p. 74-83 and 94-102) used hypothetical alternatives to elicit preferences and a regression analysis to derive objective weights in a watershed planning problem in the Research Triangle region of North Carolina.

Techcom method. The Techcom method was developed during the time frame 1970-1974 by the Technical Committee of the Water Resources Research Centers of the Thirteen Western States (Technical Committee, 1971 and 1974; Gum, et al., 1976). The Technical Committee was an ad hoc group formed to develop the Techcom method under a grant by the Office of Water Resources Research in the U. S. Department of the Interior.

The Techcom method differs from the other multiobjective decision-aiding methods reviewed herein in that its primary focus is on the identification of the preferences of different groups of people for use by a decision maker, rather than on the generation of nondominated alternatives or the elicitation of the preference structure of a decision maker. The Techcom method is composed of two parts: the development of an objectives hierarchy and an identification of the preferences of groups of people for the objectives and sub-objectives of the objectives hierarchy.

The hierarchy established by the Techcom method is composed of "goals" (highest level objectives), "sub-goals" (intermediate level objectives) and "social indicators" (lowest level objectives, which are the most readily measured). The method also contains "policy action variables" (decision variables) and "connectives" (functional relationships which map decision variables onto lowest level indicators). In many cases, the connectives merely indicate the direction of impact (i.e., +, - or 0).

The identification of the preferences of groups of people is accomplished by means of the Metfessel General Allocation Test. This test is administered by a mass mailing of questionnaires to which respondents reveal preferences by dividing 100 points between the elements of sets of sub-objectives. These are then used as weights in additive or multiplicative functions which relate social indicators, sub-goals and goals.

Andrews, et al. (1979) conducted an evaluation of the Techcom method by analyzing the social impacts of the completed Weber Basin Project in Utah and comparing those impacts with the taxonomy of impacts contained in the Techcom method. The authors found a number of areas in need of improvement.

Category C - Techniques Involving A Priori Partial Elicitation of Preferences

The techniques in Category C also involve elicitation of the preferences of the decision maker, but in contrast to Category B, these techniques involve only a partial expression of preferences. Since the entire preference structure of the decision maker is not modeled by these methods, they generally cannot be used to derive an accurate cardinal ordering of a set of widely different alternatives. With the exception of the Surrogate Worth Trade-Off (SWT) and Iterative Lagrange Multiplier (ILM) methods, these techniques are noncompensatory in nature in that they do not involve elicitation of decision maker preferences using trade-offs between objectives.

Lexicographic approach. With the exception of the work of Thampapillai and Sinden (1981), all lexicographic models discussed in this section were developed in a descriptive sense to explain cognitive decision rules. They are included in this overview of normative models because they have been used in a normative manner in water resources decision making. In its simplest form, the lexicographic approach is sometimes used to find the preferred solution from the set of all feasible alternatives by finding the alternative that is most desirable according to the most important objective and, if two or more alternatives are equally desirable at that juncture, proceeding to the next most important objective, and so on. This is the "lexicographic order of the plane" referred to by Fishburn (1974, p. 1443). Fishburn cites several examples of applications of this decision rule (p. 1442). In a variation, the lexicographic approach has been used to find the preferred solution by finding the alternative that satisfies simultaneously as many objectives as possible, beginning with the most important objective and working toward the least important objective (Haimes, et al., 1975, p. 16-17).

Another variant is lexicographic semi-ordering in which perceptible but insignificant differences are ignored (Fishburn, 1974, p. 1446). According to this decision rule, preferences will be based on the most important objective unless the difference between alternatives is less than a threshold amount, in which case the preferences will be based on the next most important objective, and so on. Choices may not be transitive under such a lexicographic semi-ordering decision rule.

The lexicographic approach has also been used to produce a partial ordering from a set of alternatives (Fishburn, 1974, p. 1451). To do this, each objective is partitioned into acceptable and unacceptable levels. Alternatives are then screened against the most important objective. Those that are acceptable are retained, while the others are discarded. Then the retained alternatives are screened against the next most important objective, and so on. If there are enough objectives or if the levels of acceptable objective attainment are high enough, this method can be used to select a single preferred alternative. A refinement to this satisficing technique (Fishburn, 1974, p. 1451-1452) approaches the goal programming algorithm of the next section. In this model, more than one satisficing level is specified for each objective. If all minimally satisfactory levels can be attained by a subset of alternatives, then the next highest level is used to further screen the alternatives, and so on. Yet another variant of lexicographic ordering with aspiration levels uses the lowest-level objective whose aspiration level is not satisfied as the basis for the decision (Keeney and Raiffa, 1976, p. 78-79).

Another lexicographic model has been presented by Tversky (1972a and 1972b). Tversky's model, which is referred to as elimination by aspects, differs from those discussed by Fishburn in that the ordering of the objectives is not specified by the decision maker prior to the decision process, but instead is determined by a probabilistic distribution during the decision process. In the elimination by aspects model, one aspect (objective level) is chosen and all alternatives that do not meet that objective threshold are eliminated. Then another aspect is chosen and the process continues until one alternative remains. Since the order of the objectives is not established prior to the analysis, any particular sequence of objectives used is regarded by Tversky (1972a, p. 296) as a reflection of the state of mind of the decision maker. Tversky (1972a, p. 298) notes that the elimination by aspects decision rule is attractive because it is easy to understand, easy to apply and easy to explain and justify. However, it can also lead to poor decisions since almost any alternative can be chosen if an appropriate sequence of aspects is devised.

Despite their inherent simplicity, lexicographic approaches have not been used widely to support decisions to problems in the water resources field. Steiner (1969, p. 32) noted, however, that a number of economists insist on an essentially lexicographic approach in the selection of water projects. That is, the view of these economists is that, although there may be a number of valid objectives in a particular situation, the national economic efficiency objective is the most important. Therefore, all project alternatives that are worth considering must provide more economic benefits to the Nation than they incur in costs. Once the set of alternatives has been thus screened, then the lesser objectives can be examined.

Thampapillai and Sinden (1979) used a lexicographic approach to induce a partial order on a set of noninferior land-use alternatives. The authors narrowed the range of noninferior solutions by calculating the mean variaton of the most important objective, average annual agricultural income, and eliminating all alternatives that did not provide at least the maximum attainable annual agricultural income less the mean variation. The authors noted that, to refine the set of remaining alternatives further the next most important objective, environmental quality, would then be examined.

Goal programming. The goal programming approach is somewhat similar to the constraint method of generating noninferior solutions. In goal programming, target levels of each objective are set by the decision maker and the alternative that minimizes the sum of the deviations from each target is sought.

The goal programming formulation for our example problem is:

$$\max_{x} \sum_{k=1}^{2} (d_k^{+} + d_k^{-}) \tag{4-24}$$

subject to

$$f_k(x) - T_k = d_k^{+} - d_k^{-} \qquad k = 1, 2 \tag{4-25}$$

$$g_j(x) \leq 0 \qquad j = 1, 2, \ldots, n \tag{4-26}$$

$$x \geq 0 \tag{4-27}$$

where Tk is the target level for objective k and d_k^{+} and d_k^{-} are the positive and negative deviations, respectively, from the target levels of the objectives.

In the goal programming algorithm, the target levels do not have to be set within the feasible set. In fact, if the target levels are within the feasible set, an inferior solution may result.

In a variant to the goal programming approach, sometimes referred to as goal attainment, weights can be assigned to the various objectives (Gembicki and Haimes, 1975, p. 769). Then (4-24) becomes:

$$\max_{x} \sum_{k=1}^{2} w_k(d_k^{+} + d_k^{-}) \tag{4-28}$$

where w_k is normalized such that $\sum_{k=1}^{2} w_k = 1$.

From this formulation, it can be seen that goal programming is similar to the optimal weighting approach in that the deviation weights w_k are analogous to the objective weights in the optimal weighting approach. However, in one sense it is more accurate than the optimal weighting approach. Both the optimal weighting and goal programming approaches are based on the assumption that preferences of the decision maker for marginal rates of substitution between the objectives are independent of the absolute levels of the objectives. However, in setting deviation weights and goal levels, the decision maker in the goal programming approach is implicitly limiting the range over which his trade-off preferences are constant to some neighborhood around the goal levels. In the optimal weighting approach, on the other hand, the trade-off preferences expressed by the decision maker apply across the entire feasible ranges of all objectives. In other words, the goal programming approach provides the decision maker with a set of absolute levels of objective attainment (i.e., his stated goal levels) upon which to base his weights, whereas the only such basis provided in the optimal weighting approach is the entire n-dimensional range over which the n objectives can vary.

Several authors (Haith and Loucks, 1973, p. 34; Neely, et al., 1976, p. 19 and 1977, p. 198) have advocated a goal programming approach as the most consistent with the planning guidelines of the Principles and Standards (U. S. Water Resources Council, 1973). Neely, et al. (1976) illustrated the applicability of goal programming to the planning of water project construction programs with a hypothetical multiproject, multiperiod problem. The authors minimized the weighted deviations from ten environmental quality and economic goals, subject to construction and operation and maintenance budget constraints. In 1977, the same authors used data from actual and proposed water projects of the Tennessee Valley Authority (TVA) to test an expanded version of their goal programming model. The actual budget levels for the period 1965-1973 were used as constraints and the objective function minimized weighted deviations from 17 national economic, regional economic and environmental quality goals. The results indicated that the portfolio of projects yielded by a model with an equal weighting of national economic, regional economic and environmental quality goals could have provided more net national economic benefits than the portfolio actually selected by TVA, in addition to improving most environmental quality indicators. Although there were some differences between projects actually selected by TVA and those selected by the model, the major differences involved the timing of project construction.

Bishop, et al. (1977) applied goal programming to a hypothetical river basin system to illustrate its usefulness to regional water quality planning under Section 208 of the Federal Water Pollution Control Act. The approach used in this effort, in a variant to that used above, did not require the decision maker to establish weights for the various objectives, but instead to establish an ordinal ranking of the objectives based on his perceptions of the relative importances of the objectives. After the rankings were established, deviations from the highest priority goal were minimized, subject to total cost, regional cost, pollution level and water quality constraints. Then, deviations from the second highest priority goal were minimized, with the optimal value of the first objective imposed as an additional constraint. This process continued until all objectives were exhausted.

In 1979, Lohani and Adulbhan presented another application of goal programming to the problem of regional water pollution management. The authors minimized deviations from the goals of waste treatment, cost and the level of dissolved oxygen in the water in each of three cases: equal weighting to both objectives, heavier weighting to the cost objective, and heavier weighting to the water quality objective.

Sellers and North (1979) used goal programming to evaluate alternatives in a restudy of the Cross Florida Barge Canal Project of the Corps of Engineers. The model developed by the authors contained 23 objectives. After identifying the preferred solution, the authors removed it from the feasible set and optimized the model again to identify the second best solution.

Can, et al. (1982) applied goal programming to the optimization of operations on a four reservoir system in the Green River Basin, Kentucky. The authors suggested that the model could be used for real-time operational decisions by using releases called for by the model only for the first day of the operating horizon and solving the goal programming problem again each day using updated inflow forecasts and storage conditions.

One major weakness of goal programming involves the elicitation of the preferences of the decision maker. None of the authors referenced herein directly addressed the problem of establishing goal levels or objective weights. In most cases, a variety of goal levels and objective weights were assumed in order to produce a corresponding variety of outputs. Sellers and North (1979, p. 173) advocated the use of maximum attainable levels of the objectives as a simple way of setting goal levels. However, such an approach fails to recognize that the goal levels may be used by the decision maker to express his objective weights, and that the maximum attainable levels of all objectives may be far from the levels of objective attainment in the preferred solution. Therefore, if the marginal rates of substitution between objectives preferred by the decision maker are not constant but instead vary with levels of objective attainment, then such an approach may introduce inaccuracies in the analysis.

ELECTRE Method. A method that requires the decision maker to specify not only an ordinal ranking of objectives but also the specification of objective weights prior to the analysis was presented by Roy in 1971 (p. 250-257). He assigned the acronym ELECTRE (elimination et choice translating reality) to the method. The method assumes that the set of noninferior solutions and the cardinal weights of the objectives, reflecting the preferences of the decision maker, are known prior to the analysis. Roy (1971, p. 254-255) wrote that these latter values can be derived from simple ordinal relationships between the objectives, but the example that he presents to illustrate this is incorrect. A better illustration of the elicitation of objective weights in the deterministic case is presented by Keeney and Raiffa (1976, p. 121-123).

The ELECTRE method involves a pairwise comparison of alternatives in an attempt to establish a stronger partial ordering on the noninferior set. For each pair of alternatives, a "concordance condition" is calculated. For alternatives $\underline{x}^i$ and $\underline{x}^j$, Roy defines the concordance index as the ratio

$$\frac{\text{sum of objective weights where } \underline{x}^i \text{ is preferred to } \underline{x}^j}{\text{sum of objective weights where } \underline{x}^j \text{ is preferred to } \underline{x}^i} \quad .$$

In addition, a "discordance condition" is established which is applied to each pairwise comparison. The discordance condition defines a range over each objective that cannot be violated by an "outranking relationship." That is, if $\underline{x}^i$ outranks $\underline{x}^j$ by the concordance index, but $\underline{x}^j$ is preferred to $\underline{x}^i$ on at least one criterion (objective measure), and the amount by which $\underline{x}^j$ exceeds $\underline{x}^i$ on that criterion is greater than the discordance index, then one cannot say that $\underline{x}^i$ is preferred to $\underline{x}^j$, despite the favorable concordance condition. In other words, necessary and sufficient conditions for alternative $\underline{x}^i$ to be preferred over alternative $\underline{x}^j$ are that both the concordance and discordance conditions must be satisfied.

Thus, in addition to specifying the objective weights, the decision maker is also required to specify a parameter which the concordance index must exceed and a range over each objective that the discordance index cannot exceed, in order for the ELECTRE method to determine that one alternative is preferred over another. These requirements have two major drawbacks. First, the requirement for the decision maker to specify objective weights assumes that the relative importances of the objectives are independent of the absolute levels of the objectives. As McKee, et al. (1981, p. 23) pointed out, such an assumption is seldom valid unless the entire analysis is conducted within a small region of the decision maker's preference structure. Where cost is a criterion, for example, it may be of overwhelming importance when extremely high cost alternatives are under consideration, but might be relatively unimportant if low cost alternatives are under consideration. Second, the requirement for the decision maker to establish concordance thresholds and discordance condition ranges certainly must reduce the clarity of the analysis from the decision maker's perspective. If the decision maker experiences severe difficulties in understanding what it is he is being asked to do, then it must detract from the accuracy and reliability of the analysis.

Despite these difficulties, the ELECTRE method has been applied to at least three problems in water resources planning. In 1976, David and Duckstein used the ELECTRE method to reduce a set of five noninferior water development alternatives for the Tisza River Basin in Hungary to a preferred subset of two alternatives. The authors used 11 evaluation criteria (objectives), the weights of which were assumed to be known. Their analysis was a straightforward application of the ELECTRE method presented by Roy (1971) with the exception that the concordance and discordance conditions were defined differently. The "concord index," as used by David and Duckstein was defined as

$$\frac{\text{sum of objective weights where } \underline{x}^i \text{ is preferred to } \underline{x}^j}{\text{total sum of weights}} .$$

The "discord index" defined the adverse difference between alternatives $\underline{x}^i$ and $\underline{x}^j$ to be a percentage of the total range of each objective. Thus the discord index was specified by the decision maker to be a fixed fraction which was applied to all objectives in the pairwise comparison procedure, rather than a specified range for each objective as defined by Roy. Various concord and discord indices were then applied to the pairwise comparisons of all alternatives. One set of indices enabled the authors to reduce the noninferior set to a preferred subset of two alternatives. A subjective evaluation was then performed on the two remaining alternatives and one was selected as the preferred solution because it represented a "more reasonable compromise" between objectives.

In 1977, Nijkamp and Vos applied the ELECTRE method to a five alternative, 12 objective problem concerning the reclamation of land from the interior sea of the Netherlands. Nijkamp and Vos also introduced four variants to the method presented by Roy (1971). First, the authors established two sets of objective weights, one for positive differences between alternatives and one for negative differences. The weights used by the authors were the averages of those elicited from a number of decision makers and interest groups. Second, the authors developed a "norm vector," the elements of which represented satisficing outcomes of each objective. Third, the authors calculated the concordance indices with respect to the norm vector for each pairwise comparison, rather than with respect to the other alternatives in the paired comparisons. Fourth, the authors used a different definition of the discordance index, wherein it measured deviations on each objective from the norm vector for each alternative. After initially specifying the concordance and discordance thresholds, the ELECTRE method was used to reduce the number of alternatives from five to four. To further order the noninferior set, the thresholds were strengthened (i.e., the concordance index was increased and the discordance index was decreased), which reduced the number of alternatives to two. The authors concluded that new information would be required to further reduce the number of alternatives to a single preferred alternative.

In 1982, Gershon, et al. (p. 193) applied the ELECTRE method in examining 25 development alternatives in terms of 13 evaluation criteria in the Santa Cruz River Basin in southern Arizona. The study provides a good example of the ELECTRE method but gives no information on the manner in which the criteria weights or concordance and discordance thresholds were established by the decision maker. The authors performed a sensitivity analysis and found that the model was fairly robust with respect to changes in scales and weights.

Compromise programming. In 1980, Duckstein and Opricovic presented an approach that was based on the work of Zeleny (1973). The method involves minimizing distances from an ideal solution vector and is oriented toward decision situations with a small number of discrete alternatives and a large number of objectives. It involves the construction of a "system versus criteria" array in which each column is composed of the objective levels for one alternative and each row is composed of the levels of one objective for all alternatives. Then, the solution is sought that solves

$$\min \left[\Sigma \alpha_i^p \left\{ \frac{|f_i^*(x) - f_i(x)|}{|f_i^*(\underline{x}) - f_i^{min}(\underline{x})|} \right\}^p \right]^{1/p} \qquad (4\text{-}29)$$

for values of $p = 1, 2$ and ∞, and $\alpha_i = 1$, where $f_i^*(\underline{x})$ is the best attainable level of objective i, $f_i^{min}(\underline{x})$ is the worst attainable level of objective i, and n is the number of objectives. The authors pointed out that this procedure reduces to goal programming for $p = 1$ and $\alpha_i = 1$; that it reduces to linear weighting for $p = 1$ and $\Sigma\alpha_i = 1$; and that it reduces to a minimax problem for $p = \infty$ and $\alpha_i = 1$.

The authors suggested presenting the solutions for (4-29) for $p = 1$, 2 and ∞ and $\alpha_i = 1$ to the decision maker for his use in selecting the preferred solution. They further suggested that the same procedure be followed again using values of α_i if the weighting coefficients can be elicited from the decision maker. The fact that the decision maker establishes the objective weights based on the initial compromise programming solution is the reason why this method appears in Category C.

Duckstein and Opricovic illustrated their method with a 12 objective, five alternative problem. They found that the first alternative was preferred with $p = 1$, but that the second alternative was preferred with $p = 2$ and $p = \infty$. At $p = 1$, the "total utility" solution resulted, while at $p = \infty$, the "individual regret" of each objective was minimized. Therefore, if the decision maker were more concerned that none of the objectives strayed far from their ideal values, then he would tend to favor the solution at $p = 2$ or $p = \infty$. On the other hand, if he were more concerned with the overall effect on the objective set without regard to any individual objective, then he would tend to favor the solution at $p = 1$.

Surrogate Worth Trade-Off Method. It is interesting to compare the Surrogate Worth Trade-Off (SWT) method (Haimes, *et al.*, 1975) with multiattribute utility theory (MAUT). One major difference between the two approaches is that preferences of the decision maker are obtained by eliciting preferences for objective trade-offs in the SWT method, but are obtained by comparing absolute levels of objective attainment in MAUT. Another difference is that the SWT method does not define the preference structure of the decision maker over the full range of objective accomplishment levels, as does the MAUT approach, but instead approximates the preference structure within a region of interest. This latter distinction is the reason the MAUT approach has been placed in Category B while the SWT method has been placed in Category C.

The SWT method starts by using the constraint method to define the noninferior set. That is, the multiobjective problem is reformulated into the problem

$$\min f_i(\underline{x}) \tag{4-30}$$

subject to

$$f_j(\underline{x}) \geq \varepsilon_j \tag{4-31}$$

$$f_k(\underline{x}) = \varepsilon_k \qquad k = 1, 2, \ldots, i-1, i+1, \ldots, j-1, j+1, \ldots, p \tag{4-32}$$

$$\underline{x} \geq \underline{0} \tag{4-33}$$

where p is the number of objective functions, the ε_j are parametrically varied levels of $f_j(\underline{x})$ and the ε_k are fixed levels of the functions $f_k(\underline{x})$. This problem is then solved for N values of ε_j, which produces, at most, N noninferior solutions. At this juncture, we have taken a look at a two-dimensional slice of the p-dimensional objective space. The dual variable (Lagrange multiplier) associated with constraint (objective) j is λ_{ij} and represents the trade-offs between objectives i and j. Next, regression analysis is used to determine the function $\lambda_{ij}(f_j(\underline{x}))$ from the calculated values of λ_{ij} and $f_j(\underline{x})$. This function relates the values of the trade-offs between objectives i and j to absolute levels of $f_j(\underline{x})$.

The next step is to repeat the above procedure with the objective j replaced by another of the $k \neq j$ objectives. Then it is repeated for all k objectives until p-1 functions $\lambda_{ij}(f_k(\underline{x}))$ are generated. Each of these functions relates the values of the trade-offs between objectives i and k to absolute levels of $f_k(\underline{x})$ with all other objectives held at fixed levels.

Next, objective i is replaced with objective $k \neq i$ and the procedure is repeated. This results in a (p-1)x(p-1) matrix of trade-off functions $\lambda_{lk}(f_k(\underline{x}))$ for $l = 1, 2, \ldots, k-1, k+1, \ldots, p$ and $k = 1, 2, \ldots, l-1, l+1, \ldots, p$.

The $(p-1)^2$ trade-off functions are then used to elicit the preference structure of the decision maker. Initially, the first trade-off function $\lambda_{ij}(f_j(\underline{x}))$, with the remaining objective functions on $f_k(\underline{x})$, $k = 1, 2, \ldots, i-1, i+1, \ldots, j-1, j+1, \ldots, p$, held fixed, is used to generate several values of λ_{ij} and corresponding values of $f_j(\underline{x})$, which are then presented to the decision maker. The decision maker is asked to assign a value between -10 and +10 to each set of λ_{ij} and corresponding $f_j(\underline{x})$ values. These values express how much he prefers trading λ_{ij} units of $f_i(\underline{x})$ for one unit of $f_j(\underline{x})$, given that all remaining objectives are fixed such that $f_k(\underline{x}) = \varepsilon_k$, $k = 1, 2, \ldots, i-1, i+1, \ldots, j-1, j+1, \ldots, p$. Since the values w_{ij} that the decision maker assigns are functions of $f_j(\underline{x})$, the function $w_{ij}(f_j(\underline{x}))$ is called the surrogate worth function of the decision maker. It is defined (Haimes, 1977, p. 228) such that

$w_{ij} > 0$ when λ_{ij} marginal units of $f_i(\underline{x})$ are preferred over one marginal unit of $f_j(\underline{x})$, given the satisfaction of all other objectives at levels ε_k;

$w_{ij} = 0$ when λ_{ij} marginal units of $f_i(\underline{x})$ are equivalent to one marginal unit of $f_j(\underline{x})$; and

$w_{ij} < 0$ when λ_{ij} marginal units of $f_i(\underline{x})$ are not preferred over one marginal unit of $f_j(\underline{x})$.

The value of λ_{ij} at which $w_{ij} = 0$ is designated λ_{ij}^*. In addition, a band of indifference (in which $w_{ij} = 0$) is asumed to exist in the neighborhood of λ_{ij}^* and is to be found with additional questioning of the decision maker. Within the indifference band, the improvement of one objective is equivalent, in the opinion of the decision maker, to the degradation of the other.

After all the bands of indifference, λ_{ij}^*, $k = 1, 2, \ldots, 1-1, 1+1, \ldots, p$ have been determined, the final step is to determine a solution vector $\underline{x}^*$ that corresponds to all λ_{ij}^*. This can be accomplished by solving the single objective maximization problem

$$\max f_i(\underline{x}) \tag{4-34}$$

subject to

$$f_k(\underline{x}) \leq f_k^*(\underline{x}), \qquad k = 1, 2, \ldots, i-1, i+1, \ldots, p \tag{4-35}$$

where the $f_k^*(\underline{x})$ are the values of the objective function $f_k(\underline{x})$ corresponding to λ_{ik}^*.

More detailed discussions of the SWT theory and variations to the procedure summarized above are contained in Haimes and Hall (1974, p. 618-621), Haimes, Hall and Freedman (1975, p. 34-35), Haimes (1977, p. 224-233), Haimes, Das and Sung (1977, p. 32-44), Haimes (1980, p. 87-96), Hall (1980) and Loucks, Stedinger and Haith (1981).

The SWT method has at least two major drawbacks. One of them is that the method is very computationally burdensome, especially for problems with a large number of objectives. The second drawback is related to the first. The method contains no technique to identify the levels at which to constrain the fixed objectives, or the p-2 values of ε_K. If the values of ε_K were selected in the neighborhood of the actual preferred solution, then this problem would not be a major one. Since this cannot be accomplished with any degree of confidence, a sensitivity analysis must be conducted. One way of doing this is to repeat the SWT method using the values of $f_K(\underline{x})$ found in the first analysis. Such a procedure compounds the computational burden of the SWT method.

The literature contains several applications of the SWT method to problems in water resources planning and design. In 1975, Haimes and Hall presented an application to a three objective water quality problem. The objectives of the Haimes and Hall problem were the minimization of wastewater treatment costs, temperature changes and algae concentrations. The authors did not report the numerical results of their analysis.

In 1977, Keith, et al. presented the results of a joint study of the Utah Water Research Laboratory and the Nevada Center for Water Resources Research to evaluate the use of the SWT method in multiobjective river basin planning. The authors reported a variety of problems in implementing the SWT method. First, problems were encountered in specifying the individual objective functions. For example, great difficulties were encountered in finding consistent relationships between different land management alternatives and groundwater levels, river flows, surface water quality measures and agricultural production. Such difficulties, however, were not due to the nature of the SWT method, but would have been encountered irrespective of the multiobjective decision-aiding method that was chosen. Second, the authors found that meaningful trade-offs among objectives did not occur in their problem. Since agricultural water use was dominant in the region, alternatives involving slight adjustments in irrigation efficiencies were found to be capable of satisfying easily all objectives. The authors felt that this fact could have been discovered with a less intensive method than the SWT method and suggested that a simpler decision-aiding technique should have been applied prior to using the SWT method. Third, the authors found that, had meaningful trade-offs between objectives been present in the problem, an objective involving the destruction of a rare species of minnow would have been particularly difficult since a group of ecologists would accept no alternative which would have destroyed it. Again, this difficulty would confront any of the multiobjective decision-aiding methods. It possibly could have been handled better as a constraint.

In 1978, Lindsay applied the SWT method to a two objective, three decision variable model of policy options for sludge disposal in Boston. The author used a questionnaire to elicit the surrogate worth functions of four decision makers. No information was given regarding whether or not an attempt was made to aggregate the preferences of the decision makers in order to arrive at a preferred solution.

Haimes and Olenik (1978) demonstrated how the SWT method could be applied to a levee design problem. In a report to the North Central

Division of the Corps of Engineers, the authors developed a procedure, referred to as the Multiobjective Statistical Method, to optimize the expected values of several objective functions over a set of alternative drainage system configurations. This approach involved the conversion of a stochastic system to a deterministic framework by using the joint probability distributions of river stages and rainfall events to determine expected values of objective accomplishment. Haimes and Olenik hypothesized six objectives of such an optimization problem (minimization of business losses, drownings, health hazards, environmental damages and land use losses, and maximization of aesthetics) and recommended ways of establishing functional relationships between the decision variables and such objectives. Haimes, et al. presented the results of an application of the Multiobjective Statistical Method to a hypothetical three objective problem in 1980.

The SWT method was used extensively in a major effort by the Case Western Reserve University and the Maumee River Basin Planning Board to develop a river basin plan for the Maumee River Basin in Indiana, Michigan and Ohio (Haimes, 1977, p. 295-323; Haimes, Das and Sung, 1979; Das and Haimes, 1979; and Haimes, 1980, p. 100-101). This project provides an excellent illustration of the tailoring of theoretically workable multiobjective decision techniques to fit the unique circumstances of a complex water resources planning problem. The Maumee River Basin Study involved the establishment of a multilevel hierarchy of objectives, multiple decision makers, and multiple planning subareas. Indifference bands were calculated for each decision maker and were used to identify areas of agreement and disagreement such that compromises could be reached. Although the final recommended plan did not fall within the indifference bands of all of the members of the Maumee Planning Board, it was consistent with the preferences of a majority of the members.

The Maumee River Basin Study provides an interesting numerical application of the SWT theory, but the most interesting aspect is perhaps the illustration that it provides of the difficulties involved in the integration of a quantitative decision-aiding method into the organizational and institutional framework of an actual river basin planning process. The difficulties involved in getting the various decision makers, influence groups and other interested parties to accept and understand the technique, and the iterative nature of the planning process, are made evident in this complex undertaking. Further, the Maumee Study vividly illustrates the reality that the SWT method, like any other multiobjective decision-aiding method, cannot be viewed as a replacement for the decision making process in the public arena, but is rather an instrument that can be a valuable aid to the decision making process if properly used.

Iterative Lagrange Multiplier Method. In 1977, Neuman and Krzysztofowicz presented a new solution technique referred to as the Iterative Lagrange Multiplier (ILM) algorithm. The method is applicable only to problems with continuously differentiable objective functions and to which assumptions of decision maker preferential independence among objectives can be applied without unacceptable loss of accuracy.

Although the algorithm is conceptually similar to the Surrogate Worth Trade-Off method, it differs in two major respects: (1) noninferior solutions are generated by use of the Lagrange multiplier method in the ILM approach instead of the constraint method of the SWT procedure, and (2) in the ILM method, decision maker preferences are elicited by direct specification of indifferences on graphical representations of objective levels versus tradeoff ratios or objective levels versus objective levels, whereas preferences under SWT are elicited by decision maker assignment of numerical values (surrogate worth values) indicating the relative desirability of marginal rates of substitution between each pair of objectives.

The authors noted the following attractions of the ILM procedure:

- it reduces complex multiobjective problems to a series of two-objective problems,
- it requires significantly fewer decision maker decisions than does the SWT method,
- it has computational advantages over techniques using the constraint method because it requires fewer constraints and can generate efficiently the Lagrange multipliers,
- decision maker preferences are elicited in the objective space rather than in the decision space,
- it overcomes problems with the constraint method wherein certain combinations of parameters may lead to infeasible results, and
- it requires no regression analysis, such as that of the SWT method.

Limitations of the ILM procedure include its failure to generate all noninferior solutions when objective functions are not strictly convex and involve a duality gap, the lack of applicability to discrete problems, and the potential for inconsistent decision maker responses when preferential independence among objectives is not a valid assumption.

Category D - Techniques Involving Progressive Elicitation of Preferences

The techniques of Category D, when applied to continuous problems, are usually used in conjunction with the nondominated set generating techniques of Category A since the Category D techniques can be used only after at least some nondominated solutions have been identified. These techniques make use of information contained in the nondominated solutions to elicit the preferences of the decision maker in an iterative fashion. These techniques are sometimes called interactive or iterative techniques. They generally involve the following steps: presentation of the decision maker with a nondominated solution, elicitation of preference information concerning that solution, use of the preference information to generate another nondominated solution, and continuation until a satisfactory solution is obtained.

Step method. This method, also known by the acronym Stem, was initially introduced by Benayoun, et al. (1971). The step method and variants to the step method been the most widely used of the interactive techniques in the water resources literature.

The step method presented by Benayoun, et al. begins with the construction of a "payoff table," which is a matrix composed of the levels attained by the set of objectives as each is optimized separately.

That is, given the multiobjective problem

$$\max \underline{f}(\underline{x}) \tag{4-36}$$

subject to

$$\underline{g}(\underline{x}) \leq \underline{0} \tag{4-37}$$

$$\underline{x} \geq \underline{0} \quad , \tag{4-38}$$

the payoff table entries are found by solving the following p problems:

$$\max f_i(\underline{x}) \qquad i = 1, 2, \ldots, p \tag{4-39}$$

subject to

$$\underline{g}(\underline{x}) \leq \underline{0} \tag{4-40}$$

$$\underline{x} \geq \underline{0} \quad . \tag{4-41}$$

The following payoff table could then be constructed:

(4-42)

	$f_1(\underline{x})$	$f_2(\underline{x})$	. . .	$f_p(\underline{x})$
$\underline{x}^1$	$f_1^*(\underline{x}^1)$	$f_2(\underline{x}^1)$	. . .	$f_p(\underline{x}^1)$
$\underline{x}^2$	$f_1(\underline{x}^2)$	$f_2^*(\underline{x}^2)$	. . .	$f_p(\underline{x}^2)$
.	.	.		.
.	.	.		.
.	.	.		.
$\underline{x}^p$	$f_1(\underline{x}^p)$	$f_2(\underline{x}^p)$	. . .	$f_p^*(\underline{x}^p)$

In this table, $\underline{x}^i$ represents the value of the decision variable vector at which $f_i(\underline{x})$ is maximized, $f_j(\underline{x}^i)$ represents the value of the j^{th} objective when the i^{th} objective is maximized, and $f_j^*(\underline{x}^j)$ represents the highest attainable value of objective j.

The solution at which all $f_j(\underline{x})$ are maximized simultaneously is denoted as the "ideal solution" by Benayoun, et al. (1971, p. 369).

Such a solution is assumed to be infeasible since, if it were feasible, the objectives would not be in conflict. After construction of the payoff table, the feasible solution is sought that minimizes the maximum deviation from the ideal solution. This is accomplished by solving the following problem:

$$\min \lambda \tag{4-43}$$

subject to

$$[f_i^*(\underline{x}) - f_i(\underline{x})]w_i \leq \lambda \qquad i = 1, 2, \ldots, p \tag{4-44}$$

$$\underline{x} \in \underline{X}^i \tag{4-45}$$

$$\lambda \geq \underline{0} \tag{4-46}$$

where the $[f_i^*(\underline{x}) - f_i(\underline{x})]$, $i = 1, 2, \ldots, p$ represent distances from the "ideal solution," the w_i are objective weights and $\underline{X}^i$ defines the feasible region at the i^{th} iteration and, at the first iteration, $\underline{X} = [\underline{x}|\underline{g}(\underline{x}) \leq \underline{0};$ $\underline{x} \geq \underline{0}]$. The weights are defined to be

$$w_i = \frac{\alpha_i}{\sum_i \alpha_i} \tag{4-47}$$

$$\alpha_i = \frac{f_i^*(x) - f_i^{min}(x)}{f_i^*(\underline{x})} \left[\sum_{k=1}^{n} (c_i^k)^2 \right] \tag{4-48}$$

where $f_i^{min}(\underline{x})$ is the minimum value of objective i in the payoff table and c_i^k is the coefficient of the kth decision variable in the i^{th} objective function. The α_i are defined such that $\sum_{i=1}^{p} w_i = 1$ and the values of the weights depend upon the deviation of the objective function $f_i(\underline{x})$ from the ideal solutions $f_i^*(\underline{x})$.

The feasible solution obtained from (4-43) - (4-46) is presented to the decision maker. If the decision maker feels that the levels of all objectives are satisfactory, then the preferred solution has been found. If the levels of none of the objectives are satisfactory, then no preferred solution exists, according to the algorithm. If some objectives are acceptable and others are not, the decision maker is asked to specify a decrease Δf_{is} in the level of one of the satisfied objectives that he would be willing to accept in order to obtain an increase in the level of the unsatisfied objectives iu. Then the problem (4-43) - (4-46) is repeated with $w_{is} = 0$ and with (4-45) redefined such that $\underline{x} \in \underline{X}^{i+1}$, where $\underline{X}^{i+1}$ is defined as

$$\underline{X}^{i+1} \begin{cases} \underline{X}^i \\ f_{is}(\underline{x}^{i+1}) \geq f_{is}(\underline{x}^i) - \Delta f_{is} \\ f_{iu}(\underline{x}^{i+1}) \geq f_{iu}(\underline{x}^i) \end{cases} \qquad (4\text{-}49)$$

The solution to this problem is presented to the decision maker and the procedure is repeated until all objectives are satisfied or until it is determined that all objectives cannot be satisfied. For a problem with p objectives, the procedure would have to be carried out for a maximum of p iterations.

Loucks (1977 and 1978) presented an application of a modified Stem approach to an irrigation planning problem in northern Africa. The four objectives established in the Loucks papers were the maximization of the yield and the reliability of the water source, and the minimization of capital costs and operation, maintenance and replacement (OMR) costs of the project. Loucks modified the definition of the w_i described in (4-47) and (4-48) to

$$w_i = \begin{cases} \left[f_i^*(\underline{x}) \left(\sum_{i \in J} \frac{1}{f_i^*(\underline{x})} \right)\right]^{-1} & \text{for unsatisfactory objectives} \\ 0 & \text{for satisfactory objectives,} \end{cases} \qquad (4\text{-}50)$$

where J is defined as the set of unsatisfactory objectives at each iteration. In addition, Loucks allowed the decision maker to specify reductions in the levels of more than one satisfied objective at each iteration and allowed the decision maker to change such levels more than once for each objective, thereby allowing the decision maker to have much more flexibility in establishing satisfactory objective levels. This approach, however, removes the guarantee that the algorithm will terminate in at least p iterations for a p objective problem. Loucks presented the results of one set of interactions with a decision maker in which a preferred solution was obtained in six iterations (for a four objective problem).

Semops method. Monarchi (1972) and Monarchi, et al. (1973) presented a method similar to the Step method. The authors called their method Semops, for "sequential multiobjective problem solving." The method involves specification by the decision maker of aspiration levels for each objective, and the algorithm seeks to minimize deviations from these aspiration levels.

Initially, the surrogate objective function

$$S = \sum_{i=1}^{p} d_i \tag{4-51}$$

is formed, where the d_i are deviations from the aspiration levels of the p objectives. The d_i can take on one of five forms, depending upon the nature of objective function i. These five forms are (p. 838):

$d = z/L$ for objectives that are to achieve less than a specified quantity,

$d = L/z$ for objectives that are to achieve more than a specified quantity,

$d = 1/2(L/z + z/L)$ for objectives that are to equal a specified quantity,

$d = [L_2/(L_1+L_2)](L_1/z + z/L_2)$ for objectives that are to remain within a specified interval, and

$d = \dfrac{L_1 + L_2}{L_2(L_1/z + z/L_2)}$ for objectives that are to remain outside a specified interval.

Here, z represents the objective level for a given solution and L, L_1 and L_2 represent aspiration levels specified by the decision maker.

After the aspiration levels are specified by the decision maker, an initial solution is obtained by solving the problem

$$\min S \tag{4-52}$$

subject to

$$\underline{g}(\underline{x}) \leq \underline{0} \tag{4-53}$$

$$\underline{x} \geq \underline{0} \quad . \tag{4-54}$$

Then a "payoff table" is completed. This differs from the payoff table of the Step method (4-42), however, in that the $f_i^*(\underline{x})$ represent the aspiration levels specified by the decision maker for each objective, rather than the best attainable levels of the objectives. The $\underline{x}^i$ represent the values of the decision variable vectors at which $f_i(\underline{x})$ attains its aspiration level, and $f_j(\underline{x}^i)$ represents the value of the j^{th} objective when the i^{th} objective attains its aspiration level.

The decision maker uses the initial solution and the payoff table to determine which objective to remove from the set of objective functions and to enter as a constraint. In the words of Monarchi, et al., he decides which aspiration level to "crystallize" (p. 839). This reduces the number of objective functions by one. Next, the surrogate objective function (4-51) is modified by removing the d_i corresponding to the "crystallized" objective and the problem (4-52) - (4-54) is repeated. This procedure continues until only one objective function remains, which is then optimized to obtain the preferred solution.

Monarchi, et al. illustrated their algorithm with a hypothetical six objective, three decision variable model.

Trade method. In 1976, Goicoechea, et al. presented the application of a variant to the Stem method to a multiobjective watershed management problem. The authors labeled their procedure Trade. The Trade algorithm begins with the construction of the payoff table in a manner identical to that of the Step method. Then a surrogate objective function $S_1(\underline{x})$ is formed

$$S_1(\underline{x}) = \sum_{i=1}^{p} G_i(\underline{x}) \tag{4-55}$$

where

$$G_i(\underline{x}) = \frac{f_i(x) - f_i^{min}(x)}{f_i^*(\underline{x}) - f_i^{min}(\underline{x})} \quad . \tag{4-56}$$

Thus, the quantities $G_i(\underline{x})$ represent percentages of goal attainment for each objective.

Next, the problem

$$\max S_1(\underline{x}) \tag{4-57}$$

subject to

$$\underline{g}(\underline{x}) \leq \underline{0} \tag{4-58}$$

$$\underline{x} \geq \underline{0} \tag{4-59}$$

is solved and is used to generate the vectors

$$\underline{f}(\underline{x}^1)^T = [f_1(x^1),\ f_2(x^1), \ldots,\ f_p(x^1)] \quad (4\text{-}60)$$

and

$$\underline{G}(\underline{x}^1)^T = [G_1(x^1),\ G_2(x^1), \ldots,\ G_p(x^1)]\ . \quad (4\text{-}61)$$

Here, $\underline{f}(\underline{x}^i)$ is a vector of objective levels in the i^{th} solution and $\underline{G}(\underline{x}^i)$ is a vector of percentages of goal attainment. The decision maker is presented with these vectors and, if he is satisfied, then the algorithm terminates. Otherwise, he selects one objective to reduce, as in the Step method, and specifies a lower acceptable level ε for that objective. Then the problem (4-57) - (4-59) is repeated with the selected objective removed from the surrogate objective function and added to the constraint set. The new problem

$$\max S_2(\underline{x}) = \max \left[\sum_{i=1}^{n-1} G_i(\underline{x}) + \sum_{i=n+1}^{p} G_i(\underline{x}) \right] \quad (4\text{-}62)$$

subject to

$$\underline{g}(\underline{x}) \leq \underline{0} \quad (4\text{-}63)$$

$$f_n(\underline{x}) - \varepsilon_n \leq 0 \quad (4\text{-}64)$$

$$\underline{x} \geq \underline{0} \quad (4\text{-}65)$$

is solved and is used to generate the vectors $\underline{f}(\underline{x}^2)$ and $\underline{G}(\underline{x}^2)$. These are then presented to the decision maker and the algorithm proceeds until a satisfactory solution is found.

Goicoechea, et al. appled their algorithm to a watershed management model containing five objective functions, 33 decision variables and 18 constraints. The authors presented the results of a series of interactions with a hypothetical decision maker to illustrate how the Trade method can be used to find a preferred watershed management policy. The solution vectors obtained on the fifth iteration were assumed to be satisfactory to the decision maker. Like the Step method, the Trade method terminates in a maximum of p iterations for a p objective problem.

In 1979, Goicoechea, et al. extended the Trade method by modifying the surrogate objective function and providing the decision maker with a sense of the risk involved in decision making situations. This algorithm, called Protrade (probabilistic Trade), used equations (4-55) - (4-59) to generate initial vectors $\underline{f}(\underline{x}^1)$ and $\underline{G}(\underline{x}^1)$ the same as in the Trade method. The authors then made use of information elicited from the decision maker regarding preferences for the various objectives and used a multiobjective utility function (p. 207) to calculate objective weights. These were then used to modify (4-55) to

$$S_1(\underline{x}) = \sum_{i=1}^{p} w_i G_i(\underline{x}) \tag{4-66}$$

which was then used to generate another solution using (4-57) - (4-59).

At this point, the levels of the objectives obtained by the current solution were expressed as normally distributed random variables. That is, using the example of Goicoechea, et al. (p. 207-208), the vector of objective attainment

$$\underline{f}(\underline{x}^1) = \begin{bmatrix} 0.370 \\ 0.480 \\ 0.354 \\ 0.998 \\ 0.016 \end{bmatrix}$$

becomes

$$\underline{f}(\underline{x}^1) = \begin{bmatrix} 0.370, & 0.5 \\ 0.480, & 0.5 \\ 0.354, & 0.5 \\ 0.998, & 0.5 \\ 0.016, & 0.5 \end{bmatrix} .$$

This indicates, for example, that the probability of attaining at least 37% of the maximum attainable level for objective 1 is 50%.

The decision maker is next asked to specify both a minimum level of objective attainment and a minimum probability of achieving that level of objective attainment for the least satisfactory objective. These specifications are added to the constraint set, and the algorithm proceeds until a satisfactory solution is found. The authors illustrated their method by applying it to a model containing five objective functions, twelve decision variables and three initial constraints.

Pairwise comparisons. The interactive use of pairwise comparisons of objectives was presented by Croley (1974) and Takama and Loucks (1981). In both of these works, the constraint method was used to generate the nondominated set. The preferred solution was obtained from the nondominated set by requiring the decision maker to express his preferences between two alternatives at a time with all but two objectives fixed. Croley favored calculating the tradeoffs between the two non-fixed objectives and providing that information to the decision maker as an aid in expressing his preferences between the two alternatives. Takama and Loucks favored presenting the decision maker only with the absolute levels of the objectives and asking the decision maker which alternative was preferred. In either case, the two dimensional search continues until indifference is reached. Then two other objectives are varied while the others are held fixed. This procedure is repeated until indifference is reached between all pairs of objectives.

Although the use of such pairwise comparisons is straightforward, the procedure could be extremely time-consuming, tedious and expensive if the problem contains at least a moderate number of objectives. In a simple three objective illustration presented by Takama and Loucks (p. 451-452), for example, a total of 36 pairwise comparisons were required before indifference between the three objectives was obtained.

Recent work has also shown that pairwise comparisons can result in intransitive behavior on the part of the decision maker if the decision problems are not carefully framed to avoid the effects of cognitive bias. Sage and White (1983) used regret theory to explain preference reversals in paired choice problems under uncertainty. Tversky and Kahneman (1974) explained how an adjustment and anchoring heuristic can lead to intransitive choices due to recency effects, improper evaluations of conjunctive and disjunctive events, and use of different approaches to subjective probability distributions.

Tradeoff Cutting Plane. Musselman and Talavage (1979 and 1980) presented the develpoment of an interactive technique, referred to as the Tradeoff Cutting Plane method, which is a modified version of an algorithm developed in 1972 by Geoffrion, et al. Musselman and Talavage applied their method to an urban storm drainage problem in West Layfayette, Indiana.

The algorithms of Geoffrion, et al. and Musselman and Talavage both elicit local preference information from the decision maker on an interactive basis. The algorithms initiate from an arbitrarily selected feasible point. The objective space solution at that point is presented to the decision maker, who is asked to specify the tradeoffs between a selected objective and all remaining objectives to which he is indifferent. That is, he is asked to specify

$$\frac{-\Delta f_2(\underline{x}^k)}{\Delta f_i(\underline{x}^k)} \quad \forall\ i.$$

In the method of Geoffrion, et al., this information is then used in the Frank-Wolfe (1956) steepest ascent algorithm to solve the problem

$$\max \quad \sum_{i=1}^{d} w_i^{\,k} \nabla_{\underline{x}} f_i(\underline{x}^k)^T \cdot \underline{y} \tag{4-67}$$

where

$$w_i = \frac{-\Delta f_2(\underline{x})}{\Delta f_i(\underline{x})} \approx \frac{\partial U(x^k)}{\partial f_i(\underline{x}^k)} \Big/ \frac{\partial U(x^k)}{\partial f_2(\underline{x}^k)} \quad ,$$

$\nabla_x f_i(\underline{x}^k)$ is the gradient of $f_i(\underline{x})$ evaluated at $\underline{x}^k$, and k is the iteration counter. The solution $\underline{y}$ is then used to calculate the most promising direction $\underline{d}^k$ in which to seek improvement of the current solution by using

$$\underline{d}^k = \underline{y}^k - \underline{x}^k \quad . \tag{4-68}$$

Next, further interaction with the decision maker is required to determine the desired distance along the direction $\underline{d}^k$ in which to proceed. This is conducted by presenting the decision maker with a display of $f_i(\underline{x}^k + t^k\underline{d}^k)\ \forall\ i$ for various values of t^k, $0 \leq t^k \leq 1$. Decision maker selection of the preferred $\underline{f}(\underline{x}^k)$ defines t^k and $\underline{x}^{k+1}$ is set equal to $\underline{x}^k + t^k\underline{d}^k$. This procedure continues until the most preferred solution is reached; that is, when $t^k = 0$.

The approach of Musselman and Talavage differs in that a modified steepest ascent approach is used with the introduction of a new constraint at each iteration. The added constraints, referred to as "tradeoff cuts," successively reduce the convex set containing the preferred solution.

That is, at each iteration, the algorithm retains both the current solution and the preferred solution.

In addition, the algorithm of Musselman and Talavage does not require the decision maker to identify preferred step sizes at each iteration. Instead of updating the current solution using the steepest ascent direction and preferred step size, the Tradeoff Cutting Plane method uses the solution of the ascent algorithm as the next solution. The algorithm terminates when the decision maker's preferred tradeoffs indicate that no further improvements can be made.

The original approach of Musselman and Talavage required that all objective functions and constraints be continuously differentiable. However, they have adopted the method for use with discrete problems, although identification of a most preferred solution in such cases is not guaranteed.

The Tradeoff Cutting Plane approach does not require step-size decisions by the decision maker, but still requires elicitations of the decision maker's preferred tradeoff rates at each iteration, and provides no guidance about how this should be conducted. This is a disadvantage of the method, as Dyer (1973), Wallenius (1975) and Takama and Loucks (1981) reported findings that decision makers are able to express preferences for absolute levels of objective attainment much more easily than for tradeoffs among objectives. A further disadvantage is the fact that the approach presented for problems with discrete solutions would be computationally intractable for some problems with a very large number of discrete feasible solutions.

Category E - Visual Attribute Level Displays

The methods of Category E do not involve explicit elicitations of the preference structure of the decision maker. Instead, these methods provide ways in which to organize measures of objective achievement from a set of alternatives in such a way that they aid the human mind in making cognitive choices. In using such methods, the decision maker can either examine the display of objective achievement levels across all alternatives to select the preferred alternative, or he can use a pairwise comparison approach to reduce the set of alternatives under consideration until a preferred alternative is identified. Such methods have the advantages that they are straightforward and easy to understand. However, for decision situations involving more than a very small number of objectives and alternatives, such methods normally are not sufficiently powerful to assist adequately the decision maker in dealing with the complexity involved.

Objective achievement matrix displays. The use of matrices to display the levels of objective achievement from a set of alternatives is conceptually the simplest cognitive decision aid of Category E. They are sometimes referred to in the literature as objective impact matrices or tabular displays. Such matrices allow the decision maker to examine directly levels of objective achievement from a set of alternatives in order to identify a preferred alternative. Such an approach provides a framework for the decision maker in which levels of objective achievement can be examined across all alternatives in an orderly fashion. Although this method does not in all cases reduce the complexity of the decision problem, it does help to manage the complexity and to reduce the level of confusion in the mind of the decision maker.

Matrix displays have been used frequently to assist in multiobjective water resources decision problems, and have been required explicitly by recent federal water project planning guidelines. In 1970, Freeman and Havemen (p. 1534) characterized the preparation of a tableau listing all monetary and non-monetary benefits and costs as the most realistic decision-aiding tool for water project selection decision problems.

A typical example of the use of objective achievement matrices to assist decision makers in multiobjective water planning decision problems was provided by Jonathan O'Riordan in 1972. O'Riordan used an evaluation matrix to compare comprehensive water resources development and management alternatives in the Okanagan Valley, British Columbia. O'Riordan's evaluation matrix consisted of a display of the impacts of a set of alternatives on a set of planning objectives. In developing the matrix, he used a scoring procedure, based on a scale of -10 to +10, to estimate impacts that could not be measured in monetary units, such as the impacts on wildlife or recreation objectives. In addition, he adjusted such non-economic impacts by objective weights, which ostensibly reflected the relative values of the non-economic objectives to society. The author used pairwise comparisons to identify the preferred alternative. To accomplish this, he first used paired comparisons in an elimination process to reduce sets of similar alternatives to a single preferred alternative within each set, and then compared these preferred alternatives with those of the other sets to arrive at an overall preferred alternative.

Variants to the matrix display approach have been developed and used by Leopold, et al. (1971), Duke, et al. (1972) and the Tulsa District of the Corps of Engineers (1972) to assist decision makers in considering the environmental consequences of water project alternatives in making water project selection decisions.

In 1973, the U. S. Water Resources Council institutionalized the use of matrix displays by requiring the development of tables to display the impacts of water project alternatives on two national planning objectives (national economic development and environmental quality) and two planning accounts (regional development and social well-being) that were to be considered in project selection decisions. Other examples of impact displays to assist decision makers in multiobjective water resources decision problems have been presented by the United Nations Economic Commission for Asia and the Far East (1972); Schwarz, Major and Frost (1975); Moriwasa and Vemuri (1975); and Major and Lenton (1979). Several of these works also used matrix displays as a part of or in conjunction with more sophisticated decision-aiding techniques.

Graphical displays. Closely related to objective achievement matrices and tabular displays are graphical displays. Essentially, graphical displays provide to the decision maker the same information that could be provided in tabular form. In some cases, however, graphical representation of data may impart to the decision maker a better appreciation of the differences among alternatives.

Graphical displays have been used to present levels of objective achievement under various alternatives as well as objective trade-offs between alternatives. Examples of the former are provided by the works of O'Riordan (1972) and Bishop (1972). Both authors used a graphical description of alternatives called a factor profile, which displays levels of objective achievement from a set of alternatives, as illustrated in Figure 4-1. The factor profile used by O'Riordan scaled objective achievement in absolute terms, whereas the factor profile of Bishop scaled objective achievement in terms of percentages of maximum possible objective achievement.

An example of the use of graphical techniques to display objective trade-offs between alternatives was provided by Byers and Miller in 1975. As indicated earlier, Byers and Miller developed a family of trade-off curves between an economic objective and each of 11 environmental objectives using the constraint method. The authors then presented the set of 11 trade-off curve families to the decision maker to assist in the decision process.

Mapping. Techniques involving the display of spatial patterns of objective achievements have been used beneficially when the spatial distributions of such achievements are of interest. Such situations occur when decision problems involve the identification of geographical areas that may be suitable for multipurpose development, or the iden-

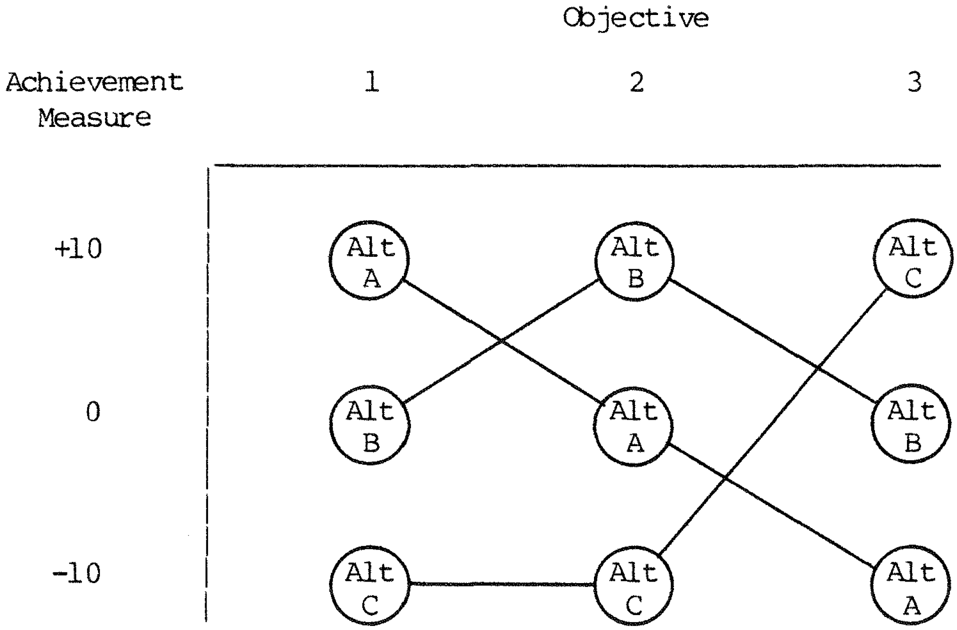


Figure 4-1

Illustration of Factor Profile

tification of areas in which constraints preclude development. The most common mapping techniques involve the use of overlays or computer-based point rating systems which aggregate resource data within specified geographical areas. An example of the use of mapping techniques to assist in multiobjective decision problems involving water resources planning within geographical regions is provided by Murray, et al. (1971).

Chapter 5

A MULTIOBJECTIVE DECISION-AIDING ALGORITHM

Over the past decade, professionals in the academic and public sectors have made extraordinary advances in the development of multi-objective or multicriteria decision support aids for water resources planning. These recent advances have been summarized in the preceding chapter. In the midst of this new wealth of knowledge, however, at least three federal water development agencies are still making extremely complex water project portfolio selection decisions without the benefit of well-designed analytical decision support systems. The portfolio selection problems of these three federal agencies were described in Chapter 2. The purpose of this chapter is to describe the development of a new multiobjective decision-aiding algorithm that is responsive to the needs of these decision problems and which will form the heart of a fully developed decision support system designed for the irrigation construction program of the Bureau of Indian Affairs.

The development of the algorithm described herein represents an extension of previous research in multiobjective decision-aiding techniques. The work is described in four parts. First, a new paradigm that was developed to assist with multiobjective decision-aiding model selection problems is described. Use of the new paradigm to identify the most appropriate multiobjective decision-aiding model for the irrigation construction program is then discussed. Second, a description of the desirable attributes that the new interactive algorithm should have to be fully responsive to the decision problem is provided. Third, a description of the new muliobjective decision-aiding algorithm is provided. Finally, a discussion of the new algorithm is presented.

Selection of Model

Although the field of multiobjective analysis has enjoyed a large amount of attention over the last decade, very little work has been devoted to examination of the conditions under which the great variety of multiobjective techniques can be used most advantageously. As indicated earlier, a significant amount of effort has been devoted to the identification of common characteristics of the various methods in order to develop useful categories into which they can be grouped. Such efforts are useful in facilitating an understanding of the methods, but stop short of providing help to researchers and practitioners in coupling multiobjective decision problems with the most appropriate solution techniques.

Despite the fact that the multiobjective model choice problem has received little attention to date, it is one of significant importance. Gershon (1981, p. 2-3) pointed out that the results from poorly matched problems and solution techniques can be suboptimal or even misleading. He further contended that such poor results can lead to a weakening demand for such techniques and ultimately a general trend away from the use of these potentially valuable tools. Duckstein, et al. (1982) demonstrated the significantly different results that can be obtained by the application of different multiobjective techniques to the same problem.

Loucks (1977, p. 158) observed that the model selection problem is not one of identifying the best model for a particular situation, but rather one of determining the most desirable trade-offs among the attributes of the various models available. Thus, the problem of selecting the most appropriate approach to apply to a specific multiobjective decision problem is itself a multiobjective decision problem.

In making a multiobjective decision-aiding model selection, an analyst typically has a number of concerns. Normally no multiobjective decision-aiding technique will satisfy fully all of these concerns, and the relative importances of such concerns is highly problem situation specific. The multiobjective problem is to identify the multiobjective technique which provides the best compromise among the concerns. This problem is confronted in the pages that follow. First, a summary of previous research into the multiobjective model selection problem is presented. Since no acceptable method of solving the model selection problem was located in the existing literature, a new multiobjective decision-aiding model selection paradigm was developed and is described in the following section. Finally, an application of the new paradigm to the BIA irrigation project portfolio selection problem is presented.

Previous Multiobjective Model Selection Research

Although the research that has been conducted to date concerning the multiobjective technique selection problem has been very limited, some attention has been devoted to this problem. Wallenius (1975) recognized the need to better match multiobjective methods and the characteristics of the decision maker. He postulated the following six criteria with which to compare methods (p. 1389):

- decision maker's confidence in the best compromise,
- ease of use of the method,
- ease of understanding the logic of the method,
- usefulness of the information provided to aid the decision maker,
- rapidity of convergence, and
- computer time required.

Wallenius conducted a laboratory experiment using these criteria to compare three multiobjective decision-aiding methods. He found that simple decision maker-analyst interactions and ease of use of the methods should be important criteria in selection decisions (p. 1391) and that there is a great need to better match multiobjective decision-aiding methods with human factor considerations (p. 1394).

Seaver, et al. (1979) proposed the following five criteria for deciding when the decision analysis approach is appropriate (p. 26):

- presence of clear-cut alternatives,
- presence of perplexing or controversial considerations,
- necessity to communicate persuasively the decision to other parties,
- presence of high stakes, and
- expectations of the recurrence of similar decision situations.

Gershon (1981) developed an algorithm to assist with the model choice problem which contained the following 27 criteria:

- ability to handle qualitative criteria,

- ability to choose among discrete sets of alternatives,
- ability to choose among continuous sets of alternatives,
- ability to solve dynamic problems,
- ability to solve stochastic problems,
- comparison to goal point,
- comparison to aspiration level,
- direct comparison,
- strongly efficient solution,
- complete ranking,
- cardinal ranking,
- ability to handle integer variables,
- computer time required,
- implementation time required,
- interaction time required,
- knowledge required of decision maker,
- consistency of results,
- robustness of results,
- applicability to case of group decision maker,
- number of objectives,
- number of systems,
- number of constraints,
- number of variables,
- level of decision maker's knowledge,
- time available for interaction,
- desire for interaction, and

- confidence in original preference structure.

These 27 criteria were divided into four groups:

- "mandatory binary criteria" which deleted techniques from further consideration if they failed to qualify;
- "non-mandatory binary criteria" which did not necessarily delete techniques from further consideration if they failed to qualify;
- "technique-dependent criteria" which were technique-specific and against which techniques were rated on a 1-10 scale; and
- "application-dependent criteria" which were problem-specific and against which techniques were rated on a 1-10 scale.

Gershon's model selection algorithm involved the selection of a subset of the 27 criteria that were relevant to the problem, assignment of weights to the criteria in the subset, assignment of values (on a 1-10 scale) for the "application-dependent criteria" in the subset, and sequential application of the subset of criteria by category to the set of candidate techniques. Gershon illustrated his model choice algorithm with a 13 criteria, 25 alternative river basin planning problem, and a two objective, continuous resource allocation problem. Gershon and Duckstein (1982) further illustrated the algorithm with a four objective, five alternative design problem.

Duckstein, et al. (1982) used the following six criteria to evaluate and compare three multiobjective decision-aiding techniques:

- type of data needed (qualitative or quantitative),
- nature of systems to be analyzed (discrete or continuous),
- consistency of results between techniques,
- robustness of results with respect to changes in parameter values,

- ease of computation, and
- amount of interaction required between the decision maker and the analyst.

Multiobjective Decision-Aiding Model Selection Paradigm

Although the existing works provide valuable insights into the model choice problem, research in this area had not progressed to the point that a suitable paradigm was available to guide the technique selection process. All of the approaches mentioned above contain provisions that make them inapplicable to the general multiobjective decision-aiding model selection problem, although each may be useful in certain situations. Such provisions include requirements to determine an *a priori* preference structure over model selection criteria, requirements to include model characteristics that are irrelevant to the decision process (such as preferences for goal point or aspiration level approaches), unnecessary elimination of methods from consideration under certain decision situations, and limited numbers of multiobjective decision-aiding methods contained in the selection procedure.

Because of this lack of a usable existing model selection procedure, a new paradigm was developed to assist with the model selection decision. This work built upon the previous work in this area and resulted in the development of a procedure which may be useful for the solution of future multiobjective decision-aiding technique selection problems.

The paradigm is based upon a set of descriptors which characterize multiobjective decision situations. For a given technique selection problem, a subset of the descriptor set is selected that accurately describes the decision situation, and that subset is used to screen sequentially the set of available techniques. Formally, the multiobjective decision-aiding technique selection procedure consists of the following steps:

1. Define list of available multiobjective decision-aiding techniques.

2. Formulate the decision problem and gain an understanding of the decision situation.

3. Examine each decision situation descriptor to determine relevance to the decision situation.

4. Select decision situation descriptor subset by deleting irrelevant descriptors.

5. Screen list of multiobjective decision-aiding techniques using templates corresponding to selected subset of decision situation descriptors.

6. If all techniques have been eliminated, identify the technique(s) eliminated by the smallest number of templates. Otherwise, go to Step 9.

7. Examine templates eliminating identified technique(s) to determine modifications which allow deficiencies to be overcome. If modifications can be identified, go to Step 11. Otherwise, go to Step 8.

8. Remove weakest descriptors from the descriptor subset (Step 4) until one or more acceptable techniques are reinstated.

9. If more than one technique remains after the completion of Step 6, develop a matrix display of decision criteria not reflected by the decision situation descriptors in Table 5-1. Otherwise, select the one remaining method as the most appropriate and stop.

10. Select the most appropriate method using the matrix display as a cognitive aid.

11. Modify identified technique(s) to overcome deficiencies. Stop.

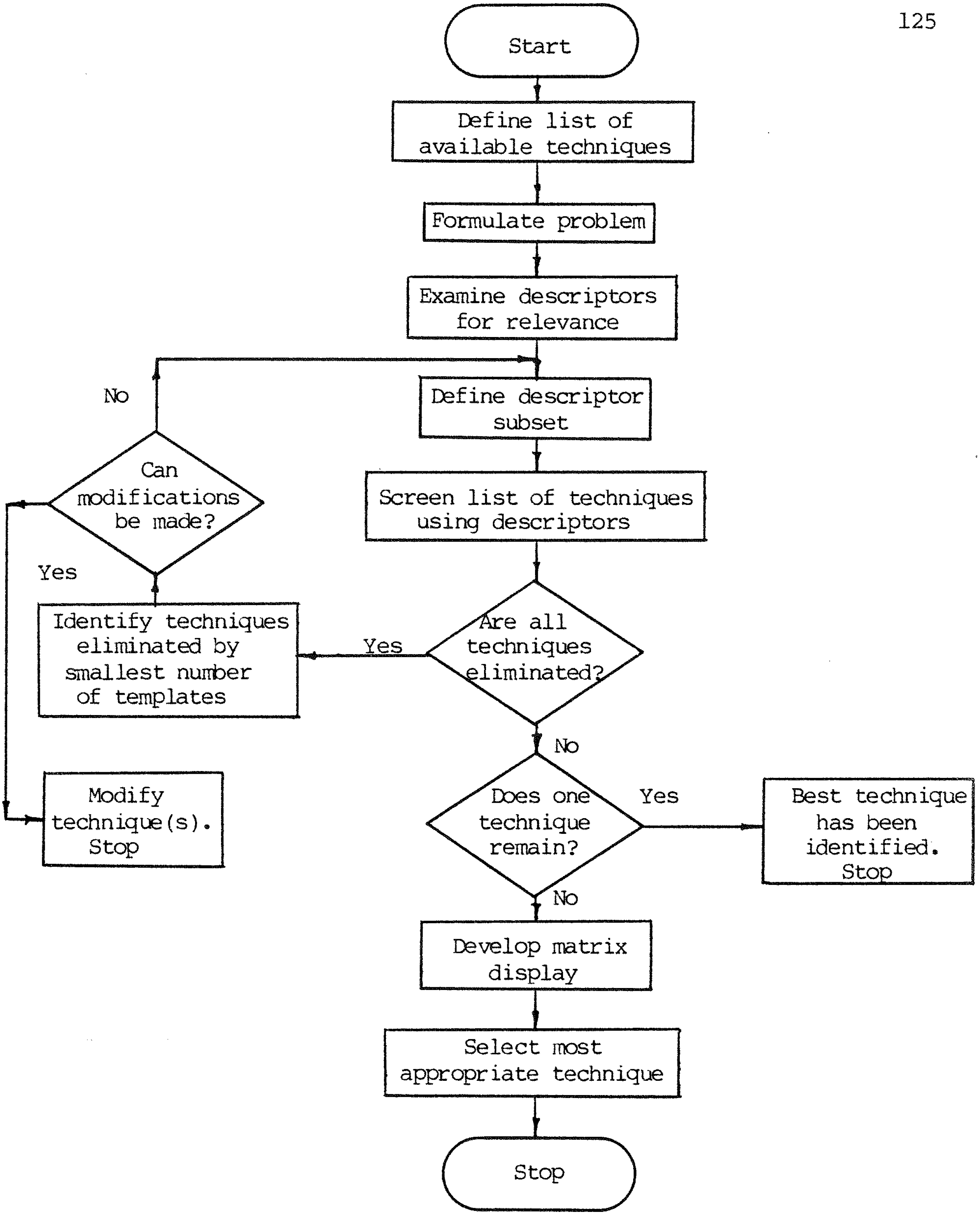


Figure 5-1

Flowchart of Model Selection Paradigm

A flow chart of the model selection paradigm appears in Figure 5-1. Each of the eight steps of the paradigm is described below.

Step 1 - Define List of Available Multiobjective Decision-Aiding Techniques. This list should include all methods to which the analyst has access. In most cases, such a list should be quite extensive.

Step 2 - Formulate Decision Problem. In this step a thorough understanding of the decision problem and the context within which the problem is to be solved should be gained. This includes knowledge of alternative solutions available, type of solution needed by the decision maker (single best solution, complete or partial ranking, ordinal or cardinal ranking, etc.), decision-maker attitude toward "satisficing" solutions, resource constraints, probability of repeated decisions, ability of the decision maker to conceptualize hypothetical situations, willingness of the decision maker to express preferences for tradeoffs among objectives explicitly, use of solution, and time available with the decision maker. In practice, this step will be carried out with Step 3 on an iterative basis. That is, proper examination of each decision situation descriptor to determine its relevance to the decision situation (Step 3) will force the analyst to return to Step 2 for additional information in each instance where a characteristic of the decision situation addressed by a descriptor is not fully understood.

Step 3 - Examine Descriptors for Relevance. Table 5-1 contains a list of descriptors that characterize multiobjective decision situations. This list represents the outcome of an investigation into the conditions under which each technique listed in Table 4-2 may be applied most

Table 5-1

Decision Situation Descriptors

A. Finite set of discrete alternatives

B. Continuous alternatives

C. Ordinal attributes

D. Ordinal ranking of alternatives sought

E. Cardinal ranking of alternatives sought

F. Portfolio of discrete alternatives sought

G. Single-stage decision problem

H. Multi-stage decision problem with changing preferences

I. Large number of objectives or discrete alternatives

J. Need for highly refined solution

K. Decision maker reluctant to express preferences explicitly

L. Decision maker experiences difficulty in conceptualizing hypothetical trade-offs or goal levels

M. Decision maker preferences for marginal rates of substitution among objectives not independent of absolute levels of objective attainment

N. Need for decision maker understanding of method

O. Limited time with decision maker available appropriately. For the model selection paradigm, Table 4-2 was augmented by the addition of the interactive methods of Geoffrion, et al. (1972) and Zionts and Wallenius (1976). The methods of Geoffrion and Zionts-Wallenius, although not developed for or applied to problems in water resources planning, have the potential to be useful in such a context. The descriptor list contains only those elements that were found to represent distinct characteristics of multiobjective decision situations that can be identified readily and which provide meaningful information to the model selection decision process.

To conduct Step 3, each descriptor is compared to the decision situation to determine which are relevant. To facilitate this step, each descriptor is described below:

A. Finite set of discrete alternatives. Multiobjective decision problems in this category contain a finite set of discrete values that can be assumed by the decision variables. An example of such a decision problem is the selection of reservoir sites from a finite set of alternative sites.

B. Continuous alternatives. This category of multiobjective problems contains decision variables which can assume a continuum of values. Continuous problems can be discretized so that discrete problem techniques can be applied to them. Such converted problems represent only approximations of the original problems. An example of a problem with continuous alternatives is a reservoir sizing problem.

C. Ordinal attributes. Problems with this characteristic have at least one attribute that is susceptible to ordinal comparisons only. That is, the degree of objective attainment along such an attribute is not measurable on a cardinal scale. Thus, the decision maker may be able to establish ordinal rankings of alternatives along such an attribute to reflect his preferences, but cannot place them on a cardinal scale. An example of such an ordinal attribute is aesthetic appeal.

D. Ordinal ranking of alternatives sought. The output of a decision process can be the identification of the single most preferred alternative, a partial or complete ordinal ranking of alternatives, or a partial or complete cardinal ranking of alternatives. In problems characterized by this descriptor, the desired output of the decision process is an ordinal ranking of alternatives.

E. Cardinal ranking of alternatives sought. In problems characterized by this descriptor, the desired output of the decision process is a cardinal ranking of alternatives. Since all decision-aiding methods that yield cardinal rankings of alternatives also yield ordinal rankings, this descriptor may be viewed as a finer screen then Descriptor D, above.

F. Portfolio of discrete alternatives sought. Problems involving the identification of a preferred portfolio of alternatives are contrasted by this descriptor from problems in which a single preferred alternative or a ranking of alternatives is sought. In such problems, the most preferred combination from a finite set of discrete alternatives, under a set of feasibility constraints, is sought.

G. Single-stage decision problem. This descriptor is appropriate for one-time decision problems. In such problems, the decision is not to be repeated and is not affected by considerations of future decisions. Identification of the complete preference structure of the decision maker in such problems may not be needed to determine preferences over the entire noninferior solution set. In addition, elicitation of preferences over an attribute that shows small variance over the set of noninferior solutions may not be necessary.

H. Multi-stage decision problem with changing preferences. This type of decision problem is characterized by the necessity to make repeated decisions, with a significant probability that the preference structure of the decision maker will change between decisions. Such problems require considerations of updating estimates of the preference structure at each stage.

I. Large number of objectives or discrete alternatives. Decision problems containing large numbers of objectives or discrete alternatives may render some methods infeasible because of severe computational implications.

J. Need for highly refined solution. In this category of decision problems, sub-optimal or "satisficing" solutions are not acceptable. The benefits of increased accuracy in such problem situations outweigh the increased costs, time and effort required to implement methods which yield more accurate and consistent solutions.

K. Decision maker reluctant to express preferences explicitly. In decision problems characterized by this descriptor, the decision maker finds it unacceptable to express preferences for tradeoffs among objectives explicitly. An example is a situation in which a decision maker wishes to mitigate political repercussions from a decision on a controversial issue.

L. Decision maker experiences difficulty in conceptualizing hypothetical tradeoffs or goal levels. In situations where the decision maker expresses difficulty in expressing preferred tradeoffs or goal levels without knowledge of feasible solutions, methods that use actual alternatives in the decision-aiding process are more appropriate than those which rely entirely on hypothetical levels of objective achievement or tradeoffs in the elicitation of decision maker preferences.

M. Decision maker preferences for marginal rates of substitution among objectives not independent of absolute levels of objective attainment. In decision situations where the assumption of independence between decision maker preferences for tradeoffs and absolute levels of objective attainment (preferential independence) is not acceptable, methods which are based upon such an assumption are not appropriate.

N. Need for decision maker understanding of method. In situations requiring decision maker understanding of the "black box", methods which are not easy to understand are inappropriate. Such situations occur when difficulty is anticipated in gaining acceptance of solutions or when the decision must be communicated persuasively to other parties. Tversky (1972, p. 296) and Dyer (1973b, p. 213) have noted the importance of this criterion in model selection.

O. Limited time with decision maker available. Since the accessability of the decision maker can vary widely from one decision problem to another, those methods which require the analyst to spend large amounts of time with the decision maker should be avoided when such access is not reasonably available.

It is noted that the above list of decision situation descriptors includes only those descriptors which provide meaningful distinctions among the various multiobjective decision-aiding methods. A number of additional descriptors which do not reflect distinct differences among the methods can also be envisioned. Examples of such additional descriptors that are related to the above list include:

- objectives susceptable to cardinal comparisons (related to Descriptor C);
- single most preferred alternative sought (related to Descriptors D and E);

- multi-stage decision problem with unchanging decision maker preferences (related to Descriptors G and H); and
- need for screening of alternative solutions (related to Descriptor J).

None of the additional decision situation desriptors are sufficiently strong to reduce a list of multiobjective decision-aiding methods under consideration for application to a particular problem.

Step 4 - Selection of Decision Situation Descriptor Subset. This step involves a reduction of the list of descriptors contained in Table 5-1 to a subset that describes accurately the decision situation under consideration. This provides a subset of descriptors which will be used to screen a list of available multiobjective decision-aiding techniques.

Step 5 - Screen List of Multiobjective Decision-Aiding Techniques. In order to screen the list of available multiobjective decision-aiding techniques developed in Step 1 using the reduced set of descriptors developed in Step 4, the screening templates contained in Appendix B are used. Each template corresponds to one of the decision situation descriptors listed in Table 5-1. These templates provide an effective and efficient means of rapidly reducing the list of available methods to a much smaller subset.

Use of the screening templates is straightforward. The analyst sequentially screens the available set of techniques from Step 1 with the template corresponding to each of the descriptors remaining in the reduced set developed in Step 4. In order to insure that the analyst understands the process and to provide a check on the sequential elimination process, each template contains a set of notes that explains the reasons why the methods are eliminated under each decision situation descriptor.

It is noted that this sequential elimination process is similar to the elimination by aspects model of Tversky (1972a and 1972b). However, it differs in that all descriptors (aspects) are used in the sequential elimination process, whereas in Tversky's model the sequential use of each aspect terminates when the set of alternatives has been reduced to a single member.

Step 6 - Identify Techniques Eliminated by Smallest Number of Templates. Step 6 is necessary only if all available techniques have been eliminated by the initial screening in Step 5. Should this occur, those techniques eliminated by the smallest number of templates in Step 5 are identified. If all available techniques were not eliminated in Step 5, the paradigm proceeds to Step 9.

Step 7 - Identify Modifications. In this step, templates eliminating the techniques identified in Step 6 are examined to determine the reasons why the techniques were eliminated. Then an attempt is made to identify modifications to overcome deficiencies that make the techniques inapplicable to the decision problem. Chances of successful modification will be higher when the number of templates eliminating the techniques are small in number. If such modifications can be developed, the paradigm proceeds to Step 11.

Step 8 - Removal of Weakest Descriptors. If modifications to overcome identified deficiencies could not be identified in Step 7, the paradigm returns the analyst to Step 4 in order to identify that element of the current element subset that is least relevant to the decision situation. That descriptor is deleted from the subset and the process continues until at least one technique is retained at the conclusion of Step 5.

Step 9 - Develop Matrix of Additional Selection Criteria. In this step, any considerations (criteria) that the analyst might have in selecting the most appropriate multiobjective decision-aiding technique, but which are not reflected in the decision situation descriptor set contained in Table 5-1, come into play. Such criteria might include such elements as the availability of the expertise needed for implementation of the method, the amount of computer time that is required, or how compatible the method is with group decision making or conflict resolution (Alter, 1977, p. 113). The matrix display is developed by labeling the rows with the list of methods remaining after Step 8 and creating column headings from the additional selection criteria. Information for the matrix entries can be obtained by reviewing the descriptions in Chapter 4 of the methods remaining under consideration, supplemented if necessary by a review of the works referenced in Appendix A that pertain to such methods.

Step 10 - Select Most Appropriate Method. At the conclusion of Step 9, the analyst has a relatively small matrix display which can be used as a cognitive aid to assist in selecting the most appropriate multiobjective decision-aiding method to use in the unique circumstances of the decision situation with which he is dealing. At this point the selection decision can be made from a small number of alternatives in consideration of the proper integration of the behavioral, institutional and quantitative aspects of the decision situation.

Step 11 - Modify Identified Technique(s). In this step, modifications identified in Step 7 are fully developed. Such modifications could involve changes to a single existing technique or the combination of desirable features of more than one technique.

Implementation of the Model Selection Paradigm

The model selection paradigm described above was used to determine the most appropriate algorithmic approach for the development of a decision support system for the BIA irrigation program portfolio selection problem. In order to describe the manner in which that selection decision was made and to illustrate the use of the model selection paradigm, the outcome of the application of each step of the paradigm to the portfolio selection problem is summarized below.

Step 1 - Define List of Multiobjective Decision-Aiding Techniques. The list of techniques considered to be available for application to the BIA irrigation program portfolio selection decision problem was the complete list contained in Table 4-2 augmented by the interactive methods of Geoffrion, et al. (1972) and Zionts and Wallenius (1976).

Step 2 - Formulate Decision Problem. Since the decision problem and the decision situation in which it is immersed have been documented earlier, they will not be repeated in detail here. It should suffice to mention that, at this step, the objectives and alternatives of the problem had been identified, and that characteristics of the decision maker and resource and institutional constraints had been assessed. In addition, it was known that a single most preferred portfolio solution was desired, that the decision would be repeated annually, and that access to the decision maker was available. Finally, a good understanding of the use of the output of the decision support system had been gained.

Step 3 - Examine Descriptors for Relevance. In this step, all decision situation descriptors in Table 5-1 were examined in the context of the decision situation. Seven descriptors were found to be irrelevant to the decision situation. A listing of those descriptors and the reasons why each was found to be irrelevant are provided below:

B. Continuous alternatives. The decision problem contains a finite set of discrete water project construction alternatives in each budget cycle (fiscal year). Therefore, the continuous alternatives descriptor was eliminated.

C. Ordinal attributes. All of the attributes related to the set of objectives to be used in the decision support system were susceptable to cardinal measurements.

D. Ordinal ranking of alternatives sought. The decision problem calls for the identification of the preferred portfolio of alternatives, as contrasted to a ranking of alternatives.

E. Cardinal ranking of alternatives sought. Same rationale as that for the deletion of Descriptor D.

G. Single-stage decision problem. The decision problem requires a portfolio selection decision to be made in each fiscal year. A significant probability exists that the preferences of the decision maker will change from year to year due to changing policies or priorities mandated by the Secretary of the Interior, the Office of Management and Budget, or Congressional authorization or appropriations committees.

M. Lack of independence between decision maker preferences and levels of objective attainment. At each stage of this decision problem, the potential range of impacts of the decision on each of the objectives is assumed to be small relative to the total unmet need in each objective. For example, the maximum possible contribution of jobs resulting from a single year's appropriation level in the irrigation program is assumed to be small compared to the number of jobs needed on the reservations potentially benefitting from the irrigation program. If the appropriation level available to the program were to be dramatically increased, then this assumption might become invalid.

O. Limited time with decision maker available. The decision maker identified in Step 2 had expressed a strong interest in the research project and free access to him in the decision making process was not anticipated to be a problem.

Step 4 - Selection of Decision Situation Descriptor Set. The descriptor subset used in this application was determined by deleting the irrelevant descriptors identified in Step 3 from the descriptor set contained in Table 5-1. The remaining descriptors were:

A. Finite set of discrete alternatives;

F. Portfolio of discrete alternatives sought;

H. Multi-stage decision problem with changing preferences;

I. Large number of objectives or discrete alternatives;

J. Need for highly refined solution;

K. Decision maker reluctant to express preferences explicitly;

L. Decision maker experiences difficulty in conceptualizing hypothetical tradeoffs or goal levels; and

N. Need for decision maker understanding of method.

Step 5 - Screen List of Multiobjective Decision-Aiding Techniques. Screening templates corresponding to the decision situation descriptors identified in Step 4 were used to screen the list of available techniques defined in Step 1. A summary of the results of this screening process is provided below. This summary illustrates the logic upon which the multiobjective decision-aiding model selection procedure is based. A more complete understanding of the reasons for the eliminations in this particular application may be obtained from a reading of the notes of the templates corresponding to the descriptors listed in Step 4.

All techniques included in the nondominated solution generating category (first category of methods in Table 4-2) were eliminated because they are not applicable to discrete problems. For discrete problems, a simple check for dominance can be used to derive the non-dominated set from the set of all alternatives.

The a priori complete elicitation techniques were eliminated because of decision maker reluctance to express tradeoffs explicitly and the difficulties involved in reassessing decision maker preferences at each decision point. Since the results of decisions made using the selected model will be disseminated throughout the organizational hierarchy of the BIA and communicated to Indian leaders on the reservations, any explicit tradeoffs between such objectives as the protection of water rights and the number of jobs provided could be extremely controversial. Because of this consideration, the BIA official identified as the decision maker in the problem situation (Chief Irrigation Engineer) indicated that he would be unwilling to express such preferences in an explicit form. All of the a priori complete elicitation methods, however, require explicit expressions of preferences. An additional difficulty with these methods involves the amount of decision maker time that is required to assess preferences. With the possible exception of the optimal weighting method, the necessity of eliciting the preference structure of the decision maker at each decision stage may be prohibitive.

The methods included in the a priori partial elicitation category were eliminated for a variety of reasons. These included the need for the decision maker and others to understand the "black box" of the selected method, the lack of acceptability of an approximate solution and computational infeasibility. The problem situation involves not only the identification of the preferred portfolio of projects, but also the effective communication of the decision support system to budget officials of the Interior Department and the Office of Management and Budget, and to the Congressional appropriations subcommittees. Therefore, an important criterion in the model selection task is the ease with which the method can be explained and the perceived credibility that is associated with it. The need to establish concordance and discordance thresholds may reduce the clarity of the ELECTRE method, and the concepts of the surrogate worth function and the surrogate worth values may introduce significant difficulties in understanding the SWT method. In addition, the lexicographic and goal programming approaches were eliminated since a more finely tuned solution was desired than these methods can deliver. Further, the lexicographic and ELECTRE methods can lead to inconsistent results between applications since the order established on the set of alternatives is a function of the order in which the objectives are used, or the threshold values chosen for the discordance condition, respectively. Finally, since the portfolio selection problem involves a large number of noninferior feasible portfolio combinations, the need to calculate concordance and discordance conditions or to develop system versus criteria arrays makes the ELECTRE and compromise programming methods computationally intractible.

Two of the methods in the progressive elicitation category were eliminated. The Tradeoff Cutting Plane method was eliminated due to computational intractibility associated with the very large number of possible feasible solutions. The methods of Geoffrion and Zionts-Wallenius were eliminated due to their lack of applicability to problems with discrete alternatives. In addition, since the decision problem contains a relatively large number of objectives, the requirement to make pairwise comparisons between all pairs of objectives would make the interaction between the decision maker and the analyst intolerably time-consuming and tedious. Therefore, the pairwise comparison approach was also eliminated.

The methods contained in the visual attribute display category were eliminated because of the large number of feasible portfolio combinations contained in the decision problem.

Thus, sequential application of the screening templates of Appendix A corresponding to the descriptors selected in Step 4 resulted in the elimination of all but three of the multiobjective decision-aiding methods contained in Table 5-1. Therefore, the paradigm proceeds to Step 9.

Step 9 - Develop Matrix of Additional Selection Criteria. Two criteria were identified in this step to select from among the remaining methods. These were: maximization of the value of the learning process inherent in the use of interactive models and effectiveness of the decision maker-model link. However, none of the models was determined to be superior on both of these counts. All three methods emphasize guaranteed convergence over extraction of the maximum value of the inherent learning process, and only the Trade approach addresses the decision maker-model link. Therefore, it was decided to incorporate the best attributes of each of the three methods into a hybrid decision-aiding algorithm which would remove the emphasis on speed of convergence, focus on extraction of the maximum learning value of the interactive methods, and contain an improved decision-aiding display.

A detailed description of the new interactive multiobjective decision-aiding algorithm that was developed as a result of the application of the model selection paradigm is provided later in this chapter.

To illustrate use of the model selection paradigm in cases where all methods are eliminated and modifications cannot be identified in Step 7, an example of the weakening of the descriptor set (Step 8) is provided below, using the same problem situation.

If no modifications were identified in Step 7 to overcome deficiencies diagnosed in Step 6, the descriptor set identified in Step 4 would be reexamined to identify the least relevant members. Of the eight members of the descriptor subset, five clearly could not be deleted since they are inalterably relevant to the decision problem. These are:

A. Finite set of discrete alternatives;

F. Portfolio of discrete alternatives sought;

H. Multi-stage decision problem with changing preferences;

I. Large number of objectives or discrete alternatives; and

K. Decision maker reluctant to express preferences explicitly.

The remaining three descriptors, however, conceivably could be deleted. These are listed in order of increasing relevance:

L. Decision maker experiences difficulty in conceptualizing hypothetical tradeoffs or goal levels;

J. Need for highly refined solution; and

N. Need for decision maker understanding of method.

Although the elimination of Descriptors L or N would not reinstate any methods, the elimination of Descriptor J would reinstate the lexicographic and goal programming approaches for further consideration.

At the conclusion of Step 8, a matrix of additional selection criteria (Step 9) would be developed and used for final selection of the most appropriate technique (Step 10), as discussed previously.

Thus, application of the model selection paradigm led to the recognition that modification of the Step, Semops or Trade interactive methods to overcome identified deficiencies could yield a more effective tool for the decision problem than was present in the set of available methods. This recognition, in turn, led to the development of a new multiobjective decision-aiding algorithm that retained the positive features of existing interactive methods while overcoming the lack of learning flexibility of the Step, Semops and Trade methods. A description of the new algorithm is presented in the pages that follow. First, desirable attributes that the new algorithm should have relative to the decision problem are identified and discussed. Then a detailed description of the algorithm is provided, followed by a short discussion of the new procedure.

Attributes of New Algorithm

In recent years, a number of interactive methods and variations have appeared in the literature to assist with the multiobjective decision making problem. Many of these are described in Chapter 4. Limited comparative evaluations of interactive methods have been presented by Wallenius (1975) and Dyer (1973b). As demonstrated by the application of the multiobjective model selection paradigm in the preceding section, interactive methods may be very suitable for portfolio selection problems of the type that is the principal focus of this research. However, in order for an interactive procedure to be fully effective in addressing that problem, it must not only overcome the previously identified disability of other interactive procedures, but must also be responsive to a number of other important considerations. These include the following elements: (1) use of absolute levels of objective attainment in eliciting decision maker preferences, (2) use of pairwise comparisons of portfolios, (3) absence of a requirement for expression of decision maker preferences among objectives in explicit terms, (4) use of real contextual situations, (5) capture of the maximum value of learning processes inherent in interactive procedures, (6) simplicity of implementation, and (7) ability to handle changing decision maker preferences. Each of these attributes is discussed briefly below.

Wallenius (1975, p. 1391) reported an experimental finding that decision makers experienced a much easier task in expressing preferences for absolute levels of objective attainment than in expressing preferences for tradeoffs or marginal rates of substitution between objectives. Dyer (1973a, p. 1379) and Takama and Loucks (1981, p. 449) reported similar findings. Therefore, it seems logical to assume that an interactive decision-aiding procedure that elicits decision maker preferences using absolute levels of objective attainment would be preferred over one that elicits statements of preferred tradeoff rates.

Cohon and Marks (1975, p. 218) and Krzysztofowicz, et al. (1977, p. 691) pointed out that the elicitation of preferences through pairwise comparisons of alternatives has major advantages over elicitation approaches that present the decision maker with more complex decisions. This would seem to be an additional desirable feature of a new interactive procedure if problems with intransitive behavior associated with paired choices, as explained by Tversky and Kahneman (1981) and Sage and White (1983), can be held to an acceptable level. Both Wallenius (1975, p. 1391) and Krzysztofowicz, et al. (1977, p. 691) expressed convictions that the decision maker-analyst interaction should be kept as simple as possible. Wallenius (1975, p. 1391) and Dinkelbach and Isermann (1980, p. 99) reported findings that speed of convergence, which has been a major objective in the development of some interactive methods, is not a significant factor in the chances for successful application of such methods to real problems in multiobjective decision making.

Loucks (1975, p. 221) observed that many decision makers are reluctant to discuss their preferences among conflicting objectives in explicit terms. Since the decision maker in the irrigation program of the Bureau of Indian Affairs may have his decisions scrutinized by groups of varied interests, this may be a significant consideration. Therefore, the decision support system should not require the decision maker to express trade-off preferences in explicit terms.

Chandler (1973, p. 419) and Zionts and Wallenius (1976, p. 653) reported findings that decision makers find it easier to respond to preference questions in the context of actual situations rather than in abstract situations. Thus, use of real alternatives in eliciting decision maker preferences would seem to be a desirable feature to incorporate into a new decision-aiding procedure.

Hammond, et al. (1977, p. 359), Krzysztofowicz, et al. (1977, p. 691) and Zeleny (1980, p. 2) emphasized the importance of the learning process that is embodied in some computer-assisted decision-aiding procedures. In order to provide for such a learning process, an interactive procedure must allow the decision maker to change his mind about earlier responses based on learning that has occurred during the interactive process. Zionts and Wallenius (1976, p. 659) and Dinkelbach and Isermann (1980, p. 99 and 103) explained that such flexibility can be provided only if early decision maker responses do not constrain the outcomes of subsequent iterations. Thus, to insure that the learning process inherent in the interactive approach is not inhibited, the new procedure must allow the decision maker to use knowledge gained in the interactive process to modify earlier decisions.

Dyer (1973b, p. 213) reported findings that some interactive procedures are appropriate for use in situations where continuous availability of expert assistance cannot be assumed. Such situations would include those in which a multiobjective decision is to be made on a repeated basis over a long period of time, and the organization in which the decisions are to be made has limited requisite internal expertise. Since such is the case in the BIA irrigation portfolio selection problem, considerations of use in the presence of limited expert assistance would seem to be significant. In addition, ease of understanding of the procedure and consequent ease of communicating results to others are significant considerations in the design of the interactive procedure in light of the decision situation.

Since the preference structure of the decision maker may change between subsequent decisions, as noted previously, the new interactive procedure should make no assumptions regarding the form of the decision maker's preference structure and should not demand full information on the complete preference structure of the decision maker. That is, it should be able to handle changing preferences between subsequent decisions.

An interactive algorithm was developed that overcomes the problems with computational intractibility inherent in previously developed interactive precedures when applied to portfolio selection problems. In addition, it is responsive to all of the considerations discussed above. A description of the new algorithm is presented below.

Algorithm Description

The new algorithm is an interactive linear multiobjective algorithm based on zero-one integer programming. As discussed previously, a significant amount of work has been devoted to the development of interactive decision-aiding methods. In addition, the literature reflects some work conducted to develop zero-one integer programming algorithms for single objective resource-constrained project scheduling problems (Pritsker, et al., 1969; and Talbot and Patterson, 1978). Further, Bitran (1977) reported the development of a multiobjective zero-one integer programming algorithm to be used to generate noninferior sets of alternatives. However, no work was identified that was focused on the development of a multiobjective zero-one integer programming algorithm that can be used on an interactive basis for decision making. This is somewhat surprising in light of the apparent usefulness of such an approach to assist with deterministic resource-constrained portfolio selection problems; a problem class that seems to be fairly common.

A collection of the notation used to explain the algorithm is presented below, followed by a description of the algorithm.

Notation

$\underline{A}$	m x n matrix of objective contributions
a_{ij}	contribution of construction project candidate i to objective j; $a_{ij} \geq 0 \; \forall \; i, j$
b	capital budget limit
$\underline{C}$	m x 1 vector of project construction capital requirements
c_i	capital requirement for the construction of project candidate i
$\Delta f_{\hat{j}}$	decision maker-specified change in objective $\hat{j}$
$f_{\hat{j}}(\underline{x})$	objective function selected for change by decision maker
$f_j{}^*(\underline{x})$	maximum level attainable by objective j
$f_j(\underline{x}^k)$	contribution to objective j of project candidate vector (portfolio) $\underline{x}^k$
$\underline{f}^*(\underline{x})$	vector of maximum values of all objectives displayed simultaneously. Referred to as the "ideal unattainable solution" vector; $\underline{f}^*(\underline{x}) = [f_j{}^*(\underline{x}): j=1, 2,..., n]$
$\underline{f}(\underline{x}^k)$	vector of objective attainment levels resulting from project candidate vector (portfolio) $\underline{x}^k$
k	cycle counter
m	number of construction project candidates
n	number of objectives
$\underline{p}^k$	vector of objective attainment percentages resulting from project candidate vector (portfolio) $\underline{x}^k$; $\underline{p}^k = [\frac{f_j(x)}{f_j{}^*(\underline{x})} : j=1, 2,..., n]$
$\underline{x}^k$	vector of project candidates $\underline{x} = (x_1,...,x_i,...,x_m)$ at iteration k; $\underline{x}^k = [x_i: i=1, 2,..., m]$

x_i integer decision variable that takes on a value of 1 if project candidate i is included in the portfolio, 0 otherwise

Algorithm

Step 1 - Input coefficients which express the potential contribution of each construction project candidate to each objective. That is, input $\underline{A} = [a_{ij}: i = 1, 2, \ldots, m; j = 1, 2, \ldots, n]$. The coefficients a_{ij} of $\underline{A}$ express the potential contributions of construction project candidate i to objective j. Such coefficients are derived from field data. Objectives that are to be minimized are converted to maximization problems by multiplying the coefficients in columns j by -1 (see Step 4).

Step 2 - Input coefficients which express capital requirements for project candidates. That is, input $\underline{C} = [c_i: i=1,2, \ldots, m]$. The coefficients c_i of $\underline{C}$ express the capital requirements of project candidates i. Such coefficients are obtained from project planning documents.

Step 3 - Input budget constraint b. Scalar b represents the capital resource constraint. Initialize cycle counter k to k = 1.

Step 4 - Calculate maximum possible contributions to each objective separately within budget constraint b without regard to the levels of other objectives. That is, calculate $\underline{f}^*(\underline{x}) = [f_j^*(\underline{x}): j=1,2,\ldots, n]$. This is accomplished by solving the n problems:

$$\left.\begin{aligned} f_j^*(\underline{x}) &= \max \sum_{i=1}^{m} a_{ij}x_i \\ \text{s.t.} &\sum_{i=1}^{m} c_i x_i \leq b \\ x_i &= 0, 1 \qquad \forall\, i \end{aligned}\right\} \quad \forall\, j \qquad (6\text{-}1)$$

The solutions to these n problems represent the maximum attainable levels of the n objectives $f_j(\underline{x})$; $j = 1, 2, \ldots, n$, without consideration of the levels of the other objectives. The 1 x n vector $\underline{f}^*(\underline{x})$ is referred to as the "ideal unattainable solution".

Step 5 - Calculate the initial solution. That is, calculate

$$\underline{x}^k = [x_i];\ \underline{f}(\underline{x}^k) = [f_j(\underline{x}^k)];\ \text{and}\ \underline{p}^k = \left[\frac{f_j(\underline{x}^k)}{f_j^*(\underline{x}^k)}\right] .$$

This is accomplished by solving the problem:

$$\min \sum_{j=1}^{n} \left[\frac{f_j^*(\underline{x}) - \sum_{i=1}^{m} a_{ij}x_i}{f_j^*(\underline{x})}\right] \qquad (6\text{-}2)$$

subject to

$$\sum_{i=1}^{m} c_i x_i \leq b \qquad (6\text{-}3)$$

$$x_i = 0, 1 \qquad \forall\, i\ . \qquad (6\text{-}4)$$

Step 6 - Present the decision maker with the initial solution. This consists of the following information:

a. $\underline{f}(\underline{x}^k) = [f_j(\underline{x}^k)]$

b. $\underline{p}^k = \left[\dfrac{f_j(x^k)}{f_j^*(\underline{x}^k)} \right]$

c. Factor profile graphic depicting $\underline{f}(\underline{x}^k)$.

Step 6 represents the initial involvement of the decision maker with the decision support system for a given decision problem. The solution display includes a vector of absolute levels of objective achievement, a vector of percentages of ideal (unattainable) objective achievement, and a graphical display of objective achievement. The display is arranged to facilitate ease of decision maker comprehension, as illustrated in the example problem in Appendix C.

Step 7 - Ask the decision maker if the current nondominated solution is his most preferred solution. It is not anticipated that an affirmative answer will be received to this question during the first iteration, even though it is entirely possible that the initial solution will ultimately be identified as the most preferred solution. Unlike most other interactive algorithms, this procedure is sufficiently flexible to enable the decision maker to explore other solutions that may be less satisfactory than the current one and still return to the current one at some future point. If an affirmative answer is received to the question, the algorithm goes to Step 11 and the procedure terminates. If a negative answer is received, the algorithm proceeds to the next step.

Step 8 - Ask the decision maker to specify an increase or decrease in the attained level of one or more objectives. This may be accomplished by asking the following four questions: (1) which objectives are the least satisfied, (2) how much change is desired in the least satisfied objective, (3) in which objectives is the decision maker willing to accept a decreased contribution, and (4) how much change is acceptable for the objectives to be decreased? Add appropriate constraints and find the next solution. That is, ask the decision maker to specify one or more objectives $\hat{j}$ and changes $\Delta f_{\hat{j}}(\underline{x})$. Add new constraints $f_{\hat{j}}(\underline{x}) \geq f_{\hat{j}}(\underline{x}^k) + \Delta f_{\hat{j}}(\underline{x})$. Note: $\Delta f_{\hat{j}}(\underline{x})$ can be positive or negative. Set $k = k + 1$. Step 8 allows the decision maker to specify an increase or decrease in one or more objectives so that the impact on the other objectives may be observed.

Step 9 - Calculate new solution. That is, calculate $\underline{x}^k$, $\underline{f}(\underline{x}^k)$ and $\underline{p}^k$. This is accomplished by solving problems (6-2)-(6-4) with the additional constraint(s)

$$f_{\hat{j}}(\underline{x}^k) \geq f_{\hat{j}}(\underline{x}^{k-1}) + \Delta f_{\hat{j}}. \qquad (6\text{-}5)$$

Step 10 - Present the decision maker with the new and previous solutions. This includes the following information:

a. Previous solution -

$\underline{f}(\underline{x}^{k-1})$; $\underline{p}^{k-1}$; factor profile

b. Current solution -

$\underline{f}(\underline{x}^k)$; $\underline{p}^k$; factor profile

Ask which solution is preferred. Set $\underline{x}^k = \underline{x}^k$ or $\underline{x}^{k-1}$, depending on the response of the decision maker. Go to Step 7.

Step 11 - The most preferred solution has been identified. Print $\underline{f}(\underline{x}^k)$, $\underline{p}^k$, $\underline{x}^k$ and factor profile. Stop.

Figure 5-2 presents a flow chart of the interactive algorithm.

For problems in which objective contributions a_{ij} can assume negative values, equation (6-2) must be modified to

$$\min \sum_{j=1}^{n} \left[\frac{f_j^*(\underline{x}) - \sum_{i=1}^{m} a_{ij} x_i}{f_j^*(\underline{x}) - f_j^{min}(\underline{x})} \right] \qquad (6\text{-}6)$$

where $f_j^{min}(\underline{x})$ is found by solving the problem

$$f_j^{min}(\underline{x}) = \min \sum_{i=1}^{m} a_{ij} x_i \qquad (6\text{-}7)$$

subject to

$$\sum_{i=1}^{m} c_i x_i \leq b \qquad (6\text{-}8)$$

$$x_i = 0, 1 \quad \forall i . \qquad (6\text{-}9)$$

In such problems, $\underline{p}^k$ must be modified to

$$\underline{p}^k = \left[\frac{f_j(x^k)}{f_j^*(\underline{x}^k) - f_j^{min}(\underline{x}^k)} \right] . \qquad (6\text{-}10)$$

Such changes are necessary to account for the fact that the lower bound of the range variation for objectives with negative a_{ij} coefficients could be less than zero.

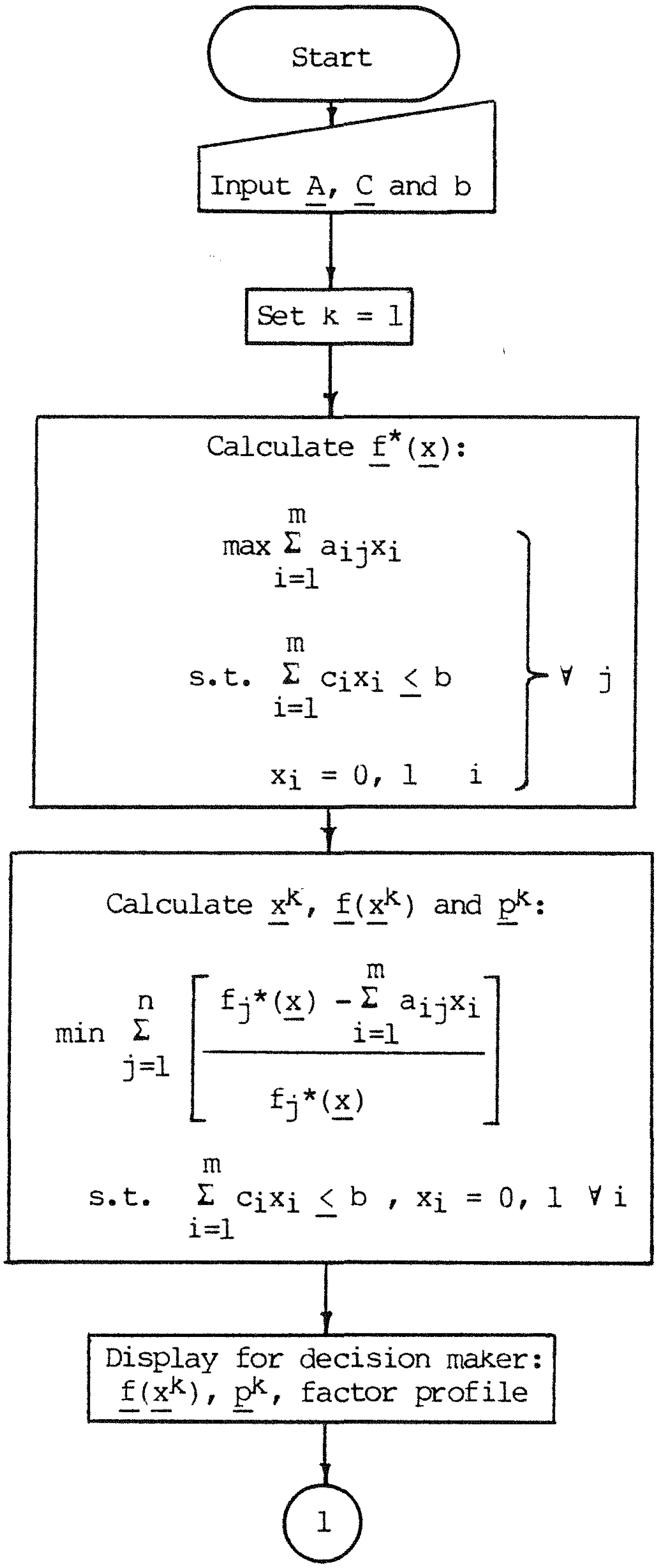


Figure 5-2

Flowchart of Interactive Algorithm

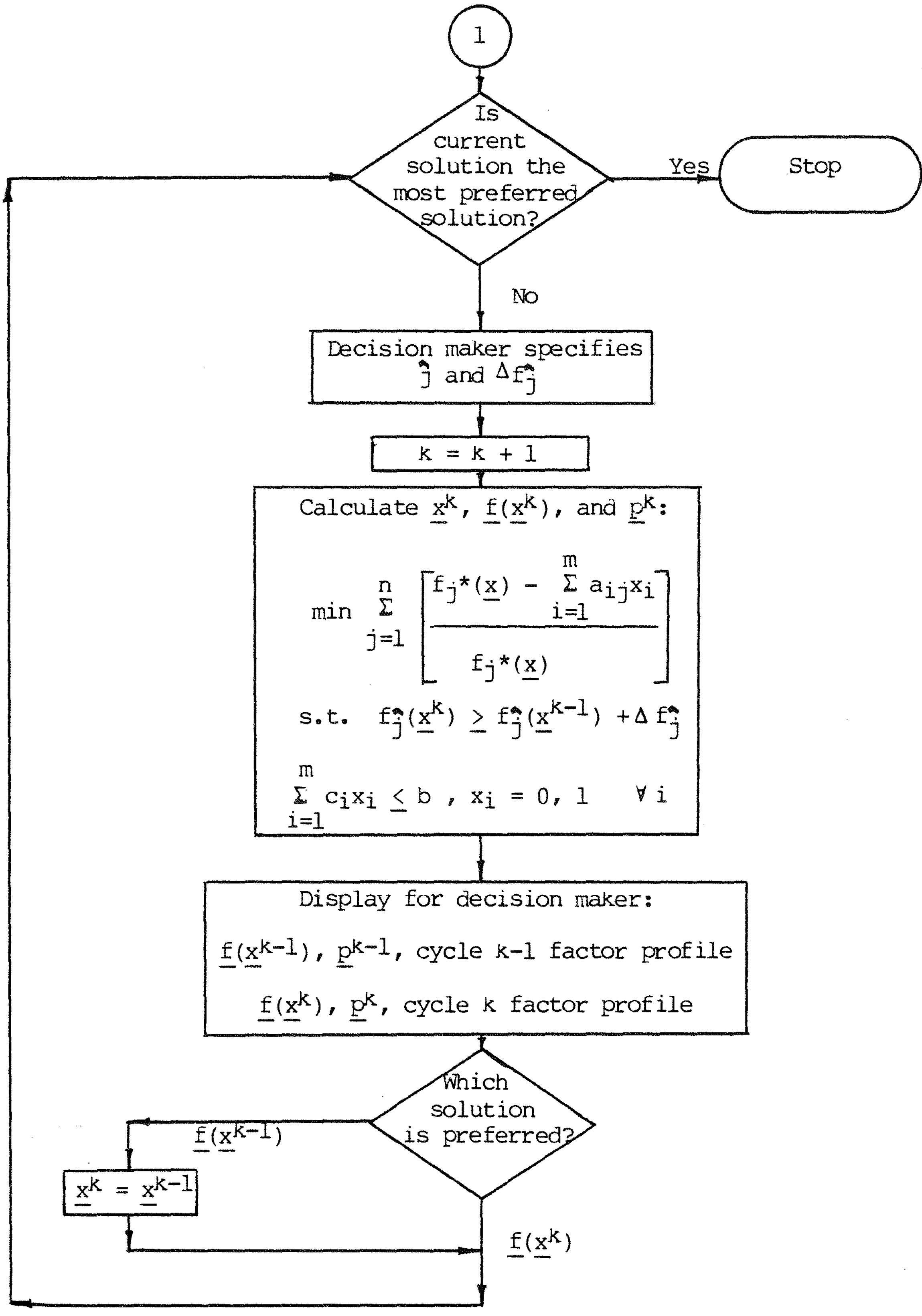


Figure 5-2 (continued)

Flowchart of Interactive Algorithm

Discussion

A number of points concerning the above algorithm warrant discussion. As stated earlier, the algorithm enters a frontier that has heretofore received little, if any, attention: the use of zero-one integer programming on an interactive basis for resource-constrained multiobjective decision making. In addition, it differs from many other multiobjective approaches in several other ways.

Most interactive methods that have been developed to date have emphasized speed of convergence at the expense of learning and flexibility. Hammond, et al. (1977), Krzysztofowicz, et al. (1977) and others have pointed to the learning process that is inherent in interactive procedures as one of their most valuable attributes. However, it would seem that speed of convergence and learning are conflicting objectives of interactive methods. This is because procedures that provide for rapid convergence to a preferred solution do not allow decision makers to use the knowledge gained in the interactive process to modify earlier statements of preference. If sufficient flexibility is incorporated into an interactive algorithm to allow a decision maker to change his mind in such a manner that earlier preference decisions do not constrain the outcomes of subsequent interactions, then convergence cannot be guaranteed. It has been noted previously that Wallenius (1975, p. 1391) and Dinkelbach and Isermann (1980, p. 99) reported experimental findings that speed of convergence does not appear to be a significant factor for success in the minds of decision makers. Thus, the new algorithm presented above emphasizes flexibility and the extraction of maximum value from the learning process over guaranteed convergence.

Some multiobjective methods that are based on minimizing distances from ideal or aspiration levels use absolute distances for the distance metric. As pointed out by Zeleny (1973, p. 299), however, such an approach does not provide for commensurate metrics when the feasible ranges of decision variables are significantly different. Therefore, the minimization problems contained in Steps 5 and 9 are based on relative distances from the "ideal unattainable solution" rather than upon absolute distances. Although an absolute distance metric could have been used, it may have resulted in the generation of initial solutions in Step 5 that were far from the preferred solution being sought, thus increasing the level of difficulty for the decision maker and increasing the number of interactions required to converge on the preferred solution.

The fact that the algorithm is based on minimization of relative distances from the ideal unattainable solution rather than from decision maker-specified aspiration levels is also significant. Methods using the aspiration level approach, such as the Semops method, require the decision maker to supply preference information in order to find an initial solution. The use of aspiration levels may introduce needless complexity into the decision problem since the decision maker may have no idea of where to place them. Payne, Laughhunn and Crum (1980) also demonstrated that use of achievable aspiration levels can result in intransitive choice behavior since decision maker preferences for incremental changes in objective achievement and attitudes toward risk can change whenever a translation involves crossing an aspiration level.

The use of maximum or minimum attainable values for each objective serves the same purpose as aspiration levels, requires no preference information to get an initial solution, and eliminates intransitive behavior associated with crossing sepiration levels.

Another important characteristic is that, since the algorithm uses pairwise comparisons of alternatives instead of pairwise comparisons between objectives to elicit decision maker preferences, the assumption of preferential independence among objectives is not a necessary condition for model use. In addition, many of the problems with intransitive behavior in some paired choice solution methodologies do not arise in use of the algorithm developed in this study. Since the model is deterministic, certain preference reversals in paired choice situations explainable by regret theory (Bell, 1982; Sage and White, 1983) and prospect theory (Tversky and Kahneman, 1981) do not occur. In the latter case, decision weights that may be associated with probabilities of outcomes are not variable, since the model is to be operated under conditions of certainty. As Tversky and Kahneman (1981, p. 454) pointed out, non-variable decision weights do not contribute to preference reversals due to framing of acts, outcomes or contingencies. The use of target levels that cannot be exceeded prevents problems with intransitivities associated with translation across aspiration levels, as described by Payne, Laughhunn and Crum (1980). Finally, the algorithm reduces the occurrence of intransitive behavior associated with inconsistent framing by allowing the portfolio selection problem to be treated as a concurrent decision problem. Tversky and Kahnemen (1981,

p. 455) pointed out that the complexity of many problems, such as portfolio selection problems, prevents decision makers from integrating alternatives even if they wanted to do so. Such problems are therefore treated as many independently framed decision problems, yielding preferences that are different than would occur if the decisions were combined. The new decision-aiding algorithm allows the decision maker to treat a water project portfolio selection decision as a concurrent decision problem instead of as a series of individual problems.

Other characteristics of the new algorithm that differ from other multiobjective decision-aiding methods, but which are responsive to the decision situation, include the requirement that the decision maker express preferences for absolute levels of objective attainment rather than preferences for tradeoff ratios between objectives, the provision for pairwise comparisons of alternative solutions rather than requirements for more complex decision maker decisions, and the use of actual non-inferior alternatives to elicit decision maker preferences rather than the use of hypothetical alternatives.

The use of both tabular and graphic output displays to aid decision making is appropriate to the decision situation. Lucas (1981) found that cognitive decision style is an important factor in successful use of decision support systems. Lucas' experimental results indicated that decision makers with heuristic decision styles respond differently to graphic output displays than do those with analytic decision styles. Generally, graphic displays were found to be more effective than tabular displays for decision makers with heuristic decision styles, although tabular displays were more useful for some purposes with analytic users. Sage (1981), on the other hand, held that separation of thought processes into analytical and heuristic models was not compatible with reality (p. 658). Sage further pointed out that cognitive processes vary not only across individuals but within the same individual and that decision support processes must provide for both analytical and heuristic support to be effective. Huber (1983) found the literature linking observed behavior and presumed cognitive style to be contradictory. He concluded that decision support systems should not be designed to fit the cognitive style of a particular decision maker, but should enable users to exercise an assortment of styles in their decision tasks. He pointed out that, not only do individual users exhibit variable decision characteristics, but that most decision support systems have multiple users over time.

Doktor and Hamilton (1973) found that managers typically have heuristic decision styles whereas management scientists typically have analytic decision styles. Decision makers (decision support system users) in the irrigation program of the Bureau of Indian Affairs typically are program managers with engineering backgrounds. It is reasonable to expect that such decision makers would exhibit both heuristic and analytic characteristics, as described by Sage (1981). Thus, use of a decision-aiding display that uses both tabular and graphic output is appropriate.

The new interactive decision-aiding algorithm is illustrated with a simple numerical example in Appendix C.

Chapter 6

DEVELOPMENT OF A DECISION SUPPORT SYSTEM

The multiobjective decision-aiding algorithm described in the previous chapter is just one of many that have been developed in recent years. Unlike most, however, this algorithm constitutes the heart of a fully developed decision support system that has been constructed to solve an actual problem in water resources decision making.

The term, "decision support system" as used herein refers to a complete, systematic procedure that is fully developed for the support of complex decisions. Such a system is normally tailored to fit the unique circumstances of a specific problem situation. It is not limited to the development of a mathematical decision-aiding algorithm, but also includes all other components that are necessary for effective decision making, such as the specification of objectives, algorithm programming, and data collection system.

This chapter describes the development of a decision support system for the water project portfolio selection problem. The decision support system is built around the decision-aiding algorithm described in the previous chapter and is set forth in the following components: preparation of a computer program to operationalize the algorithm, specification of the objectives upon which the decision is to be based, and collection of input data.

Algorithm Programming

During the development of the interactive algorithm described in Chapter 5, the potential size of the portfolio selection problem was of concern initially. The number of portfolio combinations possible with the 322 project candidates identified in the data collection effort, for example, is $2^{322} = 5.3 \times 10^{96}$. The algorithm, although conceptually sound, would not be useful if the capability did not exist to implement it with the size of problems that it was likely to encounter. Therefore, an investigation was made in conjunction with the development of the algorithm to determine the capability of modern hardware and software to solve zero-one programming problems of such an order of magnitude. The results of that investigation are summarized below, followed by a description of the program that was developed to implement the algorithm.

State of the Art of Zero-One Integer Programming

A widely accepted framework for classifying and comparing integer programming solution techniques was developed by Geoffrion and Marsten in 1972. Geoffrion and Marsten divided integer programming solution techniques into four categories: enumerative, Bender's decomposition, cutting plane and group theory. Enumerative approaches involve searches for all possible solutions in ways that make exhaustive consideration of each possible solution individually unnecessary. This category includes all implicit enumeration and branch and bound techniques. The Bender's decomposition approach converts mixed integer programming problems to equivalent all-integer problems for solution. Cutting plane methods involve the relaxation of problem constraints, followed by sequential constrictions. Group theory methods involve relaxation of nonnegativity constraints on integer variables and separation of the problem into candidate problems.

A number of authors have investigated computational efficiencies of integer programming software, with some work devoted to the solution of pure zero-one programming problems. The results of these efforts reflect the considerable progress that has taken place in recent years to improve the computational efficiencies of such software.

In 1967, Lemke and Spielberg reported computational experiences with three integer programming codes to solve 0-1 problems. Although they found widely varied efficiencies, they reported successful solutions to problems with up to 89 0-1 variables and 28 constraints.

In 1969, Geoffrion tested the relative efficiencies of five implicit enumeration programs using problems containing up to 80 0-1 variables. In addition, he found an improved implicit enumeration algorithm to be capable of solving problems with up to 90 0-1 variables.

In their 1972 work, Geoffrion and Marsten reviewed 14 integer programming packages and reported data on problem solving efficiencies on a number of these, including some results on applications to pure 0-1 programming problems. Their findings included a 114 0-1 variable, 60 row problem which was solved in 0.3 minutes of CPU time using an enumerative algorithm; and a 7,000 0-1 variable, 150 row problem which was solved in 40 minutes of CPU time using a cutting-plane algorithm.

Brue and Burdet (1974) demonstrated the efficiency of a general branch and bound algorithm to solve pure 0-1 programming problems by presenting data on the solutions to 13 problems with up to 500 0-1 variables and 200 constraints.

Granot and Granot (1980) reported findings that over 95% of 800 problems with up to 70 0-1 variables and 50 constraints were solved in less than 90 seconds of CPU time.

Hughes, et al. (1976, p. 2) and Nauss (1979, p. 5) observed that the current trend in integer programming is toward almost exclusive use of branch and bound (enumerative) approaches. Reasons for this trend have been suggested by Nauss to include the flexibility inherent in the branch and bound approach, its generation of feasible solutions as it proceeds to optimality (thereby providing good feasible solutions in the event of early termination), and its high computational efficiency.

Algorithm Program Listings

The IBM program product Mathematical Programming System Extended/370 (MPSX/370), Mixed Integer Programming/370 (MIP/370) option (IBM, 1973) was chosen for use in implementing the algorithm presented in Chapter 5 because of its capability of solving large integer programming problems and its ready availability on the Amdahl V7 computer at the U. S. Geological Survay headquaters at Reston, Virginia. The MPSX/370 package incorporates expanded speed and computational capabilities over its predecessor, the MPS/360 package used in many universities.

The MIP/370 option allows up to 32,767 integer variables to be defined. It uses a branch and bound approach to the optimization of integer programming problems.

Listings of programs developed to implement the decision-aiding algorithm are presented in Appendix D. These listings include the master program listing and 16 subroutines. These programs are written in three languages: FORTRAN, CLIST (IBM Command List language) and MPSCL (IBM Mathematical Programming System Control Language).

The master program (BIA.CLIST) is an interactive program with a feature that allows the optimization processing of MPSX/MIP to be conducted either interactively or in batch mode. Problem optimization by batch mode is appropriate when time between subsequent solutions is not important and when computer budgets are active constraints. In batch mode, time between solutions ranges from several minutes to overnight, depending upon the job priority specified. A brief statement of the functions of each of the 17 programs that are listed in Appendix D is provided below.

<u>BIA.CLIST</u> - This program, written in CLIST, is the master control program for the decision-aiding algorithm. It prompts the decision maker for required information and calls the subroutines described below.

<u>BIA7.FORT</u> - This program, written in FORTRAN, converts the input matrix provided by the using organization into the format necessary for acceptance by MPSX/MIP.

<u>RUNLP.CLIST</u> - Allocates files necessary for MPSX/MIP and causes the LP to run.

<u>INIT.FORT</u> - Initializes input file to coincide with the size of the input data array and the budget constraint vector when the

interactive mode is selected and additional constraints (other than the budget constraint) are not being used.

INITC.FORT - Performs the same function as INIT.FORT when the interactive mode is selected and additional constraints are being used.

INITB.FORT - Initializes input file to coincide with the size of the input data array and budget constraint vector when the batch mode option for optimization is selected. Not used when user specifies that additional constraints (other than the budget constraint) are to be used.

INITBC.FORT - Performs the same functions as INITB.FORT when the user specifies that additional constraints are to be used.

INIT2.FORT - Updates counter to keep track of the objective function being optimized.

INIT3. FORT - Updates counter to skip all objective functions and proceed to find the initial nondominated solution.

MPSCL.DATA - Specifies MPSX procedures called to carry out the optimization. Used when finding the maximum attainable value for each objective. Does not calculate value for all objective functions.

MPSCL2.DATA - Specifies MPSX procedures for all optimizations not handled by MPSCL.DATA. Calculates values for all objective functions.

BATCH1.CNTL - Runs the MPSCL.DATA optimization program using Class B.

BATCH2.CNTL - Runs the MPSCL2.DATA optimization program using Class B.

BATCH3.CNTL - Runs the MPSCL.DATA optimization program using Class D.

BATCH4.CNTL - Runs the MPSCL2.DATA optimization program using Class D.

FORT.CNTL - Compiles FORTRAN programs.

PRNT.CNTL - Prints program output when the batch made is not selected.

The BIA.CLIST program interactively prompts the user for the number of objectives, number of project candidates, budget constraint and name of input file. In addition, it prompts for constraints in addition to the budget constraint, allowing the user to specify the name of the data file containing the constraints, the columns within that file to be treated as constraints and the type of constraint (greater than or less than). The program also contains an option that allows the user to skip the subroutine that sets up the input file for the MPSX/MIP (BIA7.FORT) and proceed directly into the optimization when the desired input data has been set up into the proper format previously.

Information on the operating performance of the programs and a discussion of program output are contained in the next chapter as part of a description of the test application of the decision support system. Possible additional improvements have been identified which could make the program more fully interactive and to accomplish other purposes. These are described later as future research needs are discussed.

Specification of Objectives

The specification of objectives is obviously an important task in any decision making situation. It is the first step in the decision paradigms listed by such authors as Cohon (1978, p. 16) and Gibson (1979, p. 86). Several authors have emphasized the fact that the proper selection of objectives is a task that deserves a great deal of time and attention in the decision making process (Meta Systems, Inc., 1975, p. 41; Cohon, 1978, p. 18). Despite the critical nature of this early step, however, most authors have paid little attention to it in the development of multiobjective decision-aiding methods. Many simply have postulated the objectives of the decision problem with which they are dealing, resulting in objective sets that are incomplete, redundant or not operational. Others have concentrated entirely on the development of decision algorithms, arbitrarily selecting several objectives in order to demonstrate their method. Such authors frequently assume that a usable and appropriate objectives set would be available in an actual decision situation. In a major study of the use of models for water resources management, planning and policy making in the federal government, the Office of Technology Assessment (1982) found the tendency of many model developers to produce models without serious attention to the needs of decision makers to be a major barrier to successful model use (p. 15).

One of the reasons why the specification of objectives has not received the attention that it deserves may be that the specification of an appropriate and operational set of objectives is as difficult as it is important. Keeney and Raiffa (1976, p. 41) have pointed out that the objectives in almost all complex problems can be structured into a hierarchy. At the top of the hierarchy is an all-inclusive objective that takes into account all of the concerns of the decision maker. However, this broad objective is generally too vague to be of use in a decision-aiding methodology. At lower levels of the hierarchy, the objectives become progressively better defined, but larger in number. At the extreme, the lowest level objectives could become so specific and numerous that no alternative would dominate any other alternative in terms of the stated objectives (DeWispelare and Sage, 1981, p.2). This assumes, of course, that there is a little good in everything, if one looks hard enough.

The Technical Committee of the Water Resources Centers of the Thirteen Western States (1971, p. 23) addressed the problem of how far to disaggregate an objectives hierarchy by developing a stopping rule. Each sub-objective of the hierarchy was disaggregated until it reached a level at which the sub-objective could be readily measured or until there appeared to be no connection between the sub-objective and public or private water resources activities. The authors reported that such a stopping rule did cause some gaps to appear in objectives hierarchies developed in test cases, but that such oversights were felt to be minor (1971, p. 27). Hierarchies developed by the Technical Committee (1971, p. 29-30, 35-40, and 53-62; and 1974, p. 147-151) using the stopping rule seem to be very complete.

Keeney and Raiffa (1976, p. 50-53) also addressed the question of disaggregation of objectives. They suggested that an appropriate set of objectives should represent that level of the hierarchy at which the number of objectives is as small as it can be, while still maintaining sufficient specificity that contributions of alternatives towards each objective can be measured. That is, the objectives set must be both minimal and operational. In addition, Keeney and Raiffa noted that an effective set of objectives must also be complete, in that the set should cover all areas of concern for the problem; decomposable, in that the objectives should be capable of being divided into lower-level objectives; and nonredundant, in that the set should avoid the double counting of consequences.

Keeney and Raiffa (1976, p. 34-35) also provided general guidance on how to go about the development of an operational objectives set. They listed the following approaches: examination of the relevant literature, analytical study, casual empiricism, surveys of individuals affected and use of a group of knowledgeable experts. Cohon (1978, p. 19-20) listed three sources of objectives: the analyst's knowledge of the problem, conversation with the decision makers and a review of appropriate published material.

The development of the hierarchy of objectives for the irrigation construction program of the BIA was conducted in three steps. First, a general literature review was conducted to examine the types of objectives used by other analysts concerned with the objectives of water resources development in general. This review, although interesting, did not reveal a set of objectives that could be used directly in the decision support system to be developed. Therefore, a search of written documentation in the BIA archives concerning the objectives of water development on Indian reservations was undertaken. The outcome of this search yielded valuable information, but still fell short of providing the objectives set that was sought. That objectives set was finally elicited from a group of water development experts within the BIA using a group idea generating and structuring process. This exercise was conducted in two distinct steps: the design of an appropriate process, and the implementation of that process. These three phases of the development of an objectives set, review of written documentation, group process design, and group process implementation, are described below.

Review of Written Documentation

The specification of objectives for problems in water resources planning by various authors is very diverse. Howe (1971, p. 15) described a useful four-category taxomomy of possible benefits and costs:

- those for which market prices exist and for which prices correctly reflect social values;
- those for which market prices exist but for which prices do not correctly reflect social values;
- those for which no market prices exist but for which social values can be approximated in monetary units; and
- those for which no monetary value can be estimated.

All authors agree that net benefits (excess of benefits over costs) from water projects should be maximized, but there is a great deal of disagreement over which of the above benefits and costs should be included in the objectives of water resources development activities. Major (1977, p. 9-20) wrote that a very large range of objectives is socially relevant in most water resources planning operations, but that a full range of objectives was not normally operational in water project planning. Loucks, et al. (1981, p. 205), listed the following eight common objectives of water resources development: national or regional income maximization, income redistribution, environmental quality, social well-being, national security, self-sufficiency, regional growth and stability, and preservation of natural areas. Marglin (1966) discussed the use of efficiency and income redistribution as operational components of a national welfare objective. Haimes (1981, p. 23) suggested that risk should be included along with other objectives in water resources planning. James and Lee (1971, p. 96-105) listed six objectives of water resources development: maximum national income, ideal income distribution, environmental quality, institutional stability, public health, and regional development), but viewed the use of an economic efficiency objective as a useful approximation of the multiobjective approach. This viewpoint is not too far from that expressed by Eckstein in his classic work Water-Resource Development (1961). Although he recognized the non-monetary benefits of water projects, Eckstein felt that the national interest is best served by economic benefit-cost analysis, with considerations of income redistribution and other social and political objectives left to Congress and to administrators (p. vii). Mishan was even more strict in his interpretation of appropriate water project objectives. In his view, the only appropriate benefits are those "additions to social welfare that can, in Pigou's words, 'be brought into relation with the measuring rod of money'" (1976, p. 166) and the only correct investment criterion is that of economic efficiency (p. 255).

Federal reports concerning water project benefits also do not agree with each other. For example, a 1971 report conducted as part of the National Water Commission study (Meta Systems, Inc., 1975, p. 36) recommended the use of the following five objectives as those most appropriate to water resources development: increasing national income, promotion of national autonomy, redistribution of consumption, preservation of environmantal quality, and fulfilling merit wants. However, the final National Water Commission report (1973, p. 382) viewed the three objectives of national economic development, regional economic development and environmental quality as appropriate for water development. The U. S. Water Resources Council (1973, p. 6) specified only the two objectives of national economic development and environmental quality in its 1973 federal water project planning guidelines.

A great variety of objective sets can also be found in specific applications studies. Das and Haimes (1979), for example, sought to minimize sediment, BOD, phosphorus and cost in a water quality problem, while Reid and Leung (1979) used 21 objectives in a problem involving the establishment of water development priorities. Seaver, et al. (1979), on the other hand, developed a hierarchy that included project purposes as well as objectives for use with each of eight water project constituent groups.

Because of this great diversity in the specification of objectives for water resources planning problems that appears in the literature, the objectives of the BIA irrigation program could not be specified at this point. It was decided to look into the files of the BIA to see if an historical insight into the objectives of the program could be obtained. This search located six relevant documents.

The earliest was a 1961 report to the Secretary of the Interior which indicated that both income and protection of water rights are the overriding objectives of Indian water development (U. S. Department of the Interior, 1961, p. 68). A 1963 irrigation task force report to the Commissioner of Indian Affairs discussed the importance of considering social and economic aspects of Indian reservations in evaluating the future of Indian irrigation. The report recommended that the objectives to be considered in future Indian project evaluations include water rights protection, percentage of Indian usage, and economic feasibility (U. S. Bureau of Indian Affairs, 1963, p. 4-6).

In 1966, the Division of Economic Development of the Bureau of Indian Affairs issued a comprehensive analysis of the Indian irrigation program. It listed five objectives of the program: community development, improvement in general welfare, stabilization of local economies, base for the training of semi-skilled and skilled labor, and increase in property values in immediate and surrounding areas (U. S. Bureau of Indian Affairs, 1966, p. 39). The following year, a paper prepared by the Bureau of Indian Affairs for the Director of the Bureau of the Budget specified only two objectives of Indian irrigation: maximization of income and employment (U. S. Bureau of Indian Affairs, 1967).

The next list of the objectives of Indian water development appeared in 1978 when a U. S. House of Representatives report contained a list of seven criteria to be used to establish priorities for future Indian irrigation projects (U. S. Congress, 1978, p. 53). These were: time until attainment of self-sustaining status, total estimated cost of the project, number of people affected, availability of an adequate water supply, current condition of the project, ultimate annual operation and maintenance costs, and whether the project should be continued. Finally, in 1979 the BIA developed the following list of fourteen criteria for assigning such priorities (U. S. Bureau of Indian Affairs, 1979): total estimated cost of the project, ultimate annual operations and maintenence costs, time until attainment of self-sustaining status, extent of Indian operation, condition of project, number of Indians affected, availability of an adequate water supply, enhancement of the environment, conservation of water, protection of water rights, benefit/cost ratio, Indian employment effects, provision of means for subsistence, and proper water management.

As the contents of these six reports were analyzed, it became clear that two of the works studied in the literature review of the objectives of water resources development were especially pertinent to the specification of the objectives of the BIA irrigation construction program. In the first of these, Livingstone and Hazlewood (1979) provided an interesting insight into the "availability of water" criterion. According to these authors, conventional wisdom holds that the dependability of the water supply should be an important consideration on reservations where subsistence farming is practiced. The rationale behind this argument is that such Indian farmers are risk-averse since they are not far above the starvation threshold. However, Livingstone and Hazlewood pointed out that subsistence farmers may actually be able to assume a higher degree of risk than can profit-making farmers. This is because such farmers generally have a higher output value per dollar of farm development costs; they generally have no loans to be serviced and repaid (repayment of farm development costs, such as land leveling and the construction of distribution ditches, sprinklers, and drains that are provided by the BIA irrigation program are deferred by the Leavitt Act of July 1, 1932 as long as the land is held in trust by the United States); and their situation in dry years is unaffected by the project. That is, the development of a large tract of land for irrigation on a subsistence-level Indian reservation does not affect the land that can be irrigated in dry years. In fact, if the subsistence-level Indian farmer can store food from year to year, then a larger developed area could produce extra food in good years for use in bad years. Thus, the dependability of the water supply may be relatively unimportant in such situations from the viewpoint of the Indian subsistence-level farmer.

The work of Trosper (1978) relates to the "extent of Indian operation" criterion. Trosper applied statistical tests and input-output analysis to examine poverty on Indian reservations. His results indicated that production efficiencies on lands operated and owned by Indians were higher than regional norms, whereas production efficiencies on leased Indian-operated lands were relatively low. His work indicates that it might be desirable to incorporate consideration of the extent of Indian ownership into an Indian operation criterion.

Group Process Design

Although the results of both the general literature review and the BIA archival search were useful in terms of generating ideas toward the specification of a set of usable objectives for making portfolio selection decisions, such a set could still not be specified readily at this point. Each of the lists of objectives contained in the six BIA documents, for example, has major shortcomings in terms of the criteria of Keeney and Raiffa. The 1961 and 1963 lists were not sufficiently specific and were incomplete. The 1966 list was not sufficiently specific and contained redundancies. The 1967 and 1978 lists were incomplete and the 1979 list was redundant and somewhat large.

Although the search of written documentation existing in the BIA archives did not reveal a usable set of objectives, it did lead to the recognition that the necessary information did exist within the Bureau organization. As pointed out in Chapter 2, the Bureau has an extremely experienced cadre of field professionals in its irrigation program. Although the size of this staff is not large compared to the major federal water development agencies, the depth of experience of the average field professional is great. Many of these individuals have worked with Indian irrigation projects for substantially all of their professional careers. These men possessed the knowledge that was needed to properly specify the objectives of the BIA irrigation program. However, in order to elicit that knowledge in a usable form, an appropriate methodology had to be devised.

Fortunately, a fair amount of research has been conducted in the disciplines of psychology and management concerning group idea generation and structuring methods. Several authors, such Stumpf, _et al._ (1979) and Murnighan (1981) have developed step-by-step approaches to the design of appropriate group problem-solving processes. Although there are variations, the approaches consist of the following four steps:

- identification of the problem and key characteristics of the situation in which the problem is to be solved;
- selection of group members;
- selection of most effective group technique; and
- planning for group interaction.

The design of a group idea generation and structuring process to develop a usable set of objectives for the BIA irrigation program is described below.

Problem and situation characteristics identification. In the first step, identification of the problem had already been completed by the time that the need for a group process was recognized. Of the four problem types postulated by Murnighan (emotive, technical/functional, policy/planning and crisis), the problem at hand is primarily a policy/planning decision problem. In these types of problems there is frequently a lack of agreement about the goals to be accomplished or even the importance of accomplishing them (1981, p. 56).

According to the model of Stumpf, _et al._, (1979, p. 592), the first step includes the identification of three important key characteristics of group decision situations. These are: availability of expertise, decision span and intragroup conflict. The development of a usable set of objectives for the BIA irrigation program clearly required special expertise. In addition to knowledge of the special problems and needs of Indian reservations, a capability of determining whether or not the various objectives are operational was critical. In other words, professional judgement was necessary to determine if contributions toward the objectives were quantifiable and measurable and if sufficient data existed to provide accurate measurements. Further, special expertise was required to determine if a set of objectives was complete.

The decision span involved was also very important to this problem. In this case, the decision span is quite broad in that the outcome of the group process could affect all parts of the organization that participate in the irrigation program. This includes nine Area Offices that collectively have jurisdiction within 23 states, including 91 existing irrigation projects and 254 Indian reservations. This broad decision span means that the acceptance or rejection of the outcome of the group process will not be tightly controlled by the headquarters office. This necessitated that the broad decision span be considered in the selection of the group participants.

The third key characteristics of the group decision situation is the potential for intragroup conflict. The potential for intragroup conflict was judged to be very low if the group was to be composed entirely of Bureau water development professionals. Although members of such a group could have widely varied professional interests (e.g., representatives of the Albuquerque Area would have concerns with small subsistence units that generally provide no income for the project beneficiaries whereas representatives of the Portland would have concerns with large commercial projects), most field water development professionals in the Bureau have had first-hand experience in several Areas or on several irrigation projects and all would have a degree of professional objectivity. On the other hand, if the group was to be composed of representatives of the various groups potentially benefitting from the irrigation program (such as representatives of the various tribes and non-Indian water user groups), then the potential for intragroup conflict could be very high.

Selection of group members. In the problem situation described above, a decision had to be made concerning whether to choose group members with expertise or to choose members representing constituent groups. As discussed previously, the need for special expertise to properly identify a usable set of objectives for the irrigation program was highly important in the problem situation. In addition, the potential for intragroup conflict with constituent representatives argued for expert members. Finally, since many different constituent groups are potentially involved (there are 254 Indian reservations in the 23 states potentially involved in the BIA irrigation program, some of which have more that one major constituent group), it was determined that any attempt to use constituent representatives would be infeasible.

Expert group members can be drawn from within the organization, normally representing the various functional or geographical entities, or from outside the organization (Kilmann, 1977, p.220). Since the necessary expertise was available within the orgainzation, no attempt was made to locate outside expertise. Other considerations in the identification of members were that they should be of diverse professional backgrounds, should be from the same hierarchical level of the organization (Geschka, et al., 1973, p. 97), and should volunteer for the assignment (Warfield, 1976, p. 74).

Based on this analysis, it was decided to select water resources professionals from each of the nine Area Offices and the Washington, D.C. headquarters office. These members were to represent a variety of professional backgrounds.

Selection of group technique. The selection of the most appropriate group idea generating and structuring technique for the problem and problem situation could be the most important decision in the design of the group process. Even if the problem were well specified and the participants were properly selected, a poorly selected group technique could have led to suboptimal results.

There are a great number of group idea generation and structuring techniques that have appeared in the literature. At least six distinct types of procedures have relevance to the type of problem dealt with here: interacting, brainstorming/brainwriting, nominal, delphi, creative confrontation and interpretive structural modeling.

The interacting approach, also referred as ordinary group procedure, involves unconstrained, face-to-face interactions in group settings. This is by far the most common technique; it is practiced thousands of times daily in committee meetings, task forces and staff meetings in all types of organizations. Many authors have pointed out the drawbacks of the interacting approach to group meetings. Van de Ven and Delbecq (1971, p. 203) succinctly summarized the undesirable characteristics of this approach as its:

- tendency to pursue a single train of thought,
- tendency of individuals to participate only to the extent that they feel equally competent with others,
- failure of individuals to express criticisms,
- inhibiting effects of status incongruities,
- group pressures for uniformity and implied sanctions from more knowledgeable members,
- time and effort spent by the group to maintain itself, and
- tendencies to reach quick decisions before all dimensions have been considered.

Despite these disadvantages, however, interacting groups have been found to be superior to individuals working alone (Van de Ven and Delbecq, 1971, p. 205) and the interacting method has been found to be effective in building cooperation and cohesiveness among group members (Souder, 1977).

The brainstorming and brainwriting methods have been used sucessfully in a variety of problem settings to overcome some of the drawbacks of the interacting procedure. In brainstorming, the emphasis is on creativity and the production of a large quantity of ideas. Gorman and Baker (1978, p. 439) offered the following four rules for brainstorming: no criticism of ideas, no compliments of ideas, no questions or discussions regarding ideas, and combinations and improvements are sought.

Brainwriting is a variation to brainstorming in which group members silently record one or two of their ideas at a time on paper and frequently exchange these lists with other group members. This process continues until the group exhausts all its ideas, at which time the ideas are collected, edited to eliminate duplication, and organized on a master list. Warfield (1976, p. 68) lists the following reasons why brainwriting is effective:

- members work in parallel, rather than in sequence;
- the silence and presence of others creates an atmosphere conducive to high production;
- reading the ideas of others stimulates thought;
- the absence of criticism engenders open thinking;
- each individual has time to think without interference;
- every idea gets recorded, none is lost;
- dominance by strong personalities is precluded;
- premature closure is precluded;
- minority ideas are not stifled;
- conflicting ideas are given an opportunity to be aired;
- hidden agendas have no opportunity to obscure idea generation;
- responsibility for group success is shared;
- all members have a burden to help produce;
- a sense of permanence engendered by the process of writing provides incentives;
- a strong focus is provided; and
- the capacity to contribute is not adversely affected by the number of people involved.

Nominal group techniques combine elements of brainwriting, interacting and delphi. In nominal group techniques, group members individually record ideas about the problem statement for a period of time (10-20 minutes). At the end of this period each individual provides one idea from his list in a round-robin fashion, which is recorded in full view of all members. There is no discussion of the ideas allowed as the round-robin process continues until all ideas are exhausted. Then free discussion takes place for a period of time, followed by a nominal voting process which determines the outcome of the group decision. Some authors refer to this sequence as a nominal-interacting procedure.

Although it is a relatively new procedure, nominal group techniques have been used with a great deal of success in a variety of problem situations (Van de Ven and Delbecq, 1971; Souder, 1977; Voelker, 1977: Green and Taber, 1980; Gepson, et al., 1981; Murnighan, 1981; and Stephenson and Franklin, 1981). In general, the nominal group techniques combine the advantages of brainstorming listed above with the group cooperation and cohesiveness strengths of the interacting approach. Van de Ven and Delbecq (1971, p. 206-207) listed 12 advantages of nominal group techniques which are very similar to the list of advantages of brainwriting provided above.

In a comparison of nominal to brainstorming and interacting group performance, Van de Ven and Delbecq (1971, p. 205) found the nominal group techniques to be superior in terms of mean number of unique ideas, mean total number of ideas and quality of ideas produced. Green and Taber (1980) compared a nominal vote analog, in which scores for silent individual rankings were summed to identify the best solution, to consensus and majority rule voting schemes. They found that the nominal vote resulted in the highest group satisfaction and the lowest negative socio-emotional behavior, but also gave participants the lowest feelings of personal participation in the process. Stephenson and Franklin (1981, p. 26) compared a nominal group technique with interacting groups and found the nominal groups to be superior in five specific areas: balanced participation, quantity of ideas, quality of ideas, efficiency of the process, and overall sense of accomplishment felt by participants.

The delphi technique has enjoyed fairly wide use in water resources planning over the past decade. The delphi technique differs from the other procedures in that the group participants do not meet on a face-to-face basis, but instead participate by responding to a series of questionnaires. In this technique, the chairman of the group constructs an initial questionnaire concerning the problem and provides it to the other members, who respond individually to the chairman. The chairman then summarizes the responses and provides this information to the group members. The members use this feedback information in responding to a second questionnaire. This iterative procedure continues until a satisfactory solution is found.

The delphi procedure has been used for a wide variety of problems in water resources planning. Dean and Shih (1973), for example, used the delphi technique to elicit weights for an additive utility function as part of an analysis of alternative sources of water augmentation for San Angelo, Texas. Keith, et al. (1977) used it to determine predicted impacts of changes in certain physical and social factors on a set of environmental evaluation criteria. Singg and Webb (1979) used it to identify goals and impacts of a proposed watershed development project in East Texas. The U. S. Bureau of Reclamation (1982) has recently used the delphi technique in a major study of future water problems and consequent future directions of the Bureau. Canter (1979) listed several other applications of the delphi technique in water resources planning.

Murnighan (1981, p. 59) pointed out that the delphi technique has the following advantages: it avoids social pressures inherent in group meetings, it can be used with any size group, and can be used when group meetings are not feasible. He also listed the following disadvantages: misunderstandings are not easily clarified since the group never meets, the procedure is very time-consuming and can be expensive if many interactions are necessary.

The creative confrontation approach attempts to transfer the phases of the creative process into a set of procedural rules for group sessions (Geschka, et al., 1973, p. 93). With the exception of the interacting approach, it is the least structured of the six types of group procedures. The creative confrontation approach involves the development of a series of abstract analogies that take the group further and further away from the problem statement. This process culminates in a force-fit phase in which the last set of analogies is related to the problem in order to induce new solution ideas. Geschka, et al. (1973, p. 93-94) provide a good illustration of this group idea generation approach.

A disadvantage of the creative confrontation approach is that its relevance to the solution of the problem statement is not clear. Therefore, difficulties might be encountered in gaining acceptance of the group session by the participants, especially when the participants have not had prior experience with group judgemental processes. This could be a particularly severe disadvantage in those situations where group acceptance is highly important. Other disadvantages include the requirement for a thoroughly trained and experienced group leader and the requirement that the process be applied without time constraints. Finally, the approach could include a provision in which the participants remove themselves from the problem for a period of idea incubation. Such a provision may not be feasible for decision situations involving a fixed deadline. It is probably because of these disadvantages that the creative confrontation approach has not been applied to decision problems in water resources planing and management.

Interpretive structural modeling (Warfield, 1976 and Sage, 1977, p. 91-164) is the newest of the six types of group procedures. It is a very powerful method of translating abstract mental models of systems into concrete structures such as objectives hierarchies. Although it is primarily a method for the structuring of ideas, it can be combined easily with idea generation techniques such as brainstorming or brainwriting to provide an effective process for developing an objectives hierarchy. The application of the method involves the pairwise presentation of a set of elements to a group of participants who decide if a specified contextual relationship exists between the elements. Because of transitivity assumptions, the number of such pairwise comparisons required for the development of a complete structure is significantly less than the possible number of paired combinations of the elements. A disadvantage of the interpretive structural modeling method is that a working knowledge of the mechanics of method operation is more difficult to attain for this method than for the other group techniques. In addition, if the decision problem contains a large number of elements, then access to a computer with the necessary software is a necessity in order to complete the structuring process within a reasonable time frame.

Stumpf, et al. (1979, p. 595-595) have developed a paradigm that is very useful in selecting the most appropriate group technique to apply to a decision situation. Unfortunately, the paradigm does not include the creative confrontation or the interpretive structural modeling approaches in its choice set. Despite this advantage, the paradigm proved to be useful in selecting the most appropriate group technique from the other four techniques discussed above. This technique was then compared to the creative confrontation and interpretive structural modeling techniques to arrive at the one actually used.

The paradigm of Stumpf, et al. contains eight design propositions. Three of these (P1, P4 and P5) apply to the decision situation at hand. These three position are discussed below:

> P1: In methods requiring quality and acceptance, the interacting or nominal methods of group functioning are preferred (p. 594).

Quality is important in the specification of the objectives of Indian irrigation in that the objectives must meet the criteria of Keeney and Raiffa (e.g., they must be minimal, operational, complete, decomposable and nonredundant) in order to be fully effective. Especially important is the operational criterion; if effective measures of the stated objectives do not exist or if data are unavailable to conduct such measurements, then the objectives set would not be usable, despite the fact that the set might meet the other criteria. As discussed above, acceptance of the objectives set is also important to the problem. Stumpf, et al. (p. 593) point out that interaction can increase the perception of participants that they have influenced the group decision, which leads to "ownership" and acceptance. Since the delphi method does not include face-to-face interactions, proposition P1 eliminates it.

> P4: In situations requiring quality and originality, nominal or delphi methods of group functioning are preferred (p. 594).

As learned from the literature review, knowledge of established ideas concerning the objectives of the Indian irrigation program does not necessarily lead to a usable objectives set. Therefore, the group process should not be limited to established ideas only, and the interacting approach was eliminated.

> P5: In situations requiring acceptance and having a broad decision span, expert and representative group members are preferred (p. 595).

As discussed in the problem identification and problem characteristics step described above, the decision span of the problem is quite broad. Proposition P5 thus led to the elimination of the co-worker group alternative identified by Stumpf, et al.

Thus, use of the eight design propositions of Stumpf, et al. led to the identification of a nominal group process by expert or representative participants as the most appropriate for the decision situation. Representative group members were eliminated from consideration as discussed previously, leaving the nominal group approach with expert participants as the preferred combination.

Although brainstorming and brainwriting are nominal group processes in that free interaction between participants is severly limited, the nominal group technique (NGT) described earlier was chosen as more relevant to the decision situation. Since the problem to be solved involved a broad decision span and since acceptance by a relatively large number of people was critical to the ultimate success of the decision support system, the size of the group selected to specify the objectives of the Indian irrigation program necessarily would be relatively large. Group size is particularly important in brainstorming sessions, since members of large groups can feel insignificant and not participate freely (Gorman and Baker, 1978, p. 439). This disadvantage is not as severe with the nominal group technique, however. Van de Ven and Delbecq (1971, p. 208) point out that as

> the size of the group or committee increases, the superiority of the nominal group over the conventional brainstorming or interacting group increases in terms of total number of non-overlapping ideas produced.... Nominal group processes can accomodate large numbers of participants without the disfunctions of conventional discussion involving many participants.

The advantages of brainwriting listed earlier are relevant to the decision situation. However, the silent idea generation phase of the nominal group technique has all of the same advantages. In addition, the interacting and voting phases of NGT are important tools in refining and narrowing a list of objectives to a manageable set. Finally, the selection of NGT was confirmed by Stephenson and Franklin (1981, p. 25), who reported that it was found to be effective with groups involved in the identification of goals and objectives.

Although the creative confrontation and ISM approaches were not considered in the group process selection paradigm of Stumpf, et al., creative confrontation was also eliminated from consideration based on problems with the method in facilitating group acceptance, requirements for a thoroughly trained group leader, and the need for freedom from time constraints.

The ISM method has obvious advantages in terms of its strength in assisting idea structuring. Because of this characteristic, it was selected for use in conjunction with the nominal group technique. It is noted that a similar combination if the NGT and ISM methodologies was used successfully by Wood and Christakis (1982, p. 15) to generate and structure goals of citizens of the North Piedmont area of Virginia in February, 1982.

Planning for group interaction. After the selection of the group process to be used to develop a set of objectives for the BIA irrigation program, the next step was to plan for the group interaction. The concept for the development of the objectives set involved the use of the silent idea generation phase of the nominal group technique to generate a comprehensive list of ideas, followed by the interacting phase to combine redundant objectives, explain those that are unclear to all participants, and reword those that can be expressed more clearly. Finally, the voting phase of NGT would be conducted, if necessary, as a potential screening mechanism to reduce the objectives list to a manageable number. This would conclude the NGT session. The list of objectives generated during the NGT session would then be used as input to an ISM session to be conducted separately, which would be convened to convert the list into an objectives hierarchy. Finally, the objectives hierarchy would then be examined and modified, if necessary, to identify the appropriate level to be used as a basis for the decision support system to be developed.

The first step in planning for the NGT session was to select a time and place for the group interaction. An excellent opportunity was the annual national meeting of BIA water resources development personnel, which was conducted on April 6-8, 1982 in Phoenix, Arizona. Participants in the meeting included water development representatives from all nine Area Offices involved in the irrigation program, as well representatives of the headquarters office in Washington, D. C. Thus, both the required expertise and the wide representation of the Bureau, upon which acceptance of the decision support system depended, was assembled at one place at the same time. In addition, all of these representatives were from approximately the same level in the organizational structure of the Bureau. Geschka, et al. (1973, p. 97) noted the importance of this latter point, since including group participants from different hierarchical levels can inhibit open and free behavior. A further advantage of conducting the session in conjunction with the annual water development meeting was that it obviated the need to schedule a special meeting solely to develop the objectives of the program. According to Geschka, et al. (1973, p. 97), special meetings have certain elitist stigma attached to them and frequently are under stress to be successful. Finally, the group session was able to be conducted away from potential interruptions of telephone calls or other distractions.

After the decision was made to conduct the NGT session in conjunction with the annual irrigation meeting, a half day was reserved on the meeting agenda for the NGT exercise. This agenda was made available to all participants at least two weeks prior to the session. The list of potential participants at the irrigation meeting was screened to identify representatives from each of the nine affected Area Offices to insure that wide representation was obtained at the NGT session. Most of the identified participants for the NGT session were contacted by telephone one week prior to the session to provide them with background information and to ask for their voluntary participation. During these telephone calls, a summary of the purpose of the session and a description of the possible objectives of the irrigation program (obtained from the literature review) was provided to each participant. Finally, arrangements were made to have the proper equipment available in the room in which the session was to be conducted. This included a large blackboard, pencils, paper, and the arrangement of the tables in a horseshoe shape facing the blackboard. Such preliminary arrangements are discussed by Delbecq, et al. (1975, p. 40-43); Stephenson and Franklin (1981, p. 36); and Murnighan, (1981, p. 57).

Group Process Implementation

Although the NGT group was expected to be fairly large relative to the standard size of five to ten participants, it turned out to be even larger as interest in both the group technique and the subject matter grew among participants of the irrigation meeting. The NGT session was actually conducted with 23 people, including the facilitator. However, as noted above, a relatively large group is not necessarily a disadvantage when nominal group processes are employed (Van de Ven and Delbecq, 1971, p. 208; and Warfield, 1976, p. 68). In this case, the large size of the group was felt to be advantageous, since it brought to bear a great deal of expertise of the problem (the group represented 291 years of combined experience in Indian water development) and increased chances for the acceptance of the outcome within the organizational structure. In addition, conflict problems normally associated with large groups were minimal since most of the participants had worked together for many years and had a strong common desire to solve the problem.

The NGT session was opened with an explanation of the group process, a statement of the problem, and a review of the history of previous attampts to specify the objectives of the BIA irrigation construction program. Then each participant was given a pencil and paper and asked to generate silently and independently a list of objectives. This silent idea-generation process was discontinued when all members indicated completion.

The next step involved a round-robin recording session in which each member, in turn, was asked for one idea at a time, which was recorded on a blackboard in full view of the group. Delbecq, et al. (1975, p. 47) listed the following benefits of the round-robin recording session:

- equal participation in the presentation of ideas;
- increase in problem-mindedness;

- depersonalization - the separation of ideas from personalities;
- increase in the ability to deal with a large number of ideas;
- tolerance of conflicting ideas;
- encouragement of hitchhiking (use of another's idea, slightly modified); and
- provision of a written record of ideas.

The round-robin process was continued all members had exhausted their lists.

The third step, or serial discussion for clarification, proved to be the most time-consuming by far. In this step, the group discussed each item of the list, beginning with the first and proceeding sequentially through the list. The main purposes of this step were for clarification and refinement. Because of the large number of ideas generated, the large size of the group, and the interest of the group in the subject matter, the lively discussion that ensued was quite lengthy.

During the discussion, the group generally agreed that several of the items on the list were more properly classified as constraints rather that as objectives, and that several other items were not operational in that they were too politically sensitive to be used, could not be disaggregated into measurable components, or were not affected by project portfolio decisions. Althought the NGT procedure does not allow such items to be deleted, it became clear that these concerns were reflected in the subsequent voting.

Since the objectives list at this point was quite lengthy, it was decided to conduct a voting process to order the objectives in terms of their perceived importance. It was not known at the time of the NGT session whether or not access to facilities necessary to conduct a computer-assisted ISM session would be available for the subsequent structuring effort. Establishment of preliminary ordinal relationships within the initial objectives set provided flexibility to reduce the size of the objectives set to be used as input to the ISM session if manual structuring became required. To accomplish this, a rank-ordering procedure was conducted in which participants were asked to vote whether each item was considered to be "very important," "moderately important," or "unimportant." These votes were then tabulated and assigned the following weights: very important - three points; moderately important - two points; and unimportant - one point. Weighted average scores for each item were then calculated and the objectives list was arranged in order of such scores. The advantages of such a rank-ordering procedure over a concensus or majority rule procedure have been presented by Green and Taber (1980).

Table 6-1 presents the outcome of the NGT procedure. It is interesting to note that a number of objectives that are ranked low in Table 1 were the subject of concern during the open discussion portion of the NGT session. One objective was felt to be non-operational by the group because of excessive political sensitivity:

- quantification of water rights.

Two objectives were felt to be non-operational because of measurement difficulties:

- environmental quality, and
- economic stimulus.

Table 6-1

Objectives List Produced in NGT Session

(arranged in decreasing order of perceived importance)

Objectives	Weighted Scores
Effects on water rights	3.000
Number of Indians affected	2.700
Indian employment income	2.684
Indian employment	2.670
Ownership patterns	2.500
Subsistence	2.450
Indian income	2.380
Number receiving farm income	2.330
Number of garden crops	2.310
Value of garden crops	2.286
Construction cost	2.260
Indian lease income	2.250
Total cost of projects	2.150
Appropriated operation and maintenance cost	2.150
Number receiving lease income	2.143
Indian farm income	2.130
Water conservation	2.087
Consideration of non-irrigation water uses	2.072
Best soil categories	1.600
Development in conjunction with other federal projects	1.600
Vertical/horizontal distance from water	1.500
Water management	1.450
Time until self-sustaining status	1.440
Condition of projects	1.410
Percentage of Indian operated land	1.000
Environmental quality	1.000
Capability of existing staff	1.000
Utilization of developed and assessable lands	1.000
Economic stimulus	1.000
Type of crops relative to market demand	1.000
Quantification of water rights	1.000
Highest and best uses of water	1.000
Tribal support for project	1.000
Adequate quantity and quality of water available	1.000

Two objectives were felt to be irrelevant since they could not be affected by project portfolio selection decisions:

- percentage of Indian operated land, and
- type of crops relative to market demand.

Three objectives were felt to be more properly characterized as constraints rather than as objectives:

- tribal support for project,
- adequate quantity and quality of water available, and
- capability of existing staff.

As indicated earlier, the group interaction plan provided for use of the output of the NGT session (Table 6-1) as input to an ISM session for final structuring of the objectives hiearachy. The ISM methodology requires a participant group, an element set, a contextual relation, and a capability to apply the methodology.

The participant group for the ISM session was much smaller than the group involved in the NGT session. It consisted of a group of four officials of the Division of Water and Land Resources in the headquarters office of the Bureau. This group had the responsibility for administering the irrigation program nationwide, and therefore had a limited amount of bias toward the concerns of any of the Area Offices. The group also met the requirements of diverse professional backgrounds (it consisted of one economist, one civil engineer, one agricultural engineer, and one soil scientist), equivalent organizational levels and voluntary participation (Geschka, et al., 1973, p. 97; and Warfield, 1976, p. 74).

The initial element set consisted of the output from the NGT session. Since acceptability of the decision support system that was to be based on the objectives hierarchy developed in the ISM session was highly important, no additional objectives were added to the set developed in the NGT session.

The contextual relation must describe a relationship between elements and must be transitive in nature. The contextual relation "contributes to" was used in the ISM session. While it is difficult to demonstrate that this relation is inherently transitive, it proved to be sufficiently transitive for the ISM session to be successful.

The structuring process can be carried out either manually or with computer assistance. In this instance, the required software was not available for a computer assisted exercise. However, the element set used was not inordinately large and was somewhat structured before the ISM session began. Therefore, a manual approach was used to develop the objectives hierarchy as described by Warfield (1976, p. 143 and 470).

The first step of the ISM exercise after the assembly of the group involved an explanation of the methodology and the purpose of the exercise. Since only one participant of the group had also been a participant in the NGT session, the purpose and results of the NGT session and its relationship to the ISM session, as well as the relevance of the ISM session to the development of a decision support system for the irrigation program, was explained.

The objectives set produced by the NGT session was then reviewed by the group to see if it had any obvious need for revision before the ISM session was started. It was decided to delete all elements with weighted scores of 1.0. The reasons for these deletions were that most of these elements had been deemed by the NGT group to be unusable, all were unanimously rated as "unimportant" by the NGT group, and the deletions reduced the list to a more manageable number. This action reduced the element set from 34 to 24 elements.

In this discussion, several members of the group also questioned the desirability of including six other elements that had weighted scores ranging from 1.60 to 1.41. These were:

- best soil categories,
- development in conjunction with other federal projects;
- vertical/horizontal distance from water,
- water management,
- time until self-sustaining status, and
- condition of projects.

It was felt that these six elements did not represent actual objectives of the irrigation program. In addition, it was pointed out that the NGT procedure did not allow elements to be deleted, and therefore it may have been appropriate to delete them at the beginning of the ISM session. It was also noted that the weighted scores of the six elements were significantly below the score of the next lowest element in the set. After some discussion, it was decided to defer consideration of five of these elements until after an initial objectives hierarchy had been developed by the ISM procedure. One group member strongly felt that the element "best soil categories" was an important factor in the development of future irrigation projects and convinced the group to include it in the objectives set, despite its low rating from the NGT session.

The third step involved the editing of the objectives set that had been developed in the NGT session. As explained by Warfield (1976, p. 350), one method of editing an element set involves the comparison of each element with at least one other element of the set. This series of pairwise comparisons was carried out by the partial development of a reachability matrix, which is identical to the manner in which a computer-assisted exercise is conducted. A reachability matrix is described by Warfield as a square, transitive, reflexive, binary matrix, that represents relationships between elements. Both the rows and the columns of the reachability matrix were specified to consist of the vector of objectives developed in the NGT session. If any two objectives i and j satisfied the contextual relation "contributes to", that is, if it were determined by the group that attainment of objective i contributes to the attainment of objective j, then matrix entry $r_{ij} = 1$. If the group determined that attainment of objective i does not contribute to the attainment of objective j, then matrix entry $r_{ij} = 0$.

Reachability matrix entries were developed by the group by responding to a series of pairwise comparisons of objectives. To facilitate this process, each objective was written on large index cards before the group session began. The question "Does _____ contribute to _____ ?" was displayed to the group and the cards containing the objectives were inserted sequentially in the blanks. The appropriate group responses (1 or 0) were inserted in the matrix as the session progressed. The purpose of recording group responses was to enable the group to examine the consistency of their responses with the transitivity assumption. Discussions of entries that would have violated the transitivity assumption were very useful in stimulating thought and clarifying relationships between the objectives.

In order to avoid being influenced by the votes of the NGT session, the weighted scores from the NGT session were not displayed, and the card deck was shuffled at the start of the session, thus producing a random order on the objectives vector.

This editing process, which was completed in a half-day session, produced a number of changes to the objectives set. The editing process was very effective in revealing areas of misunderstanding concerning the meaning of the objectives. This led to a rewording of all the objectives to clarify meanings and to establish more consistent wording throughout the objectives set. An example of the increased focus of the objective statements is provided by the objectives "number of Indians affected" and "Indian income." The editing process revealed that the total number of Indians benefitted by a project portfolio was the proper concern of the former objective, rather than the incremental increase in the number of Indians benefitted. On the other hand, only the incremental increase in Indian income caused by the project portfolio was of interest in the latter objective. This is because the benefit to some Indian beneficiaries of past irrigation construction could be increased by the new construction, so that the number of Indians benefitted properly includes both those who were previously benefitted by a irrigation project and whose benefit was increased, and those who were not previously enjoying a benefit before the new investment, but who would receive benefits from the new construction. However, the proper measure of Indian income obviously does not include income existing before the new construction. Therefore, the "number of Indians affected" objective was changed to the objective "to maximize the number of Indians benefitted" whereas the "Indian income" objective was changed to the objective "to increase Indian income." As the editing session progressed, the meaning of each element in the objectives set became clearer in the minds of the participants. At the end of the session, comparisons were made much faster than at the beginning. It was found that clarifications developed in the editing session were instrumental to the subsequent development and review of the objectives hierarchy. The edited objectives set appears in Table 6-2.

The fourth step involved manual structuring of the new objectives set into an objectives hierarchy. This was accomplished by arranging index cards containing the modified objective statements into different hierarchical structures that were consistent with the contextual relation "contributes to." The alternative contextual relations "is a component of" and "is subordinate to" were experimented with during this exercise, although the original relation "contributes to" was retained as the most effective. After a number of variations, a satisfactory hierarchy was developed. This initial satisfactory solution involved the addition of two new top-level objectives, "increase national welfare" and "increase Indian welfare," and the deletion of the two objectives "increase contributions to subsistence economies" and "increase use of best soil

Table 6-2

Modified Objectives List Produced by ISM Editing Session

to improve protection of water rights

to maximize the number of Indians benefitted

to increase Indian job income

to increase the number of Indian jobs

to increase the number of Indian acres irrigated

to increase contributions to subsistence economies

to increase Indian income

to maximize the number of Indian direct profit recepients benefitted

to maximize the number of subsistence crop beneficiaries

to increase the value of locally consumed crops

to minimize construction costs

to increase Indian lease income

to minimize the total cost of projects

to minimize appropriated operation and maintenance cost

to maximize the number of Indian lease income recipients benefitted

to increase Indian direct farm profits

to increase water conservation

to increase non-irrigation water uses

to increase use of best soil categories

categories." This process also involved a review of the five objectives previously deferred. It was determined that the addition of the deferred objectives to the hierarchy was not desirable. The hierarchy was then transcribed onto paper and reproduced for review.

The last step in the ISM process was the detailed review of the structural model. This was conducted during the week following the ISM session by the members of the ISM group and five members of the economic development and natural resources development staffs that had been involved in neither the NGT nor the ISM sessions. Suggested changes were compiled and provided to the ISM group. After reviewing the suggestions, the group decided not to modify the objectives hierarchy, with the exception of minor wording changes. The final objectives hierarchy is presented in Figure 6-1.

The lowest level of objectives in Figure 6-1 comprises the set of objectives that was used in the development of the decision support system. This set appears to meet the criteria of Keeney and Raiffa (1976, p. 50-53) in that it is:

- complete: the objectives set covers all the main areas of concern of both the NGT and ISM groups;
- operational: each objective is measurable in quantitative terms and reliable data can be obtained to quantify the impact of alternatives on these objectives;
- decomposable: each objective can be decomposed to facilitate measurement;
- nonredundant: the objectives are defined in a manner that will minimize double counting of impacts of alternatives; and
- minimal: the objectives set is as small as it can be without masking impacts that may be of interest to the decision maker.

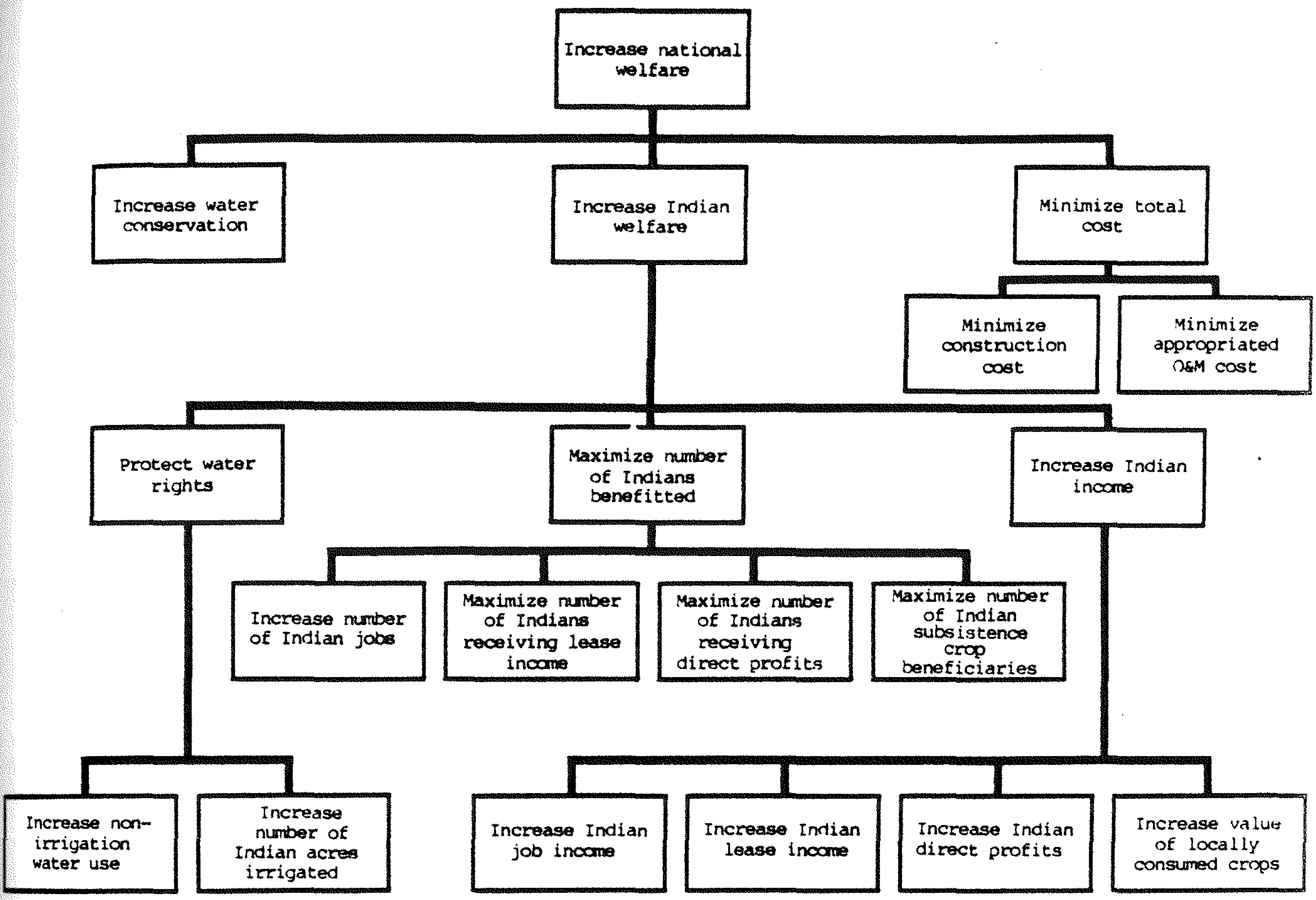


Figure 6-1

Objectives Hierarchy for the BIA Irrigation Construction Program

With the specification of a usable set of objectives for the BIA irrigation program, the critical first step in the development of a decision support system was completed. The next step involved the selection of the most appropriate model for the development of the decision support system. The process developed to make that selection is described in the next section.

Data Collection

A key element of the decision support system is data collection. The development of a highly effective decision-aiding algorithm and the identification of an appropriate objectives set will not overcome a lack of meaningful data. In this section, the data collection activities that were conducted to make the decision support system operational are described. In addition, a plan for future refinement of the data base that was developed is provided. The data collection activities are described in four steps: (1) determination of the appropriate level of aggregation of project features for data collection purposes, (2) identification of separable project divisions, (3) development of a valid data set for each project division, and (4) planning for future data refinement.

Determination of Aggregation Level

The BIA currently operates irrigation projects on 91 Indian reservations. Many of these projects are separable into divisions that are independent geographically and operationally. A long-term development plan is maintained on each project and, in some cases, on each project division. The long-term development plan is a schedule of all construction and rehabilitation elements needed to complete the project to its planned capacity and to make all facilities fully operational. It consists of a set of annual work plans which will lead to project completion over a fixed time horizon. Table 6-3 contains a sample long-term development plan to illustrate these concepts.

Table 6-3

Sample Long-Term Development Plan

1984	1985	1986	. . .	2007	2008
Main canal Construct 0.5 mi $13,200	Main canal Construct 0.5 mi $14,100	Canal # 5 Construct 0.8 mi $19,000	. . .	Canal # 5 Construct 0.7 mi $20,400	Canal # 5 Construct 0.7 mi $21,800
Canal # 1 Reshape & line 1.0 mi $26,400	Canal # 1 Reshape & line 0.9 mi $25,400	Replace pump $8,600	. . .	Replace concrete pipe 0.5 mi $9,800	Replace concrete pipe 0.4 mi $8,400
Replace check gate $2,500	Replace check gate $2,700	Canal # 4 Reshape & line 0.5 mi $13,600	. . .	Canal # 4 Reshape & line 0.5 mi $14,600	Canal # 3 Reshape & line 0.8 mi $22,200
Engineering, design and supervision $2,400	Engineering, design and supervision $2,000	Engineering, design and supervision $2,700	. . .	Engineering, design and supervision $2,100	Engineering, design and supervision $3,000
$44,500	$44,200	$43,900	. . .	$46,900	$55,400

During each appropriations cycle, elements from the annual work plans for many of the projects are submitted for funding consideration. These funding requests are screened sequentially at the Agency, Area and Central Office levels of the organizational hierarchy. Those elements considered to be of high priority at each level (based on subjective evalautions of narrative justifications) are submitted for consideration to the next level. Those elements not selected for funding during the appropriations cycle are added to future annual work plans, and project long-term development plans are adjusted accordingly. In the most recent budget cycle (FY 1984), 133 elements were considered for funding at the Central Office (Washington, D.C.) level.

An analysis of this system led to the identification of five approaches to the data collection effort. Each approach represents a different level of aggregation of construction and rehabilitation elements. These five approaches are described below in decreasing order of aggregation.

Level 1 (project portfolio approach) - This approach would involve the collection of data concerning the impacts of completion or full rehabilitation of each of the 91 irrigation projects on the identified program objectives. Data collection at this level of aggregation would be appropriate for the identification of preferred portfolios of entire irrigation projects at specified funding levels or for the establishment of an overall priority listing of projects.

Level 2 (division portfolio approach) - This approach would involve the collection of data concerning the impacts of completion or full rehabilitation of each of the separable project divisions on the identified porgram objectives. Data collection at this level of aggragation would be appropriate for the identification of preferred portfolios of separable project divisions or for the establishment of an overall priority listing of divisions.

Level 3 (project annual work plan portfolio approach) - Under this approach, all elements of the annual work plan for each project would be considered as a single unit, and data would be collected concerning the impacts of each unit on the program objectives. Data collection at this level of aggregation would be appropriate for the identification of preferred portfolios of project annual work plans.

Level 4 (division annual work plan portfolio approach) - Under this approach, all elements of the annual work plan for each separable project division would be considered as a separate unit, and data would be collected concerning the impacts of each unit on the program objectives. Data collection at this level of aggregation would be appropriate for the identification of preferred alternatives of separable project division work plans.

Level 5 (element portfolio approach) - This approach would involve using the individual elements of annual work plans to develop construction portfolios. Data concerning the impacts of each element on the identified program objectives would be collected.

It is evident that the five approaches are arranged in increasing order of political feasibility. That is, Level 1 is the least politically attractive since it involves the identification of a preferred portfolio of projects to be completed before any further work is conducted on projects not in the preferred portfolio. At the other extreme, Level 5 is the most politically attractive since a preferred portfolio of construction elements would probably contain at least some funding for a much larger number of projects than would any of the other approaches.

On the other hand, the five levels are also arranged in decreasing order of availability of valid data. It is much more difficult to gather accurate data to describe the impacts of individual construction elements (Level 5), for example, than it is to gather accurate data to describe the impacts of completion or rehabilitation of entire projects (Level 1).

Therefore, the selection of a data collection approach involves a trade-off between validity of data and political attractiveness. A discussion of this problem with officials of the Bureau of Indian Affairs led to the identification of Level 2 as the preferred approach for the initial application of the decision support system. The main reasons for the selection of Level 2 were: (1) the likelihood that reasonably accurate data could be developed from secondary sources to describe the impacts on the program objectives of the completion to planned capacity or full rehabilitation of the separable project divisions, and (2) the likelihood that a portfolio of project divisions could be acceptable politically. It was noted that if equity of funding among reservations with existing projects became a major issue in the future, then Levels 3 or 4 could be followed, although extensive collection of primary data would be required.

Identification of Separable Divisions

After the decision had been made to base the data collection effort on the Level 2 approach it became necessary to develop a listing of existing project divisions to provide a framework for the data collection effort. Unfortunately, the development of such a list was not a simple task. All of the BIA reporting systems, budget requests and project documents were based on the 91 projects that are operated by the Bureau. Although many of the projects can be separated into geographically and operationally independent units, the BIA had never utilized such a breakdown for any identifiable purpose, and a listing of separable divisions was not available.

In order to create such a list, a thorough search of the organization files and archives of the BIA and the Interior Department library was made to locate pertinent project planning reports. To be of use, such reports had to contain sufficient information to determine whether or not a given project could be divided into independent dividions. Several hundred such reports were located, 56 of which were used to identify 178 independent project divisions. Many of these divisions are in need of extensive rehabilitation construction work to bring them up to a fully operational state, new construction work to complete them to authorized or planned acreages or capacities, or both. On projects which require significant amounts of both new construction and rehabilitation work, total rehabilitation needs were treated as separate divisions from new construction needs. A total of 152 separate divisions were identified as having significant new construction needs and 170 divisions have significant rehabilitation needs, for a total of 322 divisions which were treated as candidates for funding under Level 2. These 322 divisions are listed in Appendix E.

It is noted that the listing of separate Indian irrigation divisions contained in Appendix E may not be complete. It is likely that a somewhat larger set of funding candidates could be developed by conducting on-site visits to each of the 91 projects, supplemented with interviews of operating personnel. However, such a refinement is outside the scope of this research effort.

Collection of Input Data

The results of the data collection effort are presented in Appendix F. These data were gathered from examinations of budget documents, project status reports, Indian Land Use and Status Reports (51-1 reports), and the Natural Resources Information System Reports (50-38 reports) maintained in the Division of Water and Land Resources of the BIA. Additional data were obtained from a special water conservation report (U. S. Department of the Interior, 1978) and from estimates provided by officials of the Division of Water and Land Resources. It is noted that Appendix F does not contain data for all 322 separable divisions listed in Appendix E. Although fairly reliable data were available from the secondary sources identified above for all projects, such was not the case at separate division unit level, with some exceptions. As will be discussed later, the test application of the decision support system was conducted with the 194 project candidates for which data appears in Appendix F.

It is appropriate to note at this point that the decision support system, and therefore the data collection effort, is focused on existing irrigation and power projects only and does not include potential new starts. Some information was available concerning the impacts of the construction of new projects. However, new starts are not expected to occur in significant numbers, if at all, in the foreseeable future. If new starts do occur, they will be evaluated under the procedures contained in the Economic and Environmental Principles and Guidelines for Water and Related Land Implementation Studies (U. S. Water Resources Council, 1983) if conducted by the Bureau of Reclamation, and under the procedures contained in Procedures for Evaluation of the Effects of Federal Water Water Projects that Impact Upon Indian Reservations (U. S. Department of the Interior, 1980) if conducted by the Bureau of Indian Affairs. Neither of the above two documents applies to the evaluation of expenditures for existing water projects.

Explanations of data sources and assumptions made, as well as the identification of possible sources of data inaccuracies, are discussed below. Since certain considerations apply to data describing the impacts on less than the full set of objectives, each objective is treated separately.

Objective 1 (Increase Number of Indian Acres Irrigated). In most cases, direct estimates of new Indian-owned acres to be irrigated by the projects were not available. This is because project planning reports normally are not updated for fairly long periods of time (10-20 years), whereas land ownership patterns change constantly. Therefore, data for Objective 1 were obtained by assuming that ownership patterns on newly irrigated lands on each project would be the same as on presently irrigated lands on that project. Thus, total additional irrigated acreage was multiplied by the percentage of Indian-owned land currently served by the project to obtain estimates of new Indian-owned acres to be irrigated.

It was noted in several cases that some lands reported as remaining to be developed (within planned project boundaries) were actually temporarily non-assessable (not assessed water service charges) due to such conditions as blocked distribution canals or improper drainage (waterlogging). In such cases, these lands were included in the input data set under the rehabilitation division for such projects. To the extent that such discrepancies went undetected, inaccuracies could be contained in the data for this objective. Although data were not available to quantify this source of error, it is clear that such error was small.

Objective 2 (Maximize Number of Indians Receiving Direct Profits). Data contained under this objective reflect estimates of the number of Indian farm operators that earn profits from farm operations and that are beneficially affected by the project. Since a beneficiary is defined as a farm operator, the number of beneficiaries under Objective 2 is equal to the number of Indian-owned irrigated farms that are operated for profit by the owner and that are beneficially affected by the project.

Indians that receive lease income benefits or subsistence farming benefits are not included. For construction units, these estimates were based on the assumptions that ownership patterns on newly irrigated lands on each project would be the same as on presently irrigated lands on that project, that the percentage of Indian-owned land operated for profit by the owner on each project would be the same on the newly irrigated lands as on currently irrigated lands, and that the average farm unit size on the new lands would be the same as on currently irrigated lands. Data were obtained for construction units by dividing new Indian-owned acres irrigated by the average farm unit size, and multiplying by the percentage of Indian-owned land operated for profit by Indians on currently irrigated lands.

In extrapolating ownership and operations patterns from currently irrigated lands to newly irrigated lands, acres that were in tribal ownership were converted to equivalent allotted (individually owned) holdings using average allotted land farm unit sizes from projects of similar size without large tribal irrigated farm holdings. It is noted that such a conversion might introduce some inaccuracies into the data for rehabilitation units since, for projects with large tribal farming enterprises, many individual Indians receive benefits from per capita distributions of tribal farming profits. However, treatment of tribal lands as allotted equivalents appears to lead to more consistent and meaningful results than does attempting to estimate numbers of Indian benefitting from tribal irrigated farming operations.

Objective 3 (Increase Number of Indian Jobs). These data provide projections of new jobs directly created by the investment. Only those jobs likely to be held by Indians residing on or near the reservations are included. Where seasonal Indian labor is involved, man-year equivalents of Indian labor demand are used. Where more accurate estimates were not available, the number of new Indian jobs made available by the investments was set equal to half the projected number of new farm units (Indian and non-Indian) in excess of 160 acres in size.

Objective 4 (Maximize Number of Indians Receiving Lease Income). These data reflect estimates of the number of Indian owners that would receive increased lease income due to the project. Beneficiaries under this objective were set equal to the number of Indian-owned farms that are leased to others and that are beneficially affected by the project. Beneficiaries include those who would be able to lease their presently unleased lands, those who would receive increased lease income because of the conversion of range and dry farm leases to irrigation leases, and those who would receive increased lease income from current irrigation leases because of improved facilities, more dependable water supplies, improved drainage, and the like. Indians that receive profits from farming their own lands or that receive subsistence farming benefits were not included.

The assumptions and conversions that were described under Objective 2, above, apply also to the data developed under this objective.

<u>Objective 5 (Maximize Number of Indians Receiving Subsistence Crop Benefits)</u>. Data gathered for this objective reflect the number of Indians that would derive benefits from local consumption or bartering of crops (primarily produce crops) grown on subsistence or garden-type units as a result of project construction. Beneficiaries under this objective were set equal to the number of Indian-owned irrigated farms that are operated by the owner without profit. Beneficiaries counted under this objective and those counted under Objectives 2, 3 and 4 are mutually exclusive. For example, if estimates of subsistence beneficiaries are made on lands to be served with irrigation water because of project construction, then estimates of new jobs created, numbers of Indians receiving lease income benefits, and numbers of Indian farmers earning direct profits were not made for those lands.

The asumptions and conversion that were described under Objective 2 apply also to the data developed under this objective.

<u>Objective 6 (Increase Indian Direct Profits)</u>. Data gathered to reflect impacts on Objective 6 from new construction projects were obtained by multiplying acreage estimates of newly served land to be operated for profit by Indian owners times estimates of average net farm income per acre for each project. Long-term (10-20 years) average net profits per acre were used to compensate for short-term fluctuations in commodity prices, interest rates, operating costs and similar variables. Estimates of average net profits per acre varied from $30 to $600 annually. Such wide variance is due to differences in growing season length, types of crops grown, distances to markets, quality of water and other factors.

Estimates under Objective 6 for construction projects are based on the assumptions that existing ratios of Indian versus non-Indian land ownershop, average sizes of Indian-owned farm units, percentage of Indian landowners that farm their own lands, cropping patterns and average net profits per acre will be maintained on newly served lands. To the extent that such assumptions are invalid, inaccuracies could be contained in the data. Such inaccuracies could be reduced by examining actual land ownership patterns of land to be developed, farming plans of owners and actual planned cropping patterns (which are often known with a fair degree of certainty because such information is required in applications for federal farm development loans).

Data for rehabilitation divisions were obtained by multiplying acres of irrigated land currently farmed by Indian landowners times projected average increases in net direct profits per acre attributable to rehabilitation construction. Such increases vary from $2 to $100 per acre, depending upon such factors as current condition of the project, changes in water flow control efficiencies, length of growing season and type of crops grown. In addition, these data also include, in some cases, increases in direct profits on previously irrigated lands that have gone out of production, but which will be returned to production as a result of the rehabilitation construction. Examples include the reclamation of lands lost to waterlogging which are recovered by reductions in seepage (canal lining) and improved drainage, removal of canal blockages and increases in water supplies (pheatrophyte control, canal lining, reuse and improved water control).

Objective 7 (Increase Indian Job Income). These data represent estimates of Indian job income provided as a direct result of the potential investments. In the absence of data concerning the distribution of occupational categories demanded for each unit and prevailing local wage rates for each category, a figure $10,000 per man-year job equivalent was used as input to represent annual Indian job income attributable to each respective investment opportunity. Individual analyses of occupational demand and prevailing local wages for each project unit could yield more accurate data for this objective.

Objective 8 (Increase Indian Lease Income). These data provide projections of annual income from newly served land that will be placed under farm lease by the Indian landowner as well as increases in income from existing leases that are enhanced by rehabilitation construction. Estimates of income from new construction were obtained by multiplying estimates of Indian-owned leased acreage times estimates of net annual irrigation lease income per acre for each division. Net annual irrigation lease income (gross lease per acre per year less expenses of the Indian landowner) were used instead of gross income since landowner costs vary widely among the various projects. For example, some Indian landowners pay full operation and maintenance assessments while others are totally exempt or pay only a portion of full assesments. In addition, operation and maintenance charges also vary widely from project to project. Further, some assessments are levied on a per acre basis whereas others are levied on a per acre-foot basis. In addition to variances in landowner costs, gross irrigation lease income also varies widely from project to project for the same reasons described under Objective 6 (differences in growing season length, types of crops grown, distances to markets, water quality and the like). The range of estimated net annual irrigation lease income for newly developed lands was $15 to $300 per acre.

Data for rehabilitation divisions were obtained by multiplying acres of irrigated land currently leased by Indian landowners times projected average increases in net lease income per acre attributable to rehabilitation construction. Such increases result from the reclamation of waterlogged lands, prevention of water shortages (systems reliability could increase if more freeboard is provided in canals, debris clogging is reduced and water control is improved) and the like. Average increases in net income on currently irrigated lands due to rehabilitation construction varied from $1 to $50 per acre annually.

Objective 9 (Increase Value of Locally Consumed Crops). These data reflect estimates of the market value of crops grown on subsistence or garden-type units. For construction units, these data were obtained by multiplying estimates of newly served acres to be operated by Indian landowners at no profit by estimates of the market value of those crops. Estimates of net annual subsistence crop value per acre ranged from $75 to $200.

For rehabilitation units, these data were obtained by multiplying the number of subsistence acres currently under irrigation that will benefit from rehabilitation construction times estimated increases in net subsistence crop value for each project. Estimates of increased net annual subsistence crop value ranged from $5 to $75 per acre.

Objective 10 (Increase Non-Irrigation Water Use). This objective is a contributing element to the higher level objective "to protect Indian water rights" (Figure 6-1). It is noted that it received the lowest NGT rank-ordering score of the objectives that were ultimately included in the objectives hierarchy. Data contained in Appendix F for Objective 10 were based on increased non-irrigation water uses resulting from project construction. Most project planning documents did not contain data on non-irrigation water supply features and therefore direct estimates of increased non-irrigation water usage generally were not available for such projects. In some cases where direct estimates were not available, estimates were provided by BIA irrigation program personnel based on project construction costs, new acres to be served and knowledge of individual projects. For a number of smaller projects, estimates were calculated by dividing the estimated construction costs of each unit by five. Such rough estimates of data for Objective 10 did not seem to adversely affect implementation of the decision support system since this objective was perceived as relatively unimportant by the decision maker during the test application. However, better estimates of these data should be obtained as described later in this chapter.

Objective 11 (Increase Water Conservation). Collection of data for water conservation is probably more difficult than for any of the objectives described above. This is because the relationships between water savings at a specific site and additional water made available for beneficial use within a watershed or river basin are poorly understood. Improvements in water use efficiencies can have significant effects on return flows, the flows of surface water systems and groundwater levels. In addition, the extent to which theoretical water savings can be realized in practice can be affected by considerations of water quality changes (more intensive use of water supplies often results in deterioration of return flow quality), water rights and induced economic impacts.

Much of the data collected for Objective 11 is based on data contained in the document Report on the Water Conservation Opportunities Study (U.S. Department of the Interior, 1978) which focuses on opportunities for water savings from the rehabilitation of irrigation projects operated by the Bureau of Indian Affairs and the Bureau of Reclamation. That report provides data on water conservation potential under two categories: "reduction in diversions" and "water lost to further use". Data contained in Appendix F are based on the "reduction in diversions" approach, because such data are much more consistent among projects. Data for some projects were based on extrapolations of data contained in the above report. That is, data describing average water savings per acre for certain projects were used to estimate water conservation potential for other projects located in the same geographical regions with equivalent rehabilitation expenditures. It may be noticed that such average figures per acre in Appendix F reveal a fairly wide variance among projects. Such variations are due to differences in project ages and conditions, crops cultivated and present operational practices. For example, on projects in regions with relatively short growing seasons, maintenance practices are normally unsophisticated compared to those on projects in regions with extremely long growing seasons. Poorly maintained projects generally have a high potential for water conservation.

Cost. As discussed earlier, the cost objective is treated as a constraint in the algorithm described in Chapter 5. In order to use a true estimate of costs for each of the candidate project divisions, the present value of projected future appropriated operation and maintenance (O&M) costs for each division was added to the estimated capital costs of construction. This was done because some new constuction investments involve a stream of future O&M costs that must be considered as part of the total cost of the investment. On the other hand, some rehabilitation construction investments result in a savings of future appropriated O&M costs that also should be considered in calculating the actual cost of the investment. Although any number of different discount rates could be justified to convert future O&M costs to a present value figure, ten percent was chosen in this case. For newly served lands, future annual O&M costs per acre were assumed to equal the average O&M costs per acre of the project as a whole for the last five years. Thus, appropriated O&M costs for each new construction unit were calculated by the formula

$$C_{O\&M} = (0.2) \sum_{i=1}^{5} c_j \quad (l)(p) \left[\frac{1 - (1 + I)^{-n}}{I} \right]$$

where: $C_{O\&M}$ = present value of future appropriated O&M costs,

c_j = total O&M costs per acre in year j,

l = number of acres of new land to the served by the investment,

p = percentage of O&M costs borne by appropriations,

I = discount rate, and

n = planning horizon in years.

Reductions in future O&M costs resulting from rehabilitation investments were taken directly from planning and budget documents.

Two sources of potential inaccuracies in the cost data were identified. First, it was noted that some O&M cost data may include some costs that are actually paid by non-appropriated (collected) O&M revenues. Bureauwide, non-appropriated revenues pay for about 65% of total O&M costs. Although the extent to which appropriated and collected revenues are reported incorrectly is felt to be small, several such incidents were noticed during the data collection activities. Second, multiple cost estimates were available on some projects. The fact that these estimates did not always agree indicates that room for significant improvements in the quality of the capital cost data exists.

Plan for Future Data Refinement

Although the data contained in Appendix F are adequate in quantity and quality to make the decision support system operational, it is clear that the performance of the system can be improved in two respects with refinement of the data. First, Appendix F contains data only for 194 separable project divisions, including 38 "dummy" divisions, or divisions with no costs and no impacts that were inserted to make the input data set symmetrical with respect to new construction and rehabilitation divisions. Appendix E reveals that at least 322 separable divisions exist. Although the data set in Appendix F does not exclude any of the divisions listed in Appendix E, it does aggregate the data at a higher level than is necessary for operation of the decision support system at the level of aggregation selected (Level 2 - division portfolio approach).

The development of a data set for all 322 divisions would enhance the political acceptability of solutions obtained using the decision support system.

Second, a number of sources of potential inaccuracies were identified during the data collection phase. These were mentioned in the preceding discussion of the data collection process. Refinement of the data set could remove most, if not all, inaccuracies from these sources.

The plan for future data refinement described here is based on improvements to the long-term development plans that are currently maintained on some projects and which are illustrated in Table 6-3. The plan consists of three steps, each of which would be carried out for each of the 322 separable divisions listed in Appendix E.

1. Completion Statement. This is a written statement of the planned size and condition of each division. If the division is a component of a project that has individual statutory authority (85 divisions are in this category), the ultimate size of the division (acres of land to be served) should be in accordance with the authorizing legislation or legislative history and should be stated explicitly. For divisions constructed under the general authority of the Snyder Act (U.S. Congress, 1921), the size should conform to existing planning documentation or, in the absence of such documentation, the size should be specified with the approval of the BIA Area Office and the applicable tribal council. In addition, since much of the construction needed is of a rehabilitation nature, the completion statement should also contain a description of the condition of the division to be attained upon

completion. Although this condition will normally involve bringing all facilities to fully operational states, situations may exist where the transfer of some divisions to non-federal ownership can take place with some facilities less than fully operative. Finally, the completion statement should indicate plans for ownership of the divisions upon completion. This may involve transfer of the division or project to an Indian tribe or water users' organization, and could provide for partial or full subsidy of post-transfer O&M costs by the federal government. Conversely, some plans may call for the division to remain in federal ownership as long as the lands served remain in a federal trust status.

2. Construction Plan. This plan should provide a comprehensive description of all construction activities that are necessary to complete each division in accordance with the completion statement. In addition, it should contain cost estimates for all construction items which should be updated annually, such that total costs to completion are available at all times. Finally, the construction plan should include maps of project lands, clearly identifying lands currently served by each division and lands planned to be served upon completion. Such maps should also contain information on land ownership (tribal, allotted or non-Indian), operation status (farm lease, development lease, owner-operated or temporarily non-assessable) and major unit facilities.

3. Impact Analysis. For each division, a study should be conducted to determine the impacts on each of the program objectives of completion as described in the completion statement and construction

plan. Data describing the number of Indian acres to be irrigated, and the number of Indians receiving direct profits, lease income and subsistence benefits should be calculated from land ownership and farming operation patterns for the actual lands to be served, rather from extrapolations of trends of existing project lands. Data on direct profits and subsistence crop benefits attributable to the new investments should be derived from farm budget analyses of the lands to be served, using current normalized commodity prices and operating costs. Data on job and lease income should be derived from local wage rates and land lease information. Job data should be derived from local supply and demand analyses of required occupational categories. Water conservation and non-irrigation water use potential should be gathered from local and regional water conservation and water use studies. Sources of information for such studies include federal, state, local and tribal government agencies and local universities. Data should be updated as significant changes become known.

Although completion of the data refinement plan on all 322 divisions would require a significant investment, such an investment would be small in comparison to the annual construction appropriation for the BIA irrigation program, which averaged $47.2 million during the five year period 1979-1983. In addition, the planning documentation that would result from such an initiative is sorely needed for proper management of the program, even in the absence of the decision support system. Finally, the data collection plan, once completed, could be maintained with a minimal degree of effort.

Chapter 7

IMPLEMENTATION OF THE DECISION SUPPORT SYSTEM

Despite the impressive growth of multiobjective decision-aiding algorithms that was described in Chapter 1, these methods have yet to enjoy wide success in solving actual problems in water resources planning. There are a variety of possible explanations for this, including the inherent time lag between theoretical development and practical application, the increased complexity involved in applying multiobjective techniques as compared with applying conventional methods, and a lack of familiarity of the methods among practitioners. It may also be partially due to the lack of use of multiobjective decision-aiding algorithms in the successful application of decision support systems in solving actual problems that has led to the absence of widespread acceptance of these techniques. If so, then demonstration of the utility of multiobjective decision support systems within the context of complex planning problems could lead to more rapid exploitation of the value of these methods.

This chapter provides a significant contribution to the yet miniscule track record of multiobjective decision support systems in assisting with water resources planning problems by presenting the results of a field application test of the decision support system described earlier. This test was conducted in a real decision environment in that it:

- involved interactions with an actual program decision maker,
- was conducted using the same agency facilities that will be used for future applications,

- used real input data as described in the preceding chapter, and
- used the operational objectives set developed earlier.

In order to provide a contextual framework for the presentation of the implementation process, common barriers to the effective implementation of such management science tools as decision support systems and management information systems are discussed. The decision environment into which the decision support system was introduced is then briefly discussed within this framework, followed by a description of the test application.

Barriers to Decision Support System Implementation

Although overlooked by most creators of multiobjective decision-aiding algorithms and decision support systems, organizational and behavioral factors are often critically important to the successful implementation and use of such management aids. As Hammond (1978) and Robey and Zeller (1978) pointed out, technical features of a decision support system may often be almost irrelevant to the eventual adoption or rejection of the system by the user. Despite the fact that attention is most often focused on such things as the mathematical elegance of new algorithms, software development or hardware configurations, considerations of such decision environment factors as decision maker psychology, organizational characteristics and methods of implementation may be equally important to successful implementation.

Robey and Zeller (1978) divided decision environment factors that affect successful implementation into three categories: attitudinal factors, organizational factors and implementation process factors. They found chances for successful implementation to be the highest when the problem is perceived to be urgent and the value of the management information system is perceived to improve individual job performance (attitudinal); when the organization into which the system is to be introduced is not complex, and is highly formalized and highly centralized (organizational); and when the implementation process has strong management support, follows a well-conceived introduction plan and includes effective follow-up procedures by the management scientist or a knowledgeable member of the using organization (implementation process).

Ginzberg (1978) primarily focused on the organizational category. He found the extent of organizational change required in system implementation to be an important factor. For situations in which extensive organizational changes were required, cognitive, interpersonal and political dimensions become important. On the other hand, Ginzberg felt that technical assistance alone may be all that is necessary to bring about successful system implementation when such implementation requires little organizational change.

Other authors have focused on the third category of implementation processes, perhaps because the management scientist has the greatest control over factors in this category. Ackoff (1960), for example, offered five suggestions for initiating and maintaining a strong implementation process. These were: provide for project discontinuance if intolerable conditions arise, report to an organizational level with sufficient authority to control all functions involved in the study, never report through intermediaries, complain forcibly about undesirable research conditions and never perform research at no cost to the using organization.

Doktor and Hamilton (1973) emphasized the manager-analyst interface during the implementation process. They observed that managers typically exhibit heuristic cognitive decision styles, whereas analysts commonly have analytic cognitive styles (p. 886). Therefore, a common problem during implementation processes is that the presentation of the management information system by the analyst tends to be in analytic formats, whereas decision makers might find them more acceptable in general formats (p. 889). Thus, the degree of acceptance by the decision maker could be influenced by the style of presentation of the analyst's recommendations.

DeBrabander and Edstrom (1977) explained that differences in cognitive style between decision makers and analysts are due largely to different conceptual frameworks that they bring to the decision problem. Such differences are caused by differences in experience and educational backgrounds. DeBrabander and Edstrom hypothesized that major communications problems between decision makers and analysts do not exist when conceptual frameworks are similar. When conceptual differences are present, they suggested that the use of a third party to facilitate communications could increase significantly chances for successful system implementation.

Hammond (1978) also felt that the decision maker-analyst interface was critically important. He listed the following eight potential sources of conflict between the decision maker and the analyst: goal orientation, time horizon for the analysis, comparative expertise, interpersonal style, cognitive style, problem definition, validation of analysis and the degree of structuredness required (p. 318). Hammond suggested a number of ways to overcome such differences, including frequent interaction, frequent use of intermediate results, responsive analyses, flexible and evolutionary modeling that treats changes in the decision maker's mind as progress and not annoyance, and the use of a third party to facilitate communication.

Most of Hammond's suggestions center around user involvement in system development and implementation. The importance of user involvement to ultimate successful implementation was also emphasized by DeBrabander and Edstrom (1977), Ginzberg (1978) and Robey and Farrow (1982).

Lonnstedt (1978) identified six significant barriers to implementation in a study of 107 operations research projects implemented in large companies. These were: low user participation in problem definition, no involvement of top management in project initiation, project limitations to a small part of the problem, presence of non-quantifiable variables, unobtainable data and user perceptions of low value of projects for decision making.

Implementation Environment

A conceptual framework derived from the preceding discussion of common barriers to decision support system implementation was applied to the environment within which the newly developed decision support system was to be implemented. The purpose of this exercise was to identify any potential problems that might exist so that measures to mitigate the impacts of such problems could be included in the implementation process.

The framework used contained the following three categories:

- decision problem (urgency of problem, scope of problem, quantifiability of variables and data availability),
- organization (degree of centralization and formalization, organizational changes required in decision support system implementation, management support of decision support system and initiator of project), and
- decision maker (perceived value of decision support system to individual job performance and decision style).

Decision Problem

Two decision problem characteristics posed potential implementation difficulties. Although the organizational mandate to solve the problem had seemed pressing at the time that it was issued, the perceived urgency had dissipated somewhat by the time of decision support system implementation. The FY 1979 House Appropriations Committee that mandated the development of an objective irrigation decision support system contained language that the "Committee has deferred providing additional funds for irrigation and power systems until the Bureau of Indian Affairs has submitted to the Committee a long-term plan for improving these valuable resources" (U. S. Congress, 1978, p. 52). However, appropriations for the BIA irrigation program during the five year period 1979-1983, which included $30 million in the 1983 jobs bill (U. S. Department of the Interior, 1983), were higher than during any other five year period in its 100 year history. Thus, perceptions of low problem urgency appeared to be a mild barrier to successful implementation.

The second barrier concerned data availability. As discussed in the preceding chapter, data for comprehensive implementation of the decision support system (including all 322 separable project divisions as decision variables) was not readily available.

Another potential barrier, quantifiability of variables, was not present. All objectives contained in the decision support system were measurable in quantifiable units.

Organization

No significant organizational barriers to implementation were identified. The Bureau of Indian Affairs has a highly formalized, bureaucratic organizational form. Although its field operations tend to be somewhat decentralized, budget priorities in the irrigation program are established in a highly centralized fashion. That is, budget decisions for all projects are made in the Washington, D. C. headquarters office, based on input from lower levels of the organizational hierarchy.

In addition, development of the decision support system had enjoyed top management support, primarily due to the Congressional mandate. Such support existed not only within the Bureau of Indian Affairs, but also at higher levels in the Department of the Interior. Although the particular decision support system approach that was followed was initiated by the author, the initiator of the effort to find a better way of establishing project priorities was to be the U. S. Congress and the top level administrators charged with executing the directives of the Congress.

Finally, no organizational changes were anticipated as a result of full decision support system implementation. Although it was possible that organizational shifts could have occurred at the field level due to changing construction priorities, such was not the case at the headquarters level where implementation barriers were most important. As discussed later, the results of the test application could have been accomodated with only limited field changes as well.

Decision maker

Significant decision maker-related barriers to implementation also did not exist. The Chief Irrigation Engineer of the Bureau recognized the program improvement potential of the decision support system which, if realized, would be reflected directly in perceptions of his personal professional performance. This individual's attitude toward decision support system implementation was indicated by his interest and support of the project, as well as his voluntary involvement in the development of the decision support system over a two year period.

The cognitive style of the Chief Irrigation Engineer also was not problematic. Although this individual had been a program manager for 14 years prior to the development of the decision support system, his decision style was not of the purely heuristic form typical of managers described by Doktor and Hamilton (1973). As an engineer by education and profession, the Chief Engineer was very comfortable with analytic models and communications problems were non-existent. In addition, as explained in Chapter 5, the decision-aiding output display of the decision support system contained both graphical and tabular data. Therefore, problems related to the use of an analytic model with a heuristic decision maker would have been minimized had they been present.

Decision Support System Test Application

The examination of the implementation environment identified only two potentially significant problems: perceived problem urgency and data availability. Neither of these two implementation barriers affected the test application. Any lack of urgency felt by the decision maker or other user organization participants seemed to be compensated by a recognition of the importance of good long-term program management and the potential contribution of the decision support system to that goal. As described earlier, a number of members of the user organization had participated in various stages of decision support system development. This continuous user involvement, which may be the single most important analyst-controlled variable to successful decision support system implementation, contributed heavily to a sense of user "ownership." This, in turn, may have been at least a partial reason why lack of urgency was not detected as a problem area during the test application.

Although data collection is indeed a problem for full decision support system implementation, the problem was avoided in the test application phase by aggregating separable divisions to a level at which reasonably valid secondary data could be derived. The process by which this was achieved has been described in the preceding chapter.

Before the test application is described, the question of decision maker identification will be addressed briefly. In all multiobjective decision problems, the identification of the decision maker is a key issue, although in many problems the identity of that individual (or group) is not clear. In this case, however, decision maker identification was not a problem. The formal organizational structure dictated who the decision maker was to be: the Chief Irrigation Engineer of the Bureau. The Chief Irrigation Engineer had historically made the funding priority decisions and the development of a new decision-aiding tool did not alter that fact.

The test application phase of decision support system development did not involve an abrupt change in the involvement of user organization members. Since the decision maker and other members had been involved in previous stages of the research, progression from model development to test implementation involved no user participation discontinuities. Instead, it was treated as another stage of decision support system growth. Because of this continuous user involvement, requirements for the education of the decision maker at the time of initial solution availability were very small.

The first solution presented to the decision maker appears in Figure 7-1. Although he was able to comprehend the decision-aiding display easily, the decision maker asked several questions to increase his understanding. For example, he questioned the level of Objective 8 in the initial solution. Since it was not immediately clear why Objective 8 attained a level of of only 9% at the initial nondominated solution, the solution vector was reviewed. It was determined that the reason was attributable to the major impact of one candidate project division on Objective 8. The Colorado River Irrigation Construction Division, x_{73}, contributed a value of $7,740,000 per year to Objective 8, or 95% of the

	OBJ 1 (Indian land irrig)	OBJ 2 (Indian farm benef)	OBJ 3 (Indian jobs)	OBJ 4 (Indian lease benef)	OBJ 5 (Indian subsis benef)	OBJ 6 (Indian farm profits)	OBJ 7 (Indian job income)	OBJ 8 (Indian lease income)	OBJ 9 (Value of subs crops)	OBJ 10 (Non-irr water use)	OBJ 11 (Water con-served)
Alternative A											
Objective attainment	42,880 a	2,479	463	551	2,204	$4,272M/yr	$4,630M/yr	$769M/yr	$991M/yr	6,469 AF	203,100 AF
Percent of maximum attainable	65%	67%	84%	27%	48%	62%	84%	9%	33%	66%	29%
Alternative B											
Objective attainment											
Percent of maximum attainable											

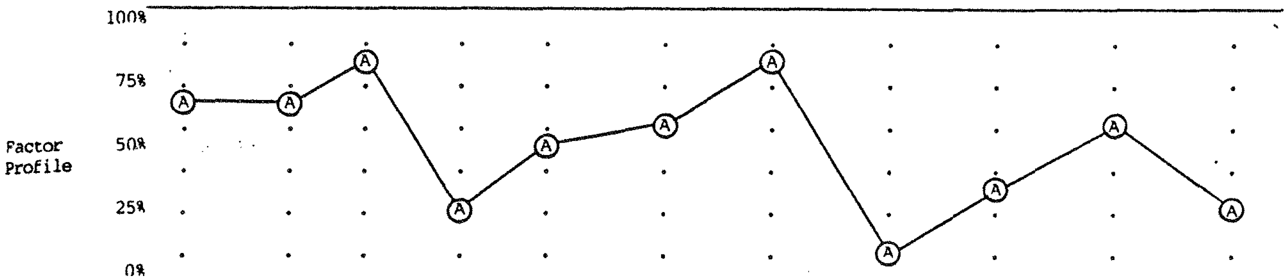


Figure 7-1

Decision-Aiding Display (Objective Space), First Iteration

	OBJ 1 (Indian land irrig)	OBJ 2 (Indian farm benef)	OBJ 3 (Indian jobs)	OBJ 4 (Indian lease benef)	OBJ 5 (Indian subsis benef)	OBJ 6 (Indian farm profits)	OBJ 7 (Indian job income)	OBJ 8 (Indian lease income)	OBJ 9 (Value of subs crops)	OBJ 10 (Non-irr water use)	OBJ 11 (Water con-served)
Alternative A											
Objective attainment	42,880 a	2,479	463	551	2,204	$4,272M/yr	$4,630M/yr	$769M/yr	$991M/yr	6,469 AF	203,100 AF
Percent of maximum attainable	65%	67%	84%	27%	48%	62%	84%	9%	33%	66%	29%
Alternative B											
Objective attainment	45,979 a	1,588	260	779	845	$3,951M/yr	$2,600M/yr	$3,022M/yr	$315M/yr	4,474 AF	125,200
Percent of maximum attainable	70%	43%	47%	39%	18%	58%	47%	37%	10%	46%	18%

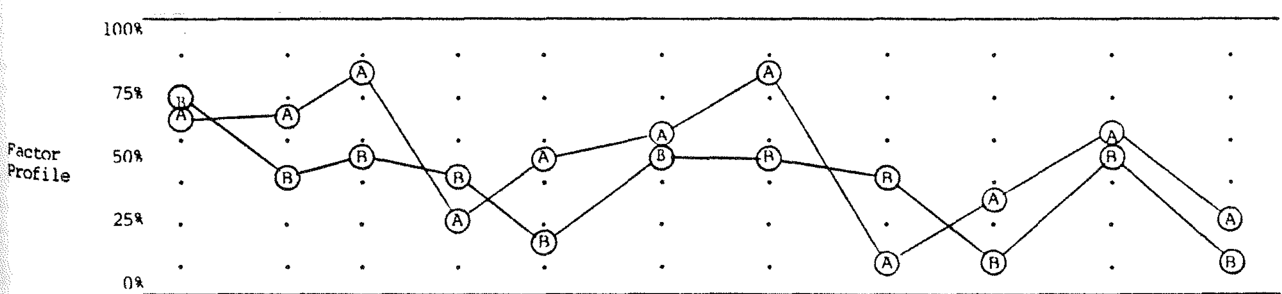


Figure 7-2

Decision-Aiding Display (Objective Space), Second Iteration maximum attainable value of that objective. The fact that the Colorado River Irrigation Construction unit was included in the solution vector for the solution yielding maximum contributions to Objective 8, but was not included in the initial soultion, explained the apparent anomaly. Questions such as this were felt to be very beneficial in that they increased the decision maker's understanding of the output display and made him more comfortable with the decision support system.

After the decision maker's questions had been answered, he was asked if the current noninferior solution (Alternative A) was his most preferred solution (Step 7, Chapter 5). Since he responded negatively, he was asked to select one or more objectives and to specify an increase or decrease in the attained levels of those objectives (Step 8). The decision maker selected Objective 8 and specified the new level to be greater than or equal to \$3,000,000 per year. The new solution was calculated (Step 9) and presented to the decision maker (Step 10). This second decision-aiding display appears in Figure 7-2.

It can be seen in Figure 7-2 that Alternative B satisfies the new constraint by increasing the contribution of Objective 8 (Indian lease income) to \$3,022,000 per year. In addition, contributions to Objective 4 (Indian lease beneficiaries) are also increased, as would be expected, and total Indian land irrigated (Objective 1) is increased. However, contributions to all other objectives are decreased.

At this point, the decision maker asked for additional information not contained in the decision-aiding display. Although he agreed that the objectivity associated with decision making in the objectives space was highly desirable, he began to feel a need to be aware of resource distribution implications of his choices. Therefore, it was decided to augment the decision-aiding display with the following decision space information about each alternative:

- total number of projects (construction, R&B and total),
- number of projects by Area (construction, R&B and total), and
- distribution of expenditures by Area (construction, R&B and total).

Tables 7-1 and 7-2 contain the decision space displays provided to the decision maker for Alternatives A and B, respectively. It is interesting to note the wide decision space variation between the two alternatives. Alternative B contains 48% fewer projects at the same budget level than Alternative A. The reduction in project numbers is greatest in the Albuquerque and Sacramento Areas. These changes reflect a shift from small, subsistence-type divisions under Alternative A to relatively large, profit-producing divisions under Alternative B. It can be seen that Alternative B reduces Indian farm profits by only 7.5% while reducing Indian farm profit beneficiaries by 36%, thus indicating a smaller number of more profitable farm units operated by Indians under Alternative B. The proportionately greater loss of projects under Alternative B from the Albuquerque and Sacramento Areas is compatible with a shift to larger, more efficient divisions, since divisions in these Areas are primarily small, non-income producing units.

In addition to the decision space information added to the output display during the test application, experiments with two other output display modifications were conducted. In the first, objective attainment

Table 7-1

Decision-Aiding Display (Decision Space), Alternative A

Area	Construction		R&B		Total	
	Projects	$(mill)	Projects	$(mill)	Projects	$(mill)
Albuquerque	5	$ 5.556	4	$2.334	9	$ 7.890
Billings	5	7.970	4	2.054	9	10.024
Navajo	0	0.000	1	0.807	1	0.807
Phoenix	5	7.456	8	2.191	13	9.647
Portland	1	12.408	0	0.000	1	12.408
Sacramento	12	7.397	11	1.807	23	9.204
Total	28	$40.787	28	$9.193	56	$49.980

Table 7-2

Decision-Aiding Display (Decision Space), Alternative B

Area	Construction		R&B		Total	
	Projects	$(mill)	Projects	$(mill)	Projects	$(mill)
Albuquerque	1	$ 0.377	1	$0.020	2	$ 0.397
Billings	4	14.427	3	1.030	7	15.457
Navajo	0	0.000	1	0.807	1	0.807
Phoenix	5	30.025	3	0.979	8	31.004
Portland	0	0.000	0	0.000	0	0.000
Sacramento	2	0.663	9	1.669	11	2.332
Total	12	$45.492	17	$4.505	29	$49.997

levels for Objectives 2, 3, 4 and 5 and Objectives 6, 7, 8 and 9 were combined to form "total Indian beneficiary" and "total Indian monetary benefit" surrogate objectives, respectively. It was felt that a reduction in the size of the objectives set from 11 to five objectives might make the decisions required of the decision maker less complex. However, such aggregation was felt by the decision maker to be undesirable since it hid important distinctions among classes of beneficiaries and income. That is, distinctions among types of Indian beneficiaries and income were considered by the decision maker to be sufficiently important to warrant the additional information. This was borne out by the decision maker's most preferred solution (Alternative D), which reflected very different preferences for different types of beneficiaries and income. The decision maker also did not find addition of the two aggregated surrogate objectives to the original objectives set to be useful. Addition of the objectives would have added complexity to the decision-aiding display without increasing the amount of useful information, in the opinion of the decision maker.

The second modification had to do with the factor profile graphical display. Since the objectives set was relatively large, the decision maker experienced some difficulty in focusing on the most significant differences between the alternatives. To increase the beneficial effects of the factor profile on the decision maker's cognition, one of the two profiles in each display was drawn in red ink. This change seemed to increase the visual separation of the alternatives in the graphical display and was felt to be a mild improvement to the decision-aiding display. The manner in which these changes were made in conjunction with the decision maker is consistent with the evolutionary approach to decision support system development recommended by Huber (1983, p. 575).

After having studied the augmented decision-aiding display, the decision maker was faced with a choice between Alternatives A and B. Alternative A was selected. For the next iteration, he specified that Objective 1 should be greater than or equal to 75% of its maximal value and that Objective 8 should be reduced to less than or equal to 5%. Figure 7-3 contains the decision-aiding display presented to the decision maker on the third iteration. Table 7-3 contains supporting decision space data for Alternative C.

Alternative C, in addition to providing greater levels of contributions to Objective 1 and less to Objective 8, also increased farm profits and non-irrigation water use, while decreasing farm lease and subsistence beneficiaries and amounts of water conserved.

After selecting Alternative C as his preferred choice, the decision maker specified that the next iteration should constrain Objective 2 to be greater than or equal to 70%, and Objectives 4, 5 and 8 to be less than or equal to 15%, 30% and 5%, respectively.

Figure 7-4 contains the decision-aiding display resulting from the choices above. Table 7-4 contains supporting decision space data for Alternative D. At this point the decision maker was satisfied with Alternative D as his most preferred solution. Table 7-5 summarizes the choices made by the decision maker in the test application.

	OBJ 1 (Indian land irrig)	OBJ 2 (Indian farm benef)	OBJ 3 (Indian jobs)	OBJ 4 (Indian lease benef)	OBJ 5 (Indian subsis benef)	OBJ 6 (Indian farm profits)	OBJ 7 (Indian job income)	OBJ 8 (Indian lease income)	OBJ 9 (Value of subs crops)	OBJ 10 (Non-irr water use)	OBJ 11 (Water con- served)
Alternative A											
Objective attainment	42,880 a	2,479	463	551	2,204	$4,272M/yr	$4,630M/yr	$769M/yr	$991M/yr	6,469 AF	203,100 AF
Percent of maximum attainable	65%	67%	84%	27%	48%	62%	84%	9%	33%	66%	29%
Alternative C											
Objective attainment	49,468 a	2,158	462	300	1,827	$4,683M/yr	$4,620M/yr	$405M/yr	$1,013M/yr	7,155 AF	176,700
Percent of maximum attainable	75%	58%	83%	15%	40%	68%	83%	5%	33%	74%	25%

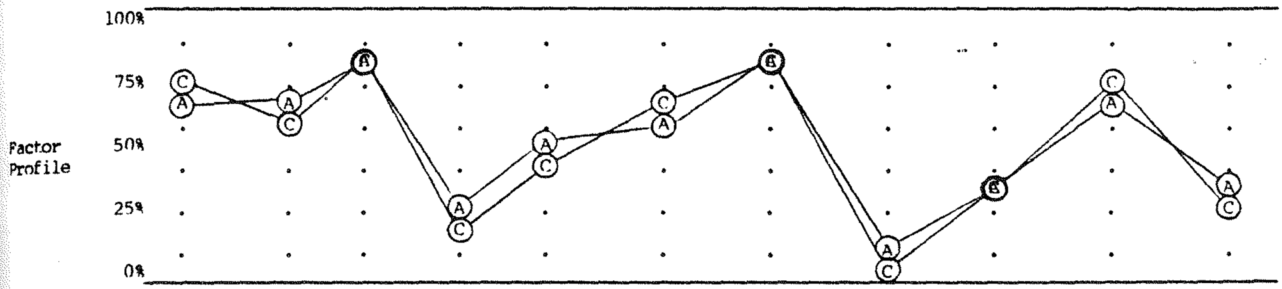


Figure 7-3

Decision-Aiding Display (Objective Space), Third Iteration

Table 7-3

Decision-Aiding Display (Decision Space), Alternative C

	Construction		R&B		Total	
Area	Projects	$(mill)	Projects	$(mill)	Projects	$(mill)
Albuquerque	4	$11.701	3	$1.784	7	$13.485
Billings	5	7.97	2	0.709	7	8.679
Navajo	0	0.000	1	0.807	1	0.807
Phoenix	3	6.373	5	1.464	8	7.837
Portland	1	12.408	0	0.000	1	12.408
Sacramento	8	6.279	9	0.505	17	6.784
Total	21	$44.731	20	$5.269	41	$50.000

	OBJ 1 (Indian land irrig)	OBJ 2 (Indian farm benef)	OBJ 3 (Indian jobs)	OBJ 4 (Indian lease benef)	OBJ 5 (Indian subsis benef)	OBJ 6 (Indian farm profits)	OBJ 7 (Indian job income)	OBJ 8 (Indian lease income)	OBJ 9 (Value of subs crops)	OBJ 10 (Non-irr water use)	OBJ 11 (Water con-served)
Alternative D											
Objective attainment	43,766 a	2,665	458	302	1,377	$4,756M/yr	$4,580M/yr	$402M/yr	$950M/yr	6,593 AF	190,800 AF
Percent of maximum attainable	66%	72%	83%	15%	30%	70%	83%	5%	31%	68%	27%
Alternative C											
Objective attainment	49,468 a	2,158	462	300	1,827	$4,683M/yr	$4,620M/yr	$405M/yr	$1,013M/yr	7,155 AF	176,700
Percent of maximum attainable	75%	58%	83%	15%	40%	68%	83%	5%	33%	74%	25%

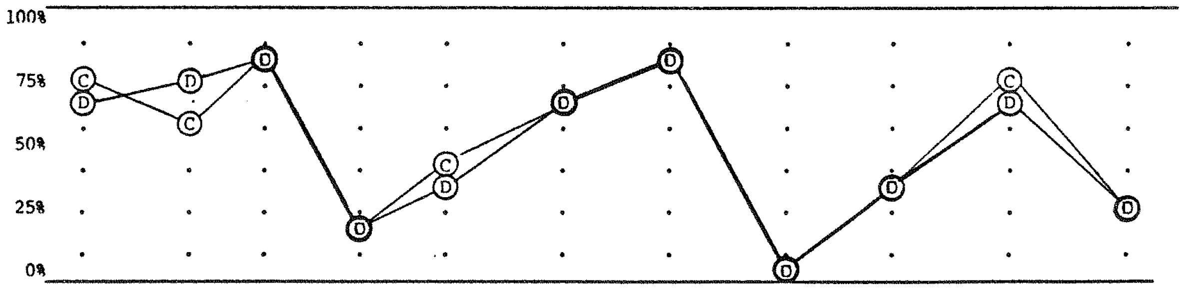


Figure 7-4

Decision-Aiding Display (Objective Space), Fourth Iteration

Table 7-4

Decision-Aiding Display (Decision Space), Alternative D

Area	Construction Projects	Construction $(mill)	R&B Projects	R&B $(mill)	Total Projects	Total $(mill)
Albuquerque	3	$ 4.498	3	$1.367	6	$ 5.865
Billings	4	7.051	2	1.700	6	8.751
Navajo	0	0.000	1	0.807	1	0.807
Phoenix	4	10.289	11	3.741	15	14.030
Portland	1	12.408	0	0.000	1	12.408
Sacramento	11	7.096	9	1.043	20	8.139
Total	23	$41.342	26	$8.658	49	$50.000

Table 7-5

Summary of Decision Maker Responses

Iteration	Options	Decision Maker Choice	Most Preferred Solution ?	New Specifications
1	A		No	Obj 8 $\geq$ \$3.0/year
2	A B	A	No	Obj 1 $\geq$ 75% Obj 8 $\leq$ 5%
3	A C	C	No	Obj 2 $\geq$ 70% Obj 4 $\leq$ 15% Obj 5 $\leq$ 30% Obj 8 $\leq$ 5%
4	C D	D	Yes	

Choices made by the decision maker in interacting with the decision-aiding model indicated that he had a relatively greater concern for Indian job and farm benefits than for lease and subsistence benefits. In addition, he apparently had low concern for water conservation. However, at no time was he required to express his relative preferences among these competing objectives explicitly.

It was somewhat surprising that the decision maker was able to converge on a satisfactory solution in only four iterations. This may have been due partially to the ample opportunities that the decision maker had to study the alternatives before making choices. In order to reduce computing costs during the test implementation phase, computer runs were made in batch mode overnight, during the least expensive processing period available. The resulting one day time frames between iterations provided the decision maker with time to fully digest the decision-aiding displays and to make well chosen decisions.

Computational experience with the decision-aiding algorithm is presented in Table 7-6. It can be seen that CPU time requirements ranged from 2.6 seconds to 136 seconds per run and that computational difficulty increased with increasing numbers of constraints. Alternatives B and D were not carried to optimality because the increased accuracy associated with the optimal solutions did not justify the additional computational expense for the test application. One of the attractive features of the MPSX/370 algorithm is that it provides good interim feasible solutions while searching for the optimal solution. Near-optimal interim feasible solutions were available for both Alternatives B and D and were sufficiently accurate to conduct the implementation test without penalty.

The request by the decision maker to use decision space information to assist with his decisions adds an interesting perspective to the decision support system. Schilling, et al. (1982) observed that decision makers may often base their decisions partially on objectives that are not included in decision-aiding analytic models. These authors pointed to equity and political acceptance as two examples of objectives that often fall into this category (p. 236). Equity and political acceptance were in fact the concerns that the decision maker expressed in asking for

Table 7-6

Decision-Aiding Algorithm Computational Experience

Run	CPU time	Total time	Cost	Class*	Integer solutions found	Branches abandoned while computing	Number of constraints
1	2.6s	1.98m	$26.83	A	4	121	1
2	6.5s	1.05 m	12.77	B	2	31	1
3	5.4s	1.17m	11.96	B	2	32	1
4	5.5s	1.22m	7.03	D	2	21	1
5	3.4s	1.48m	5.70	D	1	1	1
6	11.3s	1.91m	18.18	B	2	159	1
7	5.4s	1.44m	6.89	D	2	31	1
8	5.0s	1.23m	11.35	B	2	23	1
9	8.9s	4.34m	15.25	B	3	120	1
10	17.9s	4.59m	25.68	B	3	216	1
11	3.9s	1.09m	5.90	D	1	1	1
Alt A	16s	2.61m	17.74	D	1	195	1
Alt B	41s	2.94m	33.80	D	2	**	2
Alt C	2m 16s	10.22m	98.92	D	9	1526	3
Alt D	1m 47s	12.32m	77.13	D	4	**	5

* A = interactive
B = batch, daytime processing
D = batch, overnight processing

** Data for Alternatives B and D are for non-optimal solutions.

decision space information. The decision maker agreed with the objectives set used in the decision support system and was willing to use those objectives in identifying his most preferred solution, provided he could be assured that the final solution would be acceptable from a political perspective.

One of the positive features of the decision support system is that it allows decisions to be made apart from decision space bias. That is, since interactions with the decision maker take place in the objective space, favoritism or biases of the decision maker toward specific projects cannot affect the outcome. Therefore, the decision maker is able to get a totally detached solution without sacrificing his views on the relative importances among the objectives.

This positive feature was not violated by the addition of decision space information to the decision process. The impact of decisions made in the objective space became known only after the results of such decisions were available. Since no changes were based on subsequent consultation of the decision space information, the availability of decision space information apparently had no effect on the decision process.

The political acceptability concern of the decision maker could be viewed as a constraint, rather than as an objective. That is, the reason for requesting decision space information was not to optimize political acceptability but rather to insure that the final solution exceeded a minimum threshold of political acceptability.

The most preferred solution identified in the test application, the selection of which was based totally on information in the objective space, was found to be politically acceptable when the decision space was reviewed. Therefore, in the test application, the decision space information did not affect the outcome of the decision process. However, if the most preferred solution had not measured up from a political acceptability standpoint, then modifications to the final solution would have been required.

Brill, et al. (1982) found that different solutions frequently can be found that are very different in the decision space but are very similar ("near optimal") in the objective space. Possibilities for improved capabilities of the decision support system to handle problems in which preferred solutions based on objective space information alone are found to be politically unacceptable are addressed in Chapter 9 as future research needs are discussed.

Chapter 8

EVALUATION OF THE DECISION SUPPORT SYSTEM

The purpose of the test application described in Chapter 7 was to provide a basis upon which the effectiveness, efficiency and acceptability of the decision support system in helping to solve a real multiobjective decision problem within an actual decision environment could be evaluated. Sage (1981) provides a detailed discussion of the benefits of conducting decision support system evaluations in actual or closely simulated operational environments. The results of the test application were used to gain an understanding of the benefits to be received and costs incurred in use of the decision support system. That evaluation is described in this chapter.

Approaches to Evaluation

Although the evaluation of any systems management tool is critical to its proper use, it usually involves more than just a straightforward economic benefit-cost analysis. DeBrabander and Edstrom (1977) observed that, while the costs of management information systems normally can be calculated, estimates of benefits in commensurable quantitative terms are frequently impossible. Therefore, other means of evaluation must be found.

Gallagher (1974) discussed management information system evaluation in terms of three basic approaches. The three approaches were differentiated based on the point in the decision-making sequence at which the evaluation is conducted. In the first approach, evaluation occurs after the results of management information system use are known;

that is, after the decision has been made and the consequences of that decision have transpired. Gallagher pointed out that, while this approach is preferable in terms of availability of measurable data, effects of management information system use are frequently slow to appear. Since noncontrollable variables may change during this time, cause and effect relationships become blurred, making effective evaluation frequently impossible. In the second approach, evaluation occurs immediately after the decision has been made. This approach is based on the assumption that the consequences of alternative actions are known. The third approach involves asking the decision maker directly to make estimates of the value of the decision-aiding system. Although easily implemented, it relies of the perceptions of the decision maker and is therefore subject to bias and inaccuracy.

In this study, the second approach was used. The first approach was discarded because the long time frame required for decision support system evaluation under the first approach was prohibitive. The appropriations cycle of the federal government is such that portfolio selection decisions are made two years prior to the actual receipt of funding. Project design and construction can add from one to five years to that time before the actual consequences of the portfolio selection decision reasonably can be measured. The third approach was also discarded. Although the decision maker in the test application was favorably disposed toward the decision support system, elicitation of his direct evaluation would not have provided quantitative information for evaluation. However, his perceptions on the value of the decision support system are incorporated in the evaluation process described below.

Evaluation Procedure

The framework used to conduct the decision support system evaluation was based on a set of nine design specifications developed in the initial stages of the research project. These specifications were developed to insure that the decision support system would be effective (i.e., it would develop portfolios of projects that yield more desirable contributions to the program objectives, under equivalent constraints, than did the previous portfolio selection procedure), efficient (i.e., it would consume no more resources than its output justifies) and acceptable (measures of effectiveness and efficiency are irrelevant if the using organization fails to accept it). In order to determine how well each specification was met by the decision supprt system, each was treated as an evaluation criterion. Three of the nine criteria apply to the portfolio developed with the assistance of the decision support system and six apply to the decision support model itself. The three portfolio evaluation criteria were:

- contribution to program objectives,
- compatibility with existing construction capability of using organization, and
- political feasibility.

The six decision support system evaluation criteria were:

- cost of data collection,
- cost of computer support,
- time of decision maker required,

- compatibility with available data,
- compatibility with using organization expertise, and
- compatibility with decision style of the decision maker.

The relationships of these nine criteria to the requirements of decision support system effectiveness, efficiency and acceptability are illustrated in Figure 8-1.

Evaluation Results

Critrion 1 - Contributions to Program Objectives

The first criterion measures the degree to which the project portfolio selected with the assistance of the decision support system provides more desirable contributions to program objectives than would the portfolio selected in the absence of the decision support system. The general approach to measuring the effectiveness of the decision support system under Criterion 1 was to apply it to budget cycles of past years and compare the outputs of portfolios actually selected with the outputs of portfolios selected with the assistance of the decision support system, using identical inputs and constraints.

Unfortunately, direct comparisons of such portfolios were not possible because portfolios chosen in prior years were based on a different level of aggregation than that used in the decision support system. As discussed in Chapter 6, five different levels of funding elements were available upon which to base portfolio selection decisions. That is, the decision variables could be defined in five different ways, ranging from individual elements of annual work plans to entire projects.

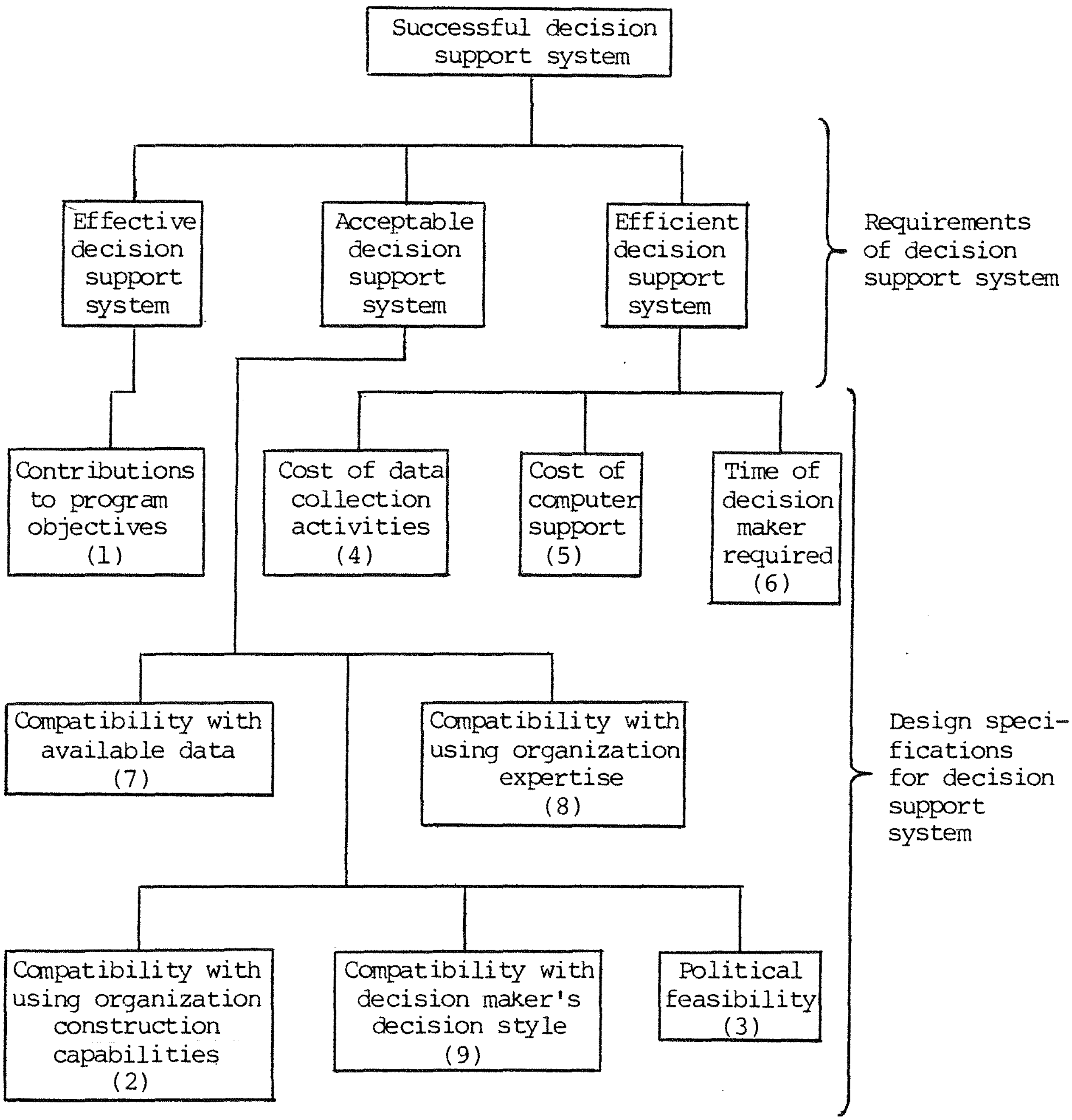


Figure 8-1

Evaluation Framework

Portfolios selected in past years were composed of individual elements of annual work plans, such as pumps, canal reaches and diversion dams, whereas portfolios selected with the assistance of the decision support system are composed of separable project divisions. Since project divisions normally were not funded to completion in a single year in past portfolios, outputs of such portfolios cannot be compared directly with outputs of portfolios selected with assistance of the decision support system.

In order to circumvent this problem, portfolios actually selected in the 1979-1983 fiscal years were examined. In that five year period, elements of 67 divisions were funded at a cost of $236.0 million. Two of those divisions (Ak Chin and Navajo Construction Divisions) were funded because of special legislative initiatives, not because of normal administrative decision-making. Six additional divisions (Standing Rock, Lower Brule, Fort Mohave, Omaha, Cheyenne River and Crow Creek Construction Divisions) were funded as "new starts" by a special initiative of the Office and Management and Budget. The remaining 59 divisions were funded as a result of the normal administrative decision-making process within the Bureau of Indian Affairs. These are listed in Table 8-1.

For comparison purposes, it was assumed that the 59 divisions selected for funding as a result of the normal decision-making process in the 1979-1983 fiscal year time frame were indicative of the current priorities of the Bureau. Full funding to complete these 59 divisions (based on current cost data) is $328.002 million. Evaluation of the decision support system in terms of Criterion 1 was conducted by comparing

Table 8-1

Irrigation and Power Divisions Actually Funded, FY 1979-1983

Division	Current cost to completion (millions)	Division	Current cost to completion (millions)
Cocopah construction	$ 2.040	Flathead Power R&B	$10.000
Colorado River Irr const	47.000	Fort Belknap R&B	0.191
Colorado River Pwr const	7.100	Fort Peck construction	2.082
Fort Apache R&B	2.721	Fort Peck R&B	0.321
Chuichu R&B	0.750	Northern Cheyenne const	1.716
San Xavier R&B	0.500	Duck Valley construction	4.919
Vaivo Vo construction	1.360	Duck Valley R&B	2.330
Gial Crossing R&B	1.900	Goshute R&B	0.335
Maricopa Colony R&B	0.600	Campbell Ranch R&B	0.275
Salt River R&B	10.300	Fallon construction	6.905
San Carlos Res const	1.763	Fallon R&B	2.640
San Carlos Irr const	56.740	Pyramid Lake R&B	0.500
San Carlos Irr R&B	20.000	Walker River R&B	4.252
San Carlos Power R&B	5.450	Jicarilla construction	0.881
Camp Verde R&B	0.098	Mescalero R&B	0.916
Havasupai R&B	0.050	San Ildefonso R&B	0.400
Kaibab construction	0.830	Acoma R&B	0.788
Big Pine R&B	0.151	Isleta R&B	0.483
Bishop R&B	0.585	Jemez R&B	0.617
Fort Independence R&B	0.100	Laguna R&B	0.876
Hoopa Valley R&B	0.533	Santa Ana R&B	0.371
Lone Pine construction	0.098	Zia R&B	0.020
Morongo R&B	0.812	Uintah R&B	26.058
Pala R&B	0.333	Wind River R&B	5.789
Pine River R&B	1.281	Fort McDowell const	0.905
Ute Mountain construction	6.572	Sandia construction	2.394
Blackfeet R&B	2.579	Rocky Boys construction	0.075
Crow R&B	0.676	Rocky Boys R&B	0.033
Flathead Irr construction	12.408	Wapato-Satus R&B	60.600
Flathead Power const	5.000		

Total number of projects: 59

Total cost/to complete: $328.002 million the outputs of a portfolio composed of those 59 divisions (referred to hereinafter as the "actual portfolio") with a portfolio of units identified with the assistance of the decision support system at a budget constraint of $328.002 million.

In order to demonstrate clearly the improved decision-making possible with the aid of the decision support system, the initial nondominated solution produced by the decision support system was used to make the comparison. Use of a final portfolio selected in accordance with the decision maker's preferences would not have been useful for such a demonstration if such a portfolio did not dominate the actual portfolio. Since the decision maker's preferences among the program objectives were widely varied, as reflected in Chapter 7, it is likely that a portfolio selected at C = $328.002 million in accordance with the decision maker's preferences might have been dominated on one or more objectives by the actual portfolio. However, a portfolio selected in accordance with the decision maker's preferences obviously would be more attractive to the decision maker than would the portfolio produced by the initial nondominated solution. Therefore, if superiority of the decision support system-produced portfolio over the actual portfolio can be demonstrated, then such an improvement properly could be viewed as a lower bound on the value of the decision support system to the decision maker.

The initial nondominated solution produced by the decision support system contained 107 project divisions at a cost of $327.992 million. Table 8-2 contains a comparison of that portfolio with the actual portfolio in both the objective space and the decision space. Table 8-2 demon-

Table 8-2

Comparison of Actual Project Selections (FY 1979-1983) and Initial Nondominated Solution

Objective Space

Objective	Actual portfolio	Nondominated portfolio	Per cent increase
1	117,484	198,252	68.7
2	3,525	4,550	29.1
3	769	1,003	30.4
4	2,353	2,736	16.3
5	1,931	4,258	120.5
6	17,917	22,249	24.2
7	7,590	10,030	32.1
8	10,647	12,557	17.9
9	417	3,039	628.8
10	14,850	31,433	111.7
11	594,550	654,060	10.0

Decision Space

	Actual selections		Nondominated solution	
Area	Projects	$(millions)	Projects	$(millions)
Albuquerque	12	$15.599	27	$40.454
Billings	9	14.190	13	52.517
Navajo	0	0.000	2	7.150
Phoenix	27	207.593	28	188.165
Portland	4	88.008	2	20.796
Sacramento	7	2.612	35	18.910
Total	59	$328.002	107	$327.992

strates that the portfolio produced by the decision support system represents an improvement over the actual portfolio on both counts. That is, it dominates the actual portfolio on all objectives and provides a more even geographical distribution of project divisions. Tables 8-3 and 8-4 contain more detailed information on the distributions of divisions and funding in the two portfolios under comparison. Again, the most preferred portfolio that could have been identified by the decision maker under a budget constraint of $328.002 million would represent a further improvement on the value structure of the decision maker over the nondominated portfolio used here for comparison.

Criterion 2 - Compatability with Construction Capability

This criterion was used to evaluate the degree to which the output portfolio can be constructed within existing user organization construction capabilities. Each organizational unit of the Bureau of Indian Affairs that is involved in the irrigation program has a relatively fixed amount of manpower and equipment resources that can be devoted to irrigation construction. Criterion 2 is concerned with the extent to which these resources would have to be shifted or reallocated in order to respond to the selected portfolio in an efficient manner. While requirements for some organizational changes would not invalidate the portfolio, BIA irrigation officials felt that requirements for Bureau field construction capabilities to be transferred to one Area Office or to two or three individual projects could not be accomodated. As Ginzberg (1978) observed, the extent of organizational changes required in decision support system implementation is directly related to

Table 8-3

Project and Funding Distribution
Based on Actual Project Selections (FY 1979-1983)

	Construction		R&B		Total	
Area	Projects	$(mill)	Projects	$(mill)	Projects	$(mill)
Albuquerque	3	$ 9.847	9	$ 5.752	12	$ 15.599
Billings	3	3.873	6	10.317	9	14.190
Navajo	0	0.000	0	0.000	0	0.000
Phoenix	10	129.562	17	78.031	27	207.593
Portland	2	17.408	2	70.600	4	88.008
Sacramento	1	0.098	6	2.514	7	2.612
Total	19	$160.788	40	$167.214	59	$328.002

Table 8-4

Project and Funding Distribution
Initial Nondominated Solution with C = $328.002 Million

	Construction		R&B		Total	
Area	Projects	$(mill)	Projects	$(mill)	Projects	$(mill)
Albuquerque	17	$ 35.532	10	$ 4.922	27	$ 40.459
Billings	7	42.095	6	10.422	13	52.517
Navajo	1	6.343	1	0.807	2	7.150
Phoenix	13	160.555	15	27.610	28	188.165
Portland	1	12.408	1	8.388	2	20.796
Sacramento	17	14.208	18	4.702	35	18.910
Total	56	$217.141	51	$56.851	107	$327.992

implementation difficulty.

In the test application, the decision support system performed well with respect to Criterion 2 in that it produced a portfolio that could be implemented with little organizational change, according to BIA irrigation officials. Table 7-4 summarizes decision space data on the portfolio selected with the assistance of the decision support system. The construction load for each Area indicated by the project numbers and dollar amounts in Table 7-4 was felt to be compatible with the existing resource levels in all Areas except Portland and Sacramento. The Phoenix Area, for example, had the greatest irrigation construction capability at the time of the evaluation and faced the greatest construction load in the selected portfolio. Some organizational shifts may have been necessary between the Portland Area, with only one project in the portfolio, and the Sacramento Area. However, BIA irigation officials felt that such shifts could be accomodated with relative ease.

The fact that the test application results performed well with respect to Criterion 2 does not mean that all portfolios selected with the help of the decision support system will do likewise. With the modification in which decision space information was added to the decision-aiding output display, however, it seems unlikely that concerns over organizational change requirements could invalidate the decision support system. Should severe organizational change implications arise in future preferred portfolios, the decision space display will enable the decision maker to modify his constraint selections in the objectives space to mitigate the severity of such impacts. It is likely that the decision maker may wish to operate only in the objective space until a preferred solution is identified and only then consult the decision space summary display to check on the organizational change implications of his selections. Should modifications be indicated at that time, an adjustment such as the "Hop-Skip-Jump" procedure of Brill, et al. (1982) could be followed. Such a possibility is discussed in the next chapter as further research needs are described.

Criterion 3 - Political Feasibility

This criterion was used to evaluate the decision maker's perceived political acceptability of the output portfolio. Although this criterion is similar to Criterion 2, the decision environment could accomodate greater flexibility with respect to construction capability than it could with respect to political acceptability. In other words, some organizational shifts could occur to make the organizational construction capabilities match the construction load imposed by the selected portfolio, but no such organizational changes could mitigate geographical imbalances in irrigation construction funding from a political standpoint. Therefore, it was expected that Criterion 3 would be more difficult to satisfy than Criterion 2.

Although the decision maker indicated during the evaluation that such an interpretation was correct, the portfolio derived in the test application (Table 7-4) was felt to be politically acceptable without modification. However, as discussed under Criterion 2, this does not mean that all portfolios selected with the assistance of the decision support system will perform well with respect to Criterion 3 without consideration of decision space information. Therefore, the discussion under Criterion 2 of the value of the addition on decision space information to the decision-aiding output display applys equally well to Criterion 3.

Criterion 4 - Cost of Data Collection Activities

Criteria 4, 5 and 6 concern the cost of the decision support system from the standpoint of the using organization. The cost data necessary to evaluate the decision support system in terms of these three criteria comprise the total cost of the decision support system.

The first component of decision support system cost involves an estimation of the costs to be incurred in the collection of input data. As discussed earlier, the cost of the input data contained in Appendix F was negligible since these data were based entirely on secondary data sources. However, to be fully effective, implementation of the decision support system would require an extensive data collection effort as described in Chapter 6. That data collection plan involves improving long-term development plans maintained on some divisions and developing such plans for those divisions that lack them.

Derivation of an accurate cost estimate to carry out the data collection plan is difficult since adequate planning documents exist on some divisions whereas others require major improvements, and still others do not exist at all. In general, the quality of existing planning documentation is directly related to division size. Some of the larger divisions, such as the Colorado River Irrigation Project, have well-conceived and comprehensive planning reports, whereas almost all of the small subsistence divisions, such as the New Mexico pueblo units or the southern California rancheria units, have no planning documentation at all.

Discussions with Bureau irrigation officials led to the use of \$5,000 as an average cost per division to develop the information described in Chapter 5. Based on the assumption that 300 divisions need at least some planning improvement, the data collection effort was estimated to cost \$1.5 million.

It is felt that all of this cost should not be attributable to the implementation of the decision support system since improvements to the long-term development plans described in Chapter 6 would be very useful to effective program management even in the absence of the decision support system. However, in order to provide a conservative cost estimate of decision support system implementation, the \$1.5 million estimate was used. It should also be pointed out that the \$1.5 million figure is a one-time cost. Maintenance of the long-term development plans on a year-to-year basis, after the improvements described in Chapter 6 have been completed, could be provided at a very modest cost. The \$1.5 million data collection cost figure was used as a part of an overall benefit-cost evaluation of the decision support system, which is described later in this chapter.

Criterion 5 - Cost of Computer Support

The cost of computer support associated with decision support system use will depend on a number of variables such as the number of iterations the decision maker needs to identify the most preferred solution, the number of project candidates that are used as input, the number of constraints the decision maker specifies in his interactions with the decision support system, hardware configurations used, and the processing class used to conduct the optimizations. In addition, it is likely that the efficiency obtained from the MPSX algorithm could be improved with additional work. Despite these variables, however, the test application demonstrated that the costs of computer support are very small. Total computer costs of the test application as displayed in Table 7-6 were $375.13.

Criterion 6 - Time of Decision Maker Required

The third component of decision support system cost from the standpoint of the using organization is decision maker time required. During the development and test application of the decision support system, the Chief Irrigation Engineer and other members of the using organization devoted extensive amounts of time to the new decision-aiding tool. These investments can be considered as initial fixed costs which will not be repeated in future use of the decision support system. Decision maker time requirements in actual decision support system use can be estimated more properly by using decision involvement times during the test application. Total decision maker time spent in studying output displays and interacting with the analyst during the test application described in the preceding chapter totaled approximately three hours. These time requirements could increase in future applications if more iterations are required to identify the most preferred solutions or if the decision process is conducted at more than one budget constraint level (in most appropriations cycles, portfolios are developed at each of five budget levels). On the other hand, it is expected that the decision maker will be able to express his preferences with greater efficiency as he becomes more familiar with the procedures, which could tend to reduce decision maker time requirements.

In any case, decision maker time requirements do not seem to constitute a significant cost of decision support system implementation. It is clear that time spent by the decisionmaker in using the decision support system to make portfolio selections is less than the average time spent in making such selections using the narrative justification approach described in Chapter 2. Therefore, since the decision support system seems to result in a net savings of decision maker time at the decision point, decision maker time costs attributable to decision support system use were estimated to be zero.

Criterion 7 - Compatibility with Available Data

Discussions with BIA irrigation officials indicated that the input data requirements of the decision support system were not a barrier to implementation. The real consideration concerning data was not availability, but rather the cost of data acquisition. As discussed in the preceding chapter, all input data needed to fully implement the decision support system was not available in secondary form. However, it was felt that all data requirements described in Chapter 6 could be met with a high degree of validity if a sufficient amount of resources were devoted to the collection of such data. Estimated costs of this data collection effort are included in the discussion of Criterion 4.

Criterion 8 - Compatibility with Using Organization Expertise

Technical staff members of the Division of Water and Land Resources of the BIA that reviewed the decision support system agreed that future use was well within the technical capability of the existing staff without requirements for the procurement of external expertise.
As noted in the next chapter, opportunities do exist to make the decision support system more "user friendly." However, the decision support system is relatively simple to use in its present state of development with a minimal amount of documentation. This finding is consistent with the finding of Dyer (1973b, p. 213) that some interactive procedures do not seem to be inhibited by the need for extensive training or the continuous availablity of external expertise.

Criterion 9 - Compatibility with Decision Maker's Decision Style

As discussed in the preceding chapter, the decision support system seemed to be fully compatible with the cognitive decision style of the decision maker during the test application. As both an engineer and an experienced manager, the Chief Irrigation Engineer was comfortable with analytic models and exhibited no significant problems in using the decision support system. Of course, since future decision makers may not exhibit identical characterictics, it is important that the decision support system be compatible with a wide range of decision styles. It is expected that the combination of both graphical and tabular output formats incorporated into the decision-aiding output displays makes the decision support system also compatible with decision makers exhibiting more purely heuristic decision styles.

Discussion

Evaluation of the decision support system revealed that it performed well on all three measures of effectiveness, efficiency and acceptability. The test for effectiveness demonstrated conclusively that the decision support system can improve dramatically the quality of decision making by increasing the level of contributions to program objectives within existing budgetary constraints. Using actual total program expenditures for the past five years as a budget constraint, the decision support system produced an initial portfolio that dominated actual project selections made during the FY 1979-1983 time frame on all objectives, and which provided a more equitable distribution of funding among regions. This result is viewed as a lower bound on the effectiveness of the decision support system since incorporation of the decision maker's preferences would lead to an even more attractive portfolio.

The tests for efficiency revealed that the only significant costs of the decision support system were for full implementation of the data collection plan. Although all benefits of the decision support system cannot be captured in commensurable terms for direct comparison with the costs, a reasonable lower bound on monetary benefits was obtained by finding the lowest cost portfolio that produced at least as great a contribution for each program objective as did the actual portfolio (Tables 8-1 and 8-2) and subtracting the cost of that portfolio from actual expenditures to yield cost savings potential.

Table 8-5 presents a display of actual and least cost portfolio outputs in both the objective space and the decision space for comparison

Table 8-5

Comparison of Actual Project Selections (FY 1979-1983)
and Least Cost Nondominated Solution

Objective Space

Objective	Actual portfolio	Least cost portfolio	Per cent increase (decrease)
1	117,484	132,388	12.7
2	3,525	3,885	10.2
3	769	812	5.6
4	2,353	2,355	0.1
5	1,931	1,937	0.3
6	17,917	17,967	2.8
7	7,590	8,120	7.0
8	10,647	10,649	0.0
9	417	466	11.8
10	14,850	15,576	4.9
11	594,550	594,609	0.0
Cost	$328,002,000	$237,827,000	(27.5)

Decision Space

	Actual selections		Least cost solution	
Area	Projects	$(millions)	Projects	$(millions)
Albuquerque	12	$15.599	14	$ 7.314
Billings	9	14.190	12	18.937
Navajo	0	0.000	1	0.807
Phoenix	27	207.593	22	173.033
Portland	4	88.008	4	24.051
Sacramento	7	2.612	21	13.685
Total	59	$328.002	74	$237.827

purposes. It can be seen that the decision support system-aided portfolio again dominated the actual portfolio on all objectives, but instead of seeking to maximize contributions to all objectives, this time the minimal cost was sought, subject to 11 constraints representing the objective attainment levels of the actual portfolio. The result is a cost savings of $90.175 million. Table 8-5 also demonstrates that the least cost portfolio provides an improved distribution of funding in the decision space. Thus, this test identified a portfolio that contains improvements over the portfolio actually selected in both the objective space and the decision space at a cost savings of $90.175 million.

If the cost savings figure were taken as a measure of benefits and the costs identified under Criteria 4, 5 and 6 were used as costs of the decision support system, then a benefit-cost ratio of $90.175/$1.500 = 60.1 would result. It is emphasized, however, that such an analysis should be viewed as a very conservative indication of decision support system worth. The benefits are understated since the portfolio used to calculate the benefit-cost ratio did not incorporate preferences of the decision maker. Full implementation of the decision support system as demonstrated in Chapter 7 would yield an improved portfolio at any budget constraint. Also, the costs attributed to the decision support system in the above analysis stem from implementation of the data collection system, an effort which is recommended for the irrigation construction program of the Bureau of Indian Affairs even in the absence of the monetary benefits of the decision support system. Since many ancillary benefits in the form of improved program management and control would accrue to the agency from implementation of the data collection plan, all costs of such implementation should not be attributed to the decision support system. Finally, non-quantifiable benefits, such as improved decision making objectivity and consistency, improved construction continuity, and enhanced communications with constituents and program reviewers at Departmental, OMB and Congressional levels, are not included in the benefit estimates used above, despite the fact that they are real to the using agency.

Evaluation of the decision support system with respect to acceptability yielded the findings that it has a satisfactory level of compatibility with the existing expertise of the using agency, the cognitive decision style of the decision maker and, given the prescribed level of resources, available input data. The test application also resulted in the identification of a preferred portfolio that was determined to be both compatible with the existing construction capabilities of the using organization and politically feasible. Although these last two findings were based on the portfolio produced in the test application rather than on an evaluation of the decision support system itself, a procedure was identified by which future portfolios could be tested for feasibility, using decision space information, according to these two criteria and adjusted if necessary.

In summary, the decision support system and the water project portfolio developed in the test application performed at satisfactory levels on all nine evaluation criteria.

Chapter 9

SUMMARY

This study has extended recent work in multiobjective decision theory to an important class of decision problems that has heretofore been ignored. This class of problems is characterized by the need to select a preferred portfolio of projects from a finite, but very large, set of discrete feasible solutions. Throughout the study, emphasis was placed on demonstration of the value of multiobjective methods in actual decision making situations. To accomplish this, a real decision problem was identified and used as a vehicle within which a large portion of the study was carried out. This decision making environment provided a context within which the newly developed decision support system was evaluated and which enabled successful use of the decision support system to be demonstrated.

An overview of the study is presented in this chapter by summarizing the research methodology used, describing results obtained, drawing conclusions and making recommendations for future research.

Research Methodology

The procedure used in the study guided the research effort along a logical course from inception to conclusion. The following major steps were followed:

1. Examination of Problem. A thorough understanding of the problem

addressed by the study was gained by undertaking an intensive examination of it. Thirty-six federal water resources programs were examined to determine the extent to which the type of decision problem under consideration existed in federal water planning agencies. This survey made use of interviews of agency officials and reviews of pertinent documents for each of the 36 programs to make these determinations. It resulted in the identification of three federal water resources development programs containing substantially identical multiobjective decision problems. The irrigation program of the Bureau of Indian Affairs was chosen from these three programs as the focal point for the study, after which an in-depth examination of that program was conducted. This involved further interviews of agency officials and scrutiny of budget documents, files, reports, pertinent statutes and regulations, and other relevant documents. Finally, an investigation into the recent history of federal water resources planning was undertaken to determine the reasons why multiobjective decision-aiding methodologies had not been used previously to assist with this program.

2. Literature review. A comprehensive review of research in multiobjective decision-aiding methods was conducted to gain an understanding of the state of the art and to provide a basis from which to extend previous work in this area.

3. Development of model selection paradigm. A new paradigm for identifying the multiobjective decision-aiding technique that can be applied most advantageously to a given multiobjective decision problem

was developed. The procedure results in a match of decision situation characteristics with the capabilities of the most appropriate multi-objective decision-aiding technique available. Application of the paradigm to the problem under study revealed that no existing method was perfectly compatible with its decision situation characteristics, but that the interactive approach was the most responsive to the problem. In addition, use of the paradigm led to the recognition that certain features of several previously developed methods could be adapted into a new algorithm tailored to fit the decision problem.

4. Development of decision-aiding algorithm. A new interactive multiobjective decision-aiding algorithm based on zero-one integer programming was developed to respond to the requirements of the decision problem.

5. Development of decision support system. Ancillary components necessary to convert the newly developed decision-aiding algorithm into a usable decision support system were developed. These components consisted of an operational objectives set, computer software, input data set, and implementation plan.

6. Decision support system implementation. A test application of the new decision support system was undertaken using actual agency data, computing facilities, and decision maker.

7. Decision support system evaluation. The decision support system was evaluated using the nine original research design specifi-

cations as evaluation criteria.

Results

Major contributions of this study to the existing body of knowledge may be summarized by five statements:

1. A new survey of multiobjective decision-aiding methods useful in water resources planning, design and management was developed. This survey is more up-to-date and comprehensive that any other existing survey. In addition, the results of the survey have been presented in the framework of a new taxonomy that promotes an understanding of relationships among multiobjective methods and the conditions under which each may used most advantageously.
2. A new multiobjective decision-aiding model selection paradigm was developed and demonstrated.
3. A new multiobjective decision-aiding algorithm was developed for deterministic decision problems in which the decision variables exhibit binary characteristics and in which optimal portfolios from finite sets of feasible candidates are sought.
4. A new procedure for the identification of an operational set of objectives using group idea generation and structuring processes was developed and demonstrated.
5. A major demonstration of the successful application of a multiobjective decision-aiding method to solve an actual problem in water resources planning was provided by building

a fully developed decision support system around a theoretically valid multiobjective algorithm and applying it to a real decision problem of high complexity.

A number of less significant accomplishments were also achieved in the course of study. These included a survey of all major federal water resources programs to identify existing problems of the class under consideration, an investigation into the reasons why recent advances in multiobjective decision-aiding techniques had not been used previously to assist with such problems, development of the software necessary to implement the new interactive algorithm, collection of data necessary to undertake trial implementation of the decision support system, development of a data collection plan to increase the effectiveness of the decision support system, examination of barriers to the effective implementation of the multiobjective decision support system, and development of a useful evaluation framework for multiobjective decision-aiding methods, including the establishment of evaluation criteria.

Conclusions

The most significant conclusion of the study is that use of the decision support system developed in the research effort can improve dramatically the effectiveness and efficiency of water project portfolio decision making in the irrigation construction program of the Bureau of Indian Affairs. The evaluation conducted in Chapter 8 demonstrated that the decision support system performed well on all nine evaluation criteria during a realistic test application. A conservative benefit-cost analysis yielded a benefit/cost ratio of 60.1 to one. A more general conclusion that may be drawn from these results is that multiobjective decision-aiding methods in general can produce useful results under real decision situation constraints if properly designed to fit the circumstances of the decision problem. Experience gained in this study has led the author to the belief that the opposite approach, modification of the decision problem to fit the capabilities of a fixed solution methodology, is much more common and also much more likely to fail.

A number of less significant conclusions derived from the study warrant mention:

1. Lack of coverage by federal planning guidelines has caused at least three important federal water project decision problems to be bypassed by recent rapid growth in the development and use of multiobjective decision-aiding methods.
2. The taxonomy developed in Chapter 4 is a useful tool to promote understanding of the many multiobjective solution methods that have been developed in the last 10 years and the relationships among them.
3. The model selection paradigm described in Chapter 5 can be used effectively to avoid mismatches between multiobjective decision problems and solution methodologies.
4. For multiobjective decision problems characterized by the attributes described in Chapter 5, the interactive approach seems to be the most appropriate.
5. The use of group idea generation and structuring techniques

can be effective aids to the specification of operational objective sets when strong human resources are available.

6. The objectives of the irrigation program of the Bureau of Indian Affairs are as described in Chapter 6.
7. Data collection at the separable division level seems to be the most appropriate level of aggregation to support water project portfolio decisions in the irrigation program of the Bureau of Indian Affairs.
8. Consideration of potential barriers related to the decision problem, client organization, and decision maker can enhance prospects for successful implementation of a multiobjective decision support system.

Recommendations

Nine promising directions for future research are recommended to increase the effectiveness and efficiency of the decision support system developed in this study and to extend it into other areas.

1. Pertubation of optimal solution. Brill, et al. (1982) and Schilling, et al. (1982) pointed out that decision makers may often consider objectives that are not modeled by multiobjective decision-aiding methods. Brill, et al. (1982) suggested that, in cases where such an occurrence is suspected, several alternatives that are "near optimal" in the objective space be generated for the decision maker's consideration. These authors found that different solutions that are near optimal in the objective space are frequently substantially different in the

decision space. Therefore, the opportunity to choose from a small set of such near optimal solutions could allow the decision maker to include non-modeled objectives in his decision without detracting significantly from the modeled objectives.

It was noted in Chapter 7 that the decision maker did request decision space information during the trial application. The reason advanced for this was that he perceived a need to consider ill-defined constraints of equity and political feasibility. In the test application, the decision space information revealed that the decision maker's equity and political feasibility constraints were not violated at the preferred solution. However, it was noted in the discussion under evaluation criteria 2 and 3 in Chapter 8 that such non-modeled objectives might be significant considerations in future applications. Thus, an important area for additional research concerns the manner in which non-modeled considerations are included in the decision support system in cases where such considerations make the solution that is identified with the assistance of the decision support system unacceptable to the decision maker. One approach, after Brill, <u>et al.</u> (1982), might be to generate other near optimal solutions in such cases using:

$$\max \sum_{i=1}^{m} x_i \qquad (9\text{-}1)$$

subject to

$$\sum_{i=1}^{m} a_{ij} x_i \geq f_j^{\dagger}(\underline{x}) - \Delta f_j \qquad \forall\, j \qquad (9\text{-}2)$$

$$\sum_{i=1}^{m} c_i x_i \leq b \qquad (9\text{-}3)$$

$$x_i = 0,\, 1 \qquad \forall\, i \; . \qquad (9\text{-}4)$$

Such an approach represents an attempt to find the greatest number of projects to include in the preferred portfolio (to satisfy equity or political acceptability concerns) while not deviating further than $\Delta \underline{f}$ from the original preferred solution $\underline{f}^{\dagger}(\underline{x})$.

2. Improvement of cognitive aids. Since the decision-aiding display illustrated and discussed in Chapters 6, 7 and 8 is the critical link between the decision support system and the decision maker, improvement of the effectiveness of this device in assisting the cognition of the decision maker is an important area for additional research. The use of state of the art computer graphics to strengthen this link could improve the effectiveness of the decision support system.

3. Simplification of decision support system operation. Although the decision support system was found to be within the operational capability of the using agency in its present state of development, there remains substantial room for improving its "user friendliness." Improvement of the decision support system in this regard could improve its acceptability to other using organizations.

4 Improved computational efficiency. Computational experience with the decision support system reported in Chapter 7 was based on use of the MPSX 370 package on an Amdahl V7 computer. Opportunities exist to increase the computational efficiency of the algorithm without changing the existing configuration. For example, since the programs developed to implement the decision support system cause the MPSX routine to restart the optimization process at each iteration, computational

efficiency could be improved by using the last solution at each iteration as the initial basic solution for the subsequent iteration. In addition, it is likely that other zero-one integer programming packages exist which could carry out the required optimizations in a more efficient manner.

5. Improved input data set. A plan to collect all primary field data necessary to fully implement the decision support system for the irrigation program of the Bureau of Indian Affairs was described in Chapter 6. Implementation of that plan is important to future successful use of the decision support system in the BIA irrigation program.

6. A posteriori evaluation/validation. The most rigorous evaluation of the decision support system would require determination of actual impacts of projects constructed as a result of decision support system implementation and comparison with those reflected in the input data set. Such an approach constitutes the first approach of Gallagher (1974). Although an a posteriori evaluation was not feasible within the constraints of this study, as explained in the preceding chapter, it does provide an interesting and important subject area for future research.

7. Incorporation of risk and uncertainty. The decision support system developed in this study is deterministic in nature. However, the problem addressed by the decision support system involves risk and uncertainty from a variety of sources. The main sources of risk are hydrologic phenomena, such as rainfall, runoff, river flows, floods, and droughts, which exhibit stochastic characteristics. Uncertainties arise from measurement errors, future demographic and economic events,

and the variable nature of social systems for which there are no known probability distributions.

The design of any model involves a trade-off between adequate representation of reality and excessive complexity. The fact that the decision support system described herein is a deterministic model represents a significant simplification of reality. Consideration of risks and uncertainties associated with the impacts of construction of each project candidate on each objective and with estimated initial and long-term costs of each project candidate could improve the accuracy of the model. In addition, recognition of the temporal nature of such benefits and costs (e.g., changes in Indian versus non-Indian land ownership patterns or changes in Indian alternative job opportunities) in the decision support system could make the model more realistic. However, a determination of whether or not such changes would improve the decision support system, in the sense that it would result in improved decision making, would require additional study. At this juncture, the incorporation of risk and uncertainty into the decision support system appears to be a promising area for future research.

8. Assurance of veridical perceptions. As mentioned in Chapter 4, the use of pairwise comparisons can lead to intransitive decision maker behavior if the potential effects of cognitive bias surveyed by Sage (1981) are not fully considered in decision support system design. Although many of the problems with intransitive behavior do not arise in use of the decision support system developed in this

study, as discussed in Chapter 5, the need to insure consistent anchoring in order to provide veridical perceptions of portfolio impacts to the decision maker at each iteration of the decision support system is an important area for further study.

9. Decision support system generalization. As discussed in Chapter 2, the decision support system developed in this study appears to be applicable to at least two other federal water project construction programs. In addition, the probability of existence of other decision problems with characteristics similar to the problem investigated herein is high. Therefore, opportunities exist to extend these advances well beyond the scope of the application context used in this study.

APPENDIX A

Overview of Multiobjective Decision-Aiding Studies in Water Resources

This Appendix contains a summary of the categories into which multiobjective decision-aiding methods for water resources planning, design and management were placed in each of seven surveys of such methods. All of the works cited by the Deason (1983) survey are discussed in Chapter 4. Symbols used in the tables of this appendix are defined in Table 4-2.

Cohon 1973	Cohon and Marks 1975	Haimes *et al.* 1975	Bishop *et al.* 1976	Cohon 1978	Mades and Tauxe 1980	Deason 1983	
						B4	Andrews, Madsen & Hardin, 1979
					A	Al	Andrews & Wyrick, 1973
			D			E2	Bishop, 1972
					B	C2	Bishop, *et al.*, 1977
				B3a		Al	Brill, Liebman & ReVelle, 1976
						Bl	Brown & Valenti, 1983
					A	Al E2	Byers & Miller, 1975
						C2	Can, Houck & Toebes, 1982
						A5	Cohon, Church & Sheer, 1979
						B3	Crews & Johnson, 1975
					C	Al D4	Croley, 1974
						Al	Croley & Rao, 1974
					A	Al C5	Das & Haimes, 1979
				A		C3	David & Duckstein, 1976
			C			Bl	Dee, *et al.*, 1972

Cohon 1973	Cohon and Marks 1975	Haimes *et al.* 1975	Bishop *et al.* 1976	Cohon 1978	Mades and Tauxe 1980	Deason 1983	
						B2	Dean & Shih, 1973/75
						B1	Dee, *et al.*, 1973
A1a B2b				B3c		A2 B1	Dorfman & Jacoby, 1970
						C4	Duckstein & Opricovic, 1980
						E1	Duke, *et al.*, 1972
A2b	B3					B1	Freeman, 1969
						E1	Freeman & Haveman, 1970
						C2	Gembicki & Haimes, 1975
						C3	Gershon, *et al.*, 1982
					A	D3	Goicoechea, Duckstein & Fogel, 1976/79
						B4	Gum, Roefs & Kimball, 1976
				B2d		A1 C5	Haimes, 1977
						C5	Haimes, 1980
					A	A1 C5 B4	Haimes, Das & Sung, 1977/79
A2d	B5		E5	B2d	C	A1 C5	Haimes & Hall, 1974
					B	A1 C5	Haimes & Hall, 1975

Cohon 1973	Cohon and Marks 1975	Haimes *et al.* 1975	Bishop *et al.* 1976	Cohon 1978	Mades and Tauxe 1980	Deason 1983	
			E3	B2d	A B	A1 C1 C5	Haimes, Hall & Freeman, 1975
						C5	Haimes, *et al.*, 1980
					A	C5	Haimes & Olenik, 1978
						A1 A2 B2 C1 C2 D1 D4 E1	Haith & Loucks, 1973
						C6	Hall, 1980
A2b						B1	Haveman, 1965
						B2	Keeney & Wood, 1973
					A	C5	Keith, *et al.*, 1977
			C			E1	Leopold, *et al.*,1971
					B	A1 C5	Lindsay, 1978
						C2	Lohani & Adulbhan, 1979
					A	D1	Loucks, 1976/78
				B2e	A	D1	Loucks, 1977
						A1 C5	Loucks, Stedinger & Haith, 1981
						A1	Louie, Yeh & Hsu, 1982

Cohon 1973	Cohon and Marks 1975	Haimes *et al.* 1975	Bishop *et al.* 1976	Cohon 1978	Mades and Tauxe 1980	Deason 1983	
					A B C	A3	Mades & Tauxe, 1980
	B3	D	E2	B1a B2b	A	B1	Major, 1969
						A2	Major, 1973
					A	B2	Major, 1974
					A	A1	Major, Cohon & Frydl, 1974
						A1 A2 E1 E2	Major & Lenton, 1979
	A1 A2				A	A1 B1	Marglin, 1966
A1a A1b	A1 A2			B1a B1b B2b		A1 A2 B1	Marglin, 1967
	A2	E	E3		A	A1 E2	Miller & Byers, 1973
					B	A1	Miller & Erickson, 1975
B1c						D2	Monarchi, 1972
	C		G	B2e	B	D2	Monarchi, Kisiel & Duckstein, 1973
						B3	Moreau, 1981
						E1	Morisawa & Vemuri, 1975
						E3	Murray, *et al.*, 1971

Cohon 1973	Cohon and Marks 1975	Haimes *et al.* 1975	Bishop *et al.* 1976	Cohon 1978	Mades and Tauxe 1980	Deason 1983	
						D5	Musselman & Talavage, 79
						D5	Musselman & Talavage, 80
						C2	Neely, North & Fortson, 1976
					B	C2	Neely, North & Fortson, 1977
					C	C6	Neuman & Krszyztofowicz, 1977
				A		C3	Nijkamp & Voss, 1977
					A	B1 E1 E2	O'Riordan, 1972/73
					C	A2	Passey, 1978
						A2	Reid, 1971
						B2	Reid & Leung, 1978
Ale	A3				A	A2	Reid & Vemuri, 1971
				B3c		A1	Rogers, 1969
					A		Schwarz & Major, 1971
						E1	Schwarz, *et al.*, 1975
						B1	Seader, 1975
						B1	Seaver, *et al.*, 1979
						C2	Sellers & North, 1979
						B2	Sinden, 1974
			A				Steinetz, 1971

Cohon 1973	Cohon and Marks 1975	Haimes *et al.* 1975	Bishop *et al.* 1976	Cohon 1978	Mades and Tauxe 1980	Deason 1983	
						D4	Takama & Loucks, 1981
						A3	Tauxe, Inman & & Mades, 1979a/79b
			F G			B4	Technical Comm, 1971
						B4	Technical Comm, 1974
						A2 C1	Thampapillai & Sinden, 1979
			C			B1 E1	Tulsa District, 1972
A1a A2b	A1 A2		E2	B2b			United Nations Ind Dev Org, 1972
	A3		E2		C	A2	Vemuri, 1974
						E1	U.N. Economic Comm, 1972
			D			E1	U.S. Water Res Coun, 1973
						B1	U.S. Interior Dept, 1978

APPENDIX B

Multiobjective Decision-Aiding Technique Screening Templates

This Appendix contains a set of 15 templates that are used in Step 5 of the multiobjective decision-aiding technique selection procedure developed in Chapter 5. Each template corresponds to a decision situation descriptor which characterizes some aspect of a multiobjective decision situation. The set of templates corresponding to a set of descriptors properly describing a multiobjective decision situation is used to screen a set of multiobjective decision-aiding techniques available to the analyst.

Decision Situation Descriptor A: Finite Set of Discrete Alternatives

Techniques Eliminated

Nondominated Solution Gen Tech
- ~~Constraint Method~~ (1)
- ~~Weighting Method~~ (1)
- ~~Multiobjective Dyn Prog~~ (1)
- ~~Multiobjective Simplex~~ (1)
- ~~Noninferior Set Est~~ (1)

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- Electre Method
- Compromise Programming
- ~~Surrogate Worth Trade-Off~~ (2)
- ~~Interactive Lagrange Mult~~ (3)

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- Pairwise Comparisons
- Tradeoff Cutting Plane
- ~~Method of Geoffrion~~ (3)
- ~~Method of Zionts-Wallenius~~ (3)

Visual Attribute Displays
- Objective Achievement Matrices
- Graphical Displays
- Mapping

Notes

(1) These methods are based on the assumption that the decision variables are continuous. In problems with discrete alternatives the decision variables are not continuous. A simple check for dominance would be used to derive the nondominated set from the set of all alternatives.

(2) Calculation of Lagrange multipliers is not relevant to discrete problems. Keith, *et al.* (1977) also found that the method fails where the preference structure of the decision maker is not continuous.

(3) Not applicable to problems not containing continuously differentiable variables.

Decision Situation Descriptor B: Continuous Alternatives

Techniques Eliminated

Nondominated Solution Gen Tech
- Constraint Method
- Weighting Method
- Multiobjective Dynamic Prog
- Multiobjective Simplex
- Noninferior Set Estimation

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- ~~Lexicographic Approach~~ (1)
- Goal Programming
- ~~Electre Method~~ (2)
- Compromise Programming
- Surrogate Worth Trade-Off
- Interactive Lagrange Multiplier

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- Pairwise Comparisons
- Tradeoff Cutting Plane
- Method of Geoffrion
- Method of Zionts-Wallenius

Visual Attribute Displays
- ~~Objective Achievement Matrices~~ (3)
- ~~Graphical Displays~~ (3)
- ~~Mapping~~ (3)

Notes

(1) Involves the comparison within a set of discrete alternatives to find a ranking according to a fixed set of rules. Cannot be applied to a problem with continuous alternatives.

(2) The Electre method involves a pairwise comparison of alternatives to establish stronger partial orderings. This could be used for continuous problems only by arbitrarily selecting points within the feasible range of each decision variable to convert the continuous problem into a discrete one.

(3) Display of an infinite set of alternatives to aid the cognition of the decision maker is not feasible.

(1, 2, and 3) If continuous problems can be converted into discrete approximations, then this template does not apply.

Decision Situation Descriptor C: Ordinal Attributes

<u>Techniques Eliminated</u>

Nondominated Solution Gen Tech
~~Constraint Method~~ (1)
~~Weighting Method~~ (1)
~~Multiobjective Dyn Prog~~ (1)
~~Multiobjective Simplex~~ (1)
~~Noninferior Set Est~~ (1)

A Priori Complete Elicitation
~~Optimal Weights~~ (2)
~~Utility Theory~~ (2)
~~Policy Capture~~ (2)
~~Techcom Method~~ (2)

A Priori Partial Elicitation
Lexicographic Approach
~~Goal Programming~~ (3)
~~Electre Method~~ (5)
~~Compromise Programming~~ (3)
~~Surrogate Worth Trade-Off~~ (1)
~~Interactive Lagrange Mlt~~ (1)

Progressive Elicitation
~~Step Method~~ (3)
~~Semops Method~~ (4)
~~Trade Method~~ (3)
~~Pairwise Comparisons~~ (1)
~~Tradeoff Cutting Plane~~ (1)
~~Method of Geoffrion~~ (1)
~~Method of Zionts-Wallenius~~ (1)

Visual Attribute Displays
Objective Achievement Matrices
Graphical Displays
Mapping

<u>Notes</u>

(1) Not applicable in the absence of a mathematically defined function over each objective.

(2) Not applicable in the absence of knowledge of locations of each alternative on cardinal scales over each objective.

(3) Not applicable in the absence of knowledge of distance from "ideal solution" over each objective.

(4) Not applicable in the absence of knowledge of deviations from "aspiration levels" over each objective.

(5) Calculation of the discordance conditions requires cardinal comparisons to be made between pairs of alternatives over each objective.

(2, 3, 4 and 5) If a scaling procedure can be developed to convert ordinal to cardinal relationships, then this template does not apply to these methods.

Decision Situation Descriptor D: Ordinal Ranking of Alternatives

Techniques Eliminated

Nondominated Solution Gen Tech
- ~~Constraint Method~~ (1)
- ~~Weighting Method~~ (1)
- ~~Multiobjective Dyn Prog~~ (1)
- ~~Multiobjective Simplex~~ (1)
- ~~Noninferior Set Est~~ (1)

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- Lexicographic Approach *
- Goal Programming **
- Electre Method
- ~~Compromise Programming~~ (2)
- ~~Surrogate Worth Trade-Off~~ (3)
- ~~Interactive Lagrange Multiplier~~ (3)

Progressive Elicitation
- ~~Step Method~~ (2)
- ~~Semops Method~~ (2)
- ~~Trade Method~~ (2)
- ~~Pairwise Comparisons~~ (2)
- ~~Tradeoff Cutting Plane~~ (2)
- ~~Method of Geoffrion~~ (2)
- ~~Method of Zionts-Wallenius~~ (2)

Visual Attribute Displays
- Objective Achievement Matrices
- Graphical Displays
- Mapping

Notes

(1) Identifies complete noninferior set. Does not rank alternatives within noninferior set.

(2) Only single preferred solution is obtained.

(3) Only solutions within trade-off indifference band are obtained.

* Normally used to select single preferred solution, but can be modified to obtain ordinal ranking of alternatives.

** Normally used to select single preferred solution, but can be modified to obtain cardinal ranking of alternatives.

Decision Situation Descriptor E: Cardinal Ranking of Alternatives

Techniques Eliminated

Nondominated Solution Gen Tech
- ~~Constraint Method~~ (1)
- ~~Weighting Method~~ (1)
- ~~Multiobjective Dynamic Prog~~ (1)
- ~~Multiobjective Simplex~~ (1)
- ~~Noninferior Set Est~~ (1)

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- ~~Lexicographic Approach~~ (2)
- Goal Programming *
- ~~Electre Method~~ (2)
- ~~Compromise Programming~~ (3)
- ~~Surrogate Worth Trade-Off~~ (4)
- ~~Interactive Lagrange Multiplier~~ (4)

Progressive Elicitation
- ~~Step Method~~ (3)
- ~~Semops Method~~ (3)
- ~~Trade Method~~ (3)
- ~~Pairwise Comparisons~~ (3)
- ~~Tradeoff Cutting Plane~~ (3)
- ~~Method of Geoffrion~~ (3)
- ~~Method of Zionts-Wallenius~~ (3)

Visual Attribute Displays
- ~~Objective Achievement Matrices~~ (5)
- ~~Graphical Displays~~ (5)
- ~~Mapping~~ (5)

Notes

(1) Identifies complete noninferior set. Does not rank alternatives within noninferior set.

(2) Normally used to select single preferred solution, but can be modified to obtain ordinal ranking of alternatives.

(3) Only single preferred solution is obtained.

(4) Only solutions within trade-off indifference band are obtained.

(5) Contain no mechanism for establishing cardinal values over set of objectives.

* Normally used to select single preferred solution, but can be modified to obtain cardinal ranking of alternatives.

Decision Situation Descriptor F: Portfolio of Discrete Alternatives Sought

Techniques Eliminated

Nondominated Solution Gen Tech
- ~~Constraint Method~~ (1)
- ~~Weighting Method~~ (1)
- ~~Multiobjective Dyn Prog~~(1)
- M~~ultiobjective Simplex~~ (1)
- ~~Noninferior Set Est~~ (1)

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- ~~Electre Method~~ (2)
- ~~Compromise Programming~~ (3)
- ~~Surrogate Worth Trade-Off~~ (4)
- ~~Interactive Lagrange Mult~~ (4)

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- Pairwise Comparisons
- ~~Tradeoff Cutting Plane~~ (6)
- ~~Mhod of Geoffrion~~ (7)
- ~~Method of Zionts-Wallenius~~ (7)

Visual Attribute Displays
- ~~Objective Ach Matrices~~ (5)
- ~~Graphical Displays~~ (5)
- Mapping

Notes

(1) Since problems seeking an optimal portfolio of alternatives involve a finite (although possibly large) set of discrete alternatives, a simple check for dominance is all that is required to obtain the noninferior set.

(2) Since a portfolio selection problem could involve a very large number of noninferior feasible portfolio combinations, the calculation of concordance and discordance conditions for all possible pairs of portfolios would be computationally intractible for even a moderate number of alternatives.

(3) Since a portfolio selection problem could involve many noninferior feasible portfolio combinations, the construction of a "system versus criteria array" would be computationally intractible for even a moderate number of alternatives.

(4) Problems seeking an optimal portfolio of alternatives involve a set of discrete alternatives, and calculation of the Lagrange multipliers is not relevant to discrete problems.

(5) These methods are appropriate only for problems with a relatively small number of alternatives. Since a portfolio selection problem could involve a large number of noninferior feasible portfolio combinations, these methods are not suitable for such problems.

Notes

(6) Although applicable to problems with discrete solutions, problems with very large numbers of discrete feasible solutions would cause computational intractibility.

(7) Not applicable to problems not containing continuously differentiable variables.

Decision Situation Descriptor G: One-Time Decision Problem

Techniques Eliminated	Notes
Nondominated Solution Gen Tech	
Constraint Method	(1) Elicitation of the complete preference structure of the decision maker may be largely wasted for a one-time decision. Much effort may be devoted to the determination of preferences for attributes that vary little over the set of noninferior solutions and which do not play a significant role in the decision.
Weighting Method	
Multiobjective Dynamic Prog	
Multiobjective Simplex	
Noninferior Set Estimation	
A Priori Complete Elicitation	
Optimal Weights	
~~Utility Theory~~ (1)	
Policy Capture	
Techcom Method	
A Priori Partial Elicitation	
Lexicographic Approach	
Goal Programming	
Electre Method	
Compromise Programming	
Surrogate Worth Trade-Off	
Interactive Lagrange Multiplier	
Progressive Elicitation	
Step Method	
Semops Method	
Trade Method	
Pairwise Comparisons	
Tradeoff Cutting Plane	
Method of Geoffrion	
Method of Zionts-Wallenius	
Visual Attribute Displays	
Objective Achievement Matrices	
Graphical Displays	
Mapping	

Decision Situation Descriptor H: Multi-Stage Decision Problem with Changing Preferences

Techniques Eliminated

Nondominated Solution Gen Tech
- Constraint Method
- Weighting Method
- Multiobjective Dynamic Prog
- Multiobjective Simplex
- Noninferior Set Estimation

A Priori Complete Elicitation
- Optimal Weights
- ~~Utility Theory~~ (1)
- ~~Policy Capture~~ (1)
- ~~Techcom Method~~ (1)

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- Electre Method
- Compromise Programming
- ~~Surrogate Worth Trade-Off~~ (1)
- ~~Interactive Lagrange Multiplier~~ (1)

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- Pairwise Comparisons
- Tradeoff Cutting Plane
- Method of Geoffrion
- Method of Zionts-Wallenius

Visual Attribute Displays
- Objective Achievement Matrices
- Graphical Displays
- Mapping

Notes

(1) In a multiple stage decision problem with changing decision maker preferences, the a priori preference elicitation techniques could be applied to a series of single stage decision problems. However, this would require the assessment of the preferences of the decision maker at each stage, which would be a burdensome task for the more decision maker-intensive methods.

Decision Situation Descriptor I: Large Number of Objectives, Alternatives, Constraints or Decision Variables

Techniques Eliminated

Nondominated Solution Gen Tech
- ~~Constraint Method~~ (1)
- ~~Weighting Method~~ (1)
- ~~Multiobjective Dyn Prog~~ (1)
- Multiobjective Simplex
- Noninferior Set Estimation

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- ~~Electre Method~~ (2)
- ~~Compromise Programming~~ (3)
- ~~Surrogate Worth Trade-Off~~ (4)
- ~~Interactive Lagrange Ml~~ (4)

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- ~~Pairwise Comparisons~~ (5)
- ~~Tradeoff Cutting Plane~~ (5)
- ~~Method of Geoffrion~~ (5)
- ~~Method of Zionts-Wallenius~~ (5)

Visual Attribute Displays
- ~~Objective Achievement Mat~~ (6)
- ~~Graphical Displays~~ (6)
- Mapping

Notes

(1) The presence of more than three objectives can have severe computational implications.

(2) For problems with a large number of alternatives, calculation of concordance and discordance conditions for all pairs of alternatives would be burdensome.

(3) A large number of alternatives makes the "system versus criteria" array unwieldy. However, it is good for problems with a large number of objectives and a small number of alternatives.

(4) A large number of objectives would require the decision maker to make a large number of judgements concerning trade-offs. This increases the chances for error, introduces stress on the decision maker, may increase intransitive responses, and requires more time from the decision maker.

(5) A large number of objectives or alternatives requires excessive decision maker-analyst interaction time.

(6) Since the objectives achievement matrices and graphical displays do not reduce complexity, a large number of alternatives or objectives greatly reduces the value of these approaches in assisting the cognition of the decision maker.

Decision Situation Descriptor J: Highly Refined Solution Needed

<u>Techniques Eliminated</u>	<u>Notes</u>
Nondominated Solution Gen Tech Constraint Method Weighting Method Multiobjective Dynamic Prog Multiobjective Simplex Noninferior Set Estimation	(1) Methods yield approximations of preferred solutions. Appropriate to situations in which benefits from increased accuracy of solutions do not warrant the increased costs, time and effort required to implement more accurate methods.
A Priori Complete Elicitation Optimal Weights Utility Theory Policy Capture Techcom Method	(2) May lead to somewhat inconsistent results between applications because the order established on the set of alternatives by the method is a function of the threshold value chosen for the discordance condition. If different thresholds are chosen in subsequent applications, the order could be changed significantly.
A Priori Partial Elicitation ~~Lexicographic Appr~~ (1) ~~Goal Programming~~ (1) ~~Electre Method~~ (2) Compromise Programming Surrogate Worth Trade-Off Interactive Lagrange Multiplier	(3) Aids to decision maker cognition may result in solutions that are sub-optimal and which may not be replicated with a high degree of accuracy.
Progressive Elicitation Step Method Semops Method Trade Method Pairwise Comparisons Tradeoff Cutting Plane Method of Geoffrion Method of Zionts-Wallenius	
Visual Attribute Displays ~~Objective Achievement Matrices~~ (3) ~~Graphical Displays~~ (3) ~~Mapping~~ (3)	

Decision Situation Descriptor K: Decision Maker Reluctant to Express Tradeoffs Explicitly

Techniques Eliminated	Notes
Nondominated Solution Gen Tech	(1) Involves explicit specification of decision maker preferences for tradeoffs among objectives.
Constraint Method	
Weighting Method	
Multiobjective Dynamic Prog	
Multiobjective Simplex	
Noninferior Set Estimation	
A Priori Complete Elicitation	
~~Optimal Weights~~ (1)	
~~Utility Theory~~ (1)	
~~Policy Capture~~ (1)	
~~Tecceom Method~~ (1)	
A Priori Partial Elicitation	
Lexicographic Approach	
Goal Programming	
~~Electre Method~~ (1)	
Compromise Programming	
~~Surrogate Worth Trade-Off~~ (1)	
~~Interactive Lagrange Multiplier~~ (1)	
Progressive Elicitation	
Step Method	
Semops Method	
Trade Method	
Pairwise Comparisons	
Tradeoff Cutting Plane	
Method of Geoffrion	
Method of Zionts-Wallenius	
Visual Attribute Displays	
Objective Achievement Matrices	
Graphical Displays	
Mapping	

Decision Situation Descriptor L: Decision Maker Expresses Difficulty in Conceptualizing Hypothetical Trade-offs or Goal Levels

Techniques Eliminated	Notes
Nondominated Solution Gen Tech	(1) Requires specification by the decision maker of preferences for objective weights, trade-offs or goal levels in the absence of actual alternatives.
Constraint Method	
Weighting Method	
Multiobjective Dynamic Prog	
Multiobjective Simplex	
Noninferior Set Estimation	
A Priori Complete Elicitation	
~~Optimal Weights~~ (1)	
~~Utility Theory~~ (1)	
~~Policy Capture~~ (1)	
~~Techcom Method~~ (1)	
A Priori Partial Elicitation	
~~Lexicographic Approach~~ (1)	
~~Goal Programming~~ (1)	
~~Electre Method~~ (1)	
Compromise Programming	
~~Surrogate Worth Trade-Off~~ (1)	
~~Interactive Lagrange Multiplier~~ (1)	
Progressive Elicitation	
Step Method	
Semops Method	
Trade Method	
Pairwise Comparisons	
Tradeoff Cutting Plane	
Method of Geoffrion	
Method of Zionts-Wallenius	
Visual Attribute Displays	
Objective Achievement Matrices	
Graphical Displays	
Mapping	

Decision Situation Descriptor M: Decision Maker Preferences for Marginal Rates of Substitution Not Independent of Absolute Levels of Objective Attainment

Techniques Eliminated	Notes

Nondominated Solution Gen Tech
- Constraint Method
- Weighting Method
- Multiobjective Dynamic Prog
- Multiobjective Simplex
- Noninferior Set Estimation

A Priori Complete Elicitation
- ~~Optimal Weights~~ (1)
- Utility Theory
- ~~Policy Capture~~ (1)
- ~~Techcom Method~~ (1)

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- ~~Electre Method~~ (1)
- Compromise Programming
- ~~Surrogate Worth Trade-Of~~f (2)
- ~~Interactive Lagrange Multiplier~~ (2)

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- Pairwise Comparisons
- Tradeoff Cutting Plane
- Method of Geoffrion
- Method of Zionts-Wallenius

Visual Attribute Displays
- Objective Achievement Matrices
- Graphical Displays
- Mapping

Notes

(1) Assumes that decision maker preferences for trade-offs among objectives is constant at all levels of objective attainment.

(2) Conditional decision maker judgements required by lack of preferential independence may lead to inconsistency in decision maker responses.

Decision Situation Descriptor N: Need for Decision Maker Understanding of Method*

Techniques Eliminated

Nondominated Solution Gen Tech
- Constraint Method
- Weighting Method
- Multiobjective Dynamic Prog
- Multiobjective Simplex
- Noninferior Set Estimation

A Priori Complete Elicitation
- Optimal Weights
- Utility Theory
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- ~~Electre Method~~ (1)
- Compromise Programming
- ~~Surrogate Worth Trade-Off~~ (2)
- Interactive Lagrange Multiplier

Progressive Elicitation
- Step Method
- Semops Method
- Trade Method
- Pairwise Comparisons
- Tradeoff Cutting Plane
- Method of Geoffrion
- Method of Zionts-Wallenius

Visual Attribute Displays
- Objective Achievement Matrices
- Graphical Displays
- Mapping

Notes

(1) Requirement for decision maker to establish concordance and discordance thresholds reduces clarity for decision maker.

(2) Decision maker may have significant difficulties understanding the meaning of the surrogate worth function and the surrogate worth values that he is called upon to estimate. The requirements to make a large number of conditional judgements may add to the confusion to the decision maker.

* This descriptor is also appropriate when the decision must be communicated persuasively to other parties or when difficulty is anticipated in gaining acceptance of solutions.

Decision Situation Descriptor O: Limited Time With Decision Maker Available

Techniques Eliminated

Nondominated Solution Gen Tech
- Constraint Method
- Weighting Method
- Multiobjective Dynamic Prog
- Multiobjective Simplex
- Noninferior Set Estimation

A Priori Complete Elicitation
- Optimal Weights
- ~~Utility Theory~~ (1)
- Policy Capture
- Techcom Method

A Priori Partial Elicitation
- Lexicographic Approach
- Goal Programming
- Electre Method
- Compromise Programming
- ~~Surrogate Worth Trade-Off~~ (2)
- Interactive Lagrange Multiplier

Progressive Elicitation
- ~~Step Method~~ (3)
- ~~Semops Method~~ (3)
- ~~Trade Method~~ (3)
- ~~Pairwise Comparisons~~ (3)
- ~~Tradeoff Cutting Plane~~ (3)
- ~~Method of Geoffrion~~ (3)
- ~~Method of Zionts-Wallenius~~ (3)

Visual Attribute Displays
- Objective Achievement Matrices
- Graphical Displays
- Mapping

Notes

(1) Elicitation of complete preference structure of the decision maker requires a large amount of the decision maker's time.

(2) Not as time consuming as multi-attribute utility theory, but does require significant amounts of the decision maker's time.

(3) Interactive methods require significant amounts of the decision maker's time.

Appendix C

Numerical Example of Interactive Zero-One Integer Programming Algorithm

The following simple numerical example was developed to illustrate use of the interactive algorithm developed in Chapter 5. This problem contains five variables (project candidates) and three objectives. For illustrative purposes, assume that the objectives are (1) to maximize the number of acres of Indian-owned land irrigated, (2) to maximize the number of Indian people beneficially affected, and (3) to maximize the number of acre-feet of water conserved annually.

Step 1

Input

$$\underline{A} = \begin{bmatrix} 3000 & 1000 & 2000 \\ 2000 & 1000 & 2000 \\ 1000 & 0 & 3000 \\ 3000 & 3000 & 0 \\ 2000 & 2000 & 1000 \end{bmatrix}$$

where coefficients a_{ij} express contributions of project candidates i to objectives j. For example, project x_1, if constructed, would irrigate an additional 3000 Indian-owned acres, benefit 1000 Indian people and conserve 2000 acre-feet of water annually.

Step 2

Input

$$\underline{C} = \begin{bmatrix} 20 \\ 15 \\ 25 \\ 30 \\ 10 \end{bmatrix}$$

where coefficients c_i express the capital requirements of project candidate i. For example, construction of project x_1 would cost $20,000,000.

Step 3

Input b = 50, where b is the budget constraint, or $50,000,000.

Step 4

The algorithm of Balas (1965) is used in carrying out Step 4 to illustrate one of a number of algorithms that have been developed to solve zero-one integer problems. A flow chart of Balas' algorithm is provided in Figure C-1. Only simple problems, such as the one illustrated here, can be solved manually with such algorithms. Unfortunately, Balas' algorithm is difficult to follow since he did not provide a comprehensive list of notational definitions. As an aid to understanding the following application, a list of definitions of Balas' notation is provided below:

$\underline{A}$	matrix of constraint coefficients (q x n matrix)
$\underline{a}_j$	jth column of $\underline{A}$
$\underline{b}$	vector of right-hand sides
$C_k^s (k \leq s)$	set of subscripts for which values of v_j^s have been cancelled before the solution $\underline{u}^s$ has been obtained
$\underline{I}(m)$	unit matrix
J_p	set of subscripts corresponding to decision variables that are equal to 1
J_s	subset of N in which $x_j=1 \ \forall j \in J_s$
$j_1 \ldots j_r$	subscripts corresponding to decision variables with value equal to 1
M	set of counters for elements of $\underline{b}$

M_j^{s-}	set of subscripts such that $y_i^s - a_{ij} < 0$
m	number of slack variables
N	set of all subscripts corresponding to all decision variables; $N = (1, 2,...,n)$
N_s	set of subscripts that indicate the improving vectors for solution $\underline{u}^s$
n	number of variables
P	transformed solution
P^s	linear program in which $x_j = 1$ for $j \in J_s$ at iteration s
p	iteration number in which last value of v_j^p was cancelled $(p < s)$
Q	set of constraints; $Q = (1,..., q)$
q	number of constraints
s	iteration counter
$\underline{u}$	solution vector $[1 \times (n + m)]$
$\underline{u}^s$	vector of decision variables and slack variables that are equal to 1 at iteration s
v_j^s	sum of the negative components of $\underline{u}^{s+1}$
$\underline{x}^s$	vector of decision variables that are equal to 1 at iteration s
$\underline{y}$	vector of slack variables
y_i^s	the value of slack variable y_i at iteration s
$\underline{y}^s$	vector of slack variables that equal 1 at iteration s
Z_s	set of all values of the converted objective function through iteration s
$z^*(s)$	the smallest element in $\underline{z}(s)$; ceiling for $\underline{u}^s$
z_p	value of converted objective function at iteration p
z_s	value of converted objective function at iteration s

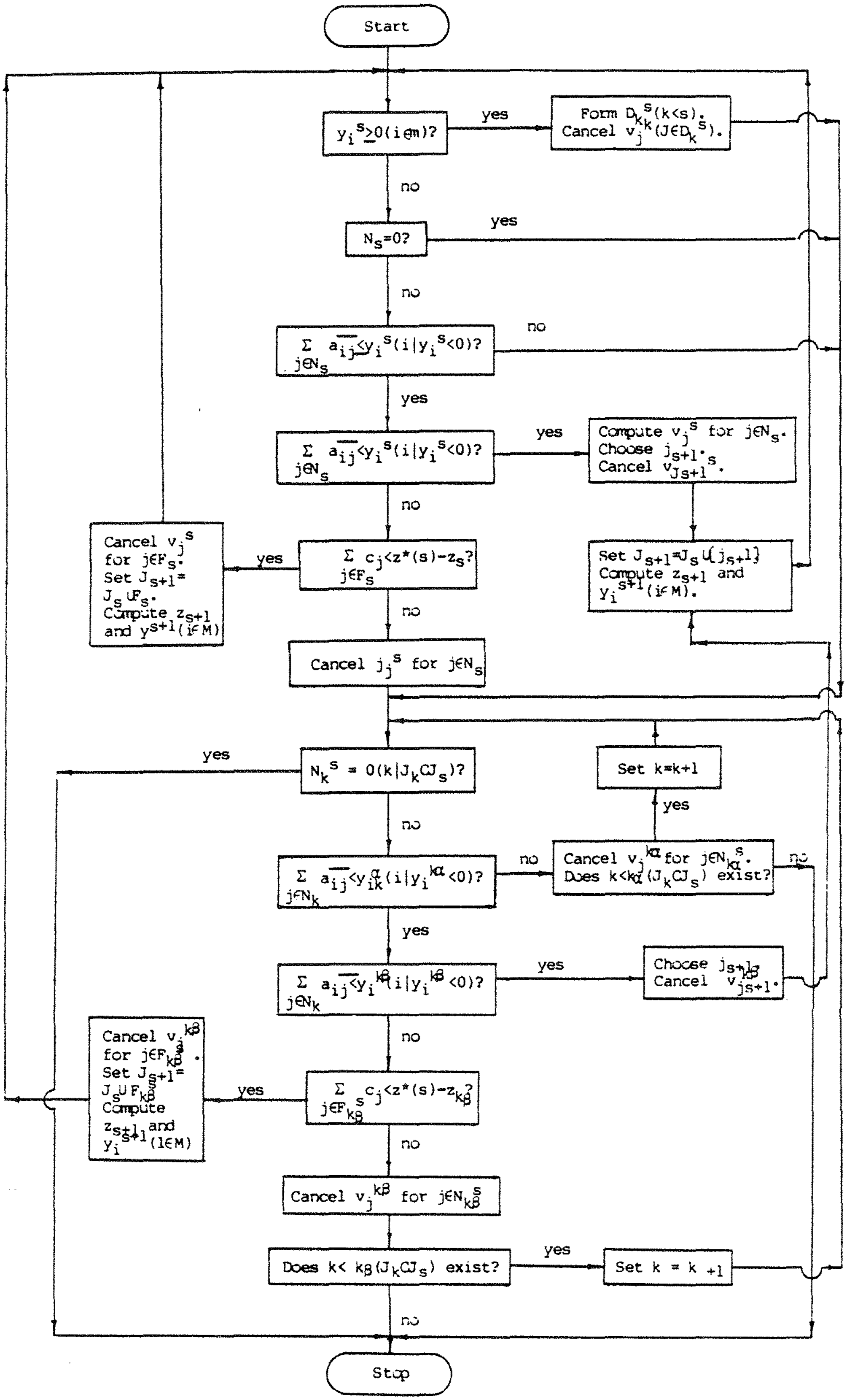


Figure C-1

Flow Chart of Zero-One Integer Programming Algorithm of Balas (1965)

For Step 4, the notation of Balas is used. However, Balas' numerical step designations are changed to alphabetical ones to avoid confusion with the numerical step designations of Chapter 5. That is, Step 1 of Balas is designated Step A, and so on.

First objective function:

$$\max\ (3x_1 + 2x_2 + x_3 + 3x_4 + 2x_5)$$

$$\text{s.t.}\quad 20x_1 + 15x_2 + 25x_3 + 30x_4 + 10x_5 \leq 50$$

$$x_j = 0, 1 \quad \forall\ j$$

To place in the canonical form of Balas (1965, p. 519), multiply the objective function by (-1), set $x_j = 1 - x_j' \ \forall j$, and ignore constants in the objective function. This yields:

$$\min\ (3x_1' + 2x_2' + x_3' + 3x_4' + 2x_5')$$

$$\text{s.t.}\ -20x_1' - 15x_2' - 25x_3' - 30x_4' - 10x_5' \leq -50$$

$$x_j = 0, 1 \quad \forall j$$

<u>Iteration 1</u>

Step A. $y_i^0 + -50 < 0$ for $i = 1, \therefore$ situation 1b.

Step B. $N_0 = N - (C^0 \cup D_0 \cup E_0) = (1, 2, 3, 4, 5) - (0)$

$= (1, 2, 3, 4, 5).$

$N_0 \neq \emptyset$, $\therefore$ situation 2b.

Step C. $\sum_{j \in N_0} \overline{a_{ij}} = -100 < y_1^0 = -50, \therefore$ situation 3b.

$y_1^0 - a_{11} = -50 - (-20) = -30$

$v_1^0 = \sum_{i \in M_1^{0-}} (y_i^0 - a_{i1}) = \sum_{i \in M_1^{0-}} (y_1^0 - a_{11}) = -30$

$v_2^0 = \sum_{i \in M_2^{0-}} (y_2^0 - a_{12}) = -35$

$v_3^0 = -25$; $v_4^0 = -20$; $v_5^0 = -40$

$v_{j1}^0 = \max_{j \in N_0} (v_j^0) = v_4^0 = -20$, $\therefore$ cancel v_4^0 and pass to Step H.

Step H. $J_1 = J_0 \cup (4) = (4)$; $z_1 = z_0 + c_4 = 0 + 3 = 3$

$y_1^1 = y_1^0 - a_{14} = -50 - (-30) = -20$

Iteration 2

Step A. $y_i^1 = -20 \quad 0$ for $i = 1$, $\therefore$ situation 1b.

Step B. $N_1 = N - (C^1 \cup D_1 \cup E_1) = (1, 2, 3, 4, 5) - (4)$

$= (1, 2, 3, 5)$

$N_1 \not\models$, $\therefore$ situation 2b.

Step C. $\sum_{j \in N_1} a_{ij}^- = -70 < y_1^1 = -20$, $\therefore$ situation 3b.

$y_1^1 - a_{11} = -70 - (-20) = -50$

$v_1^1 = \sum_{i \in M_1^{1-}} (y_1^1 - a_{i1}) = \sum_{i \in M_1^{1-}} (y_1^1 - a_{11}) = -50$

$v_2^1 = \sum_{i \in M_2^{1-}} (y_2^1 - a_{12}) = -55$

$v_3^1 = -45$; $v_5^1 = -60$

$v_{j1}^1 = \max_{j \in N_1} (v_j^1) = v_3^1 = -45$, $\therefore$ cancel v_3^1 and pass to Step H.

Step H. $J_2 = J_1 \cup (3) = (4, 3)$

$z_2 = z_1 + c_3 = 3 + 1 = 4$

$y_1^2 = y_1^1 - a_{13} = -20 - (-25) = 5$

Iteration 3

Step A. $y_i^2 \geq 0 \quad \forall i \in M$, $\therefore$ situation 1a.

Set $z_2 = 4 = z^{*(2)}$

$N_1 = (1, 2, 3, 5)$, $C_1^2 = (3)$

$N_1 - C_1^2 = (1, 2, 5)$ $\quad C_1 = 3 > 4 - 3$

$C_2 = 2 > 4 - 3$

$C_5 = 2 > 4 - 3$

$\therefore D_1^2 = (1, 2, 5)$

$N_0 = (1, 2, 3, 4, 5)$, $C_0^2 = (4)$

$N_o - C_0^2 = (1, 2, 3, 5)$ $\quad C_1 = 3 < 4 - 0$

$C_2 = 2 < 4 - 0$

$C_3 = 1 < 4 - 0$

$C_5 = 2 < 4 - 0$

$\therefore D_1^2 = \emptyset$, cancel v_1^1, v_2^1, v_5^1 and pass to Step E.

Step E. $N_1^2 = N_1 - (C_1^2 \cup D_1^2) = (1, 2, 3, 5) - [(3) \cup (1, 2, 5)] = \emptyset$

$\therefore z^*(2) = 4$ is optimal

$x'^2_3 = x'^2_4 = 1$; $x'^2_1 = x'^2_2 = x'^2_5 = 0$

Corresponding optimal solutions to the original problem are:

$x_1 = 1 - x_1^1 = 1 - 0 = 1$

$x_2 = x_5 = 1$; $x_3 = x_4 = 0$

In the notation of Chapter 5, $f_1^*(\underline{x}) = 7$ at $\underline{x} = (1, 1, 0, 0, 1)$. Similarly, it can be determined that maximization of the second objective function yields

$f_2^*(\underline{x}) = 5$ at $\underline{x} = (0, 0, 0, 1, 1)$

and that maximization of the third objective function yields

$f_3^*(\underline{x}) = 6$ at $\underline{x} = (0, 1, 1, 0, 1)$.

Step 5

The initial solution is found by solving the problem:

$$\min \sum_{j=1}^{3} \left[\frac{f_j^*(\underline{x}) - \sum_{i=1}^{5} a_{ij} x_i}{f_j^*(\underline{x})} \right]$$

$$\text{s.t.} \quad 20x_1 + 15x_2 + 24x_3 + 30x_4 + 10x_5 \leq 50$$

$$x_j = 0, 1 \quad \forall\ j,$$

or equivalently:

$$\begin{aligned} \min\ (7/7 - 3/7x_1 - 2/7x_2 - 1/7x_3 - 3/7x_4 - 2/7x_5 \\ + 5/5 - 1/5x_1 - 1/5x2 \qquad - 3/5x_4 - 2/5x_4 \\ + 6/6 - 2/6x_1 - 2/6x_2 - 3/6x_3 \qquad - 1/6x_5) \end{aligned}$$

$$\text{s.t.} \quad 20x_1 + 15x_2 + 24x_3 + 30x_4 + 10x_5 \leq 50$$

$$x_j = 0, 1\ \forall\ j\ .$$

This may be placed equivalently in the canonical form of Balas as:

$$\min\ (-101/105x_1 - 86/105x_2 - 9/14x_3 - 108/108x_4 - 179/210x_5)$$

$$\text{s. t.} \quad -20x_1 - 15x_2 - 25x_3 - 30x_4 - 10x_5 \quad -50$$

$$x_j = 0, 1 \quad \forall\ j\ .$$

This yields

$$\underline{x}^1 = (1, 1, 0, 0, 1)$$

$$\underline{f}(\underline{x}^1) = (7, 4, 5)$$

$$\underline{p}^1 = (1.00, 0.80, 0.83)$$

Step 6

The decision maker is presented with the following information:

	Objective 1 (Indian acres irrigated)	Objective 2 (Indian beneficiaries)	Objective 3 (Water conserved)
Objective attainment	7000 acres	4000 people	5000 acre-feet
Percent of maximum attainable	100%	80%	83%

Step 7

The decision maker is asked to decide if the current solution is his most preferred solution. In this example, it it assumed that the decision maker responds with a "no".

Step 8

The decision maker specifies an increase in Objective 2 of 1000 people. Thus, a new constraint

$$\hat{f}_3(\underline{x}^2) \geq \hat{f}_3(\underline{x}^1) + \Delta \hat{f}_3$$

$$\text{or} \quad 2x_1 + 2x_2 + 3x_3 + x_5 \geq 4000 + 1000$$

is added.

Step 9

The new solution is calculated, yielding:

$$\underline{x}^2 = (0, 0, 0, 1, 1)$$

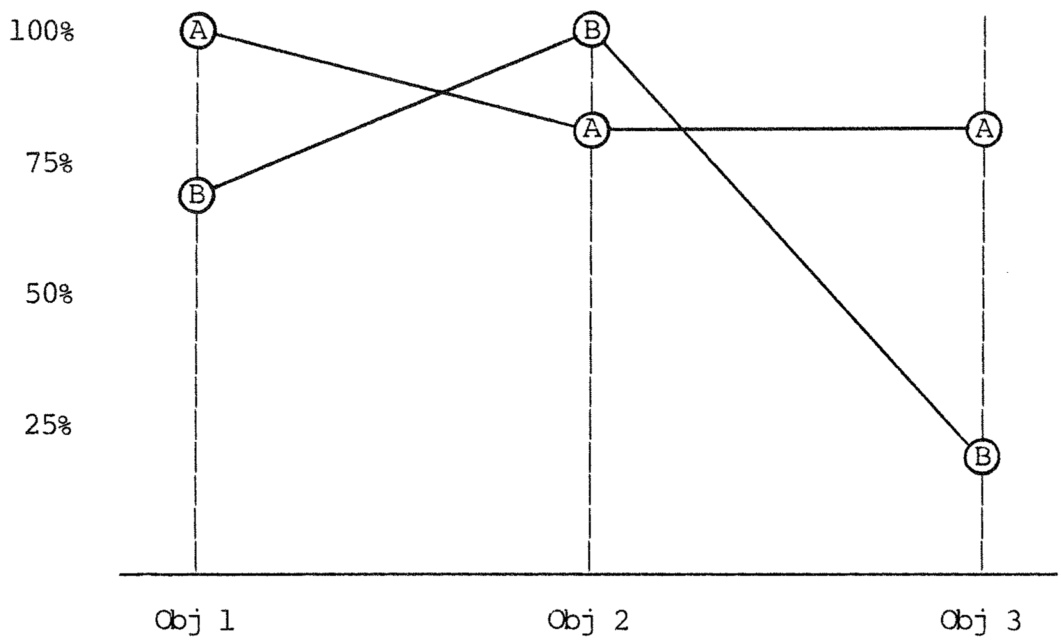
$$\underline{f}(\underline{x}^2) = (5, 5, 1)$$

$$\underline{p}^2 = (0.71, 1.00, 0.17)$$

Step 10

The following information is presented to the decision maker:

Alternative A			Alternative B		
Obj 1	Obj 2	Obj 3	Obj 1	Obj 2	Obj 3
7000 acres	4000 people	5000 AF	5000 acres	5000 people	1000 AF
100%	80%	83%	71%	100%	17%



The decision maker is asked which solution is preferred. Assume that Alternative A is selected. The algorithm proceeds to Step 7.

Step 7

The decision maker is asked to decide if the current solution is his most preferred solution. Assume that the decision maker responds with a "yes". The algorithm proceeds to Step 11.

Step 11

The preferred solution has been found. Print:

	Objective 1 (Indian acres irrigated)	Objective 2 (Indian beneficiaries)	Objective 3 (Water conserved)
Objective attainment	7000 acres	4000 people	5000 acre-feet
Percent of maximum attainable	100%	80%	83%
Preferred Portfolio	(1, 1, 0, 0, 1)		

APPENDIX D

Decision-Aiding Algorithm Program Listings

The programs contained in this appendix were designed to implement the interactive multiobjective decision-aiding algorithm described in Chapter 5 on an Amdahl V7 computer using the IBM optimization package MPSX/MIP 370. Descriptions of the function of each of the 17 programs listed in the pages that follow are contained in Chapter 6.

Programs designed by: Larry C. Harms and Jonathan P. Deason

BIA.CLIST

```
PROC 0 BRIEF(NO) SITE(N5R190) LIST(' ')
CONTROL END(ENDO) NOMSG
ATTN OFF
/* IF BREAK KEY HIT, FREEALL BEFORE LEAVING */
ATTN DO
GOTO ENDIT
ENDO
/* */
/* DEFAULT PRINTER IS WCC USER ROOM */
/* */
IF &SITE = RESTON THEN SET &SITE = N4R0
IF &SITE = RMT14 THEN SET &SITE = N4R14
IF &SITE = ITEL THEN SET &SITE = N5R0
/* */
WRITE BIA LINEAR PROGRAM(LP) SYSTEM
WRITE
/* */
IF &BRIEF = NO THEN DO
 WRITE
 WRITE COMMAND      MEANING
 WRITE
 WRITE   ALL      WILL EXECUTE FORTRAN PROGRAM TO TRANSLATE THE
 WRITE            POINT MATRIX INTO LP INPUT SYNTAX.  THE LP
 WRITE            PROGRAM CAN THEN BE EXECUTED TO PROVIDE THE
 WRITE            SOLUTIONS FOR ALL THE CRITERIA AND THE INITIAL
 WRITE            LP SOLUTION FOR THE COMPLETE PROBLEM
 WRITE
 WRITE   LP       EXECUTES THE LP PROGRAM. PROMPTING THE USER FOR
 WRITE            THE INPUT FILE AND THE OUTPUT FILE.
 WRITE
 WRITE   ALLB     EXECUTES THE FORTRAN PROGRAM FOR A PARTICULAR
 WRITE            CRITERION OR INITAL SOLUTION.  THE LP PROGRAM
 WRITE            IS RAN AS A BATCH JOB USING THE FILE LPIN DATA
 WRITE            AS INPUT
 WRITE
 WRITE   LPB      EXECUTES LP PROGRAM AS A BATCH JOB, PROMPTING
 WRITE            THE USER FOR THE INPUT FILE AND OUTPUT FILE
 WRITE
ENDO
/* */
WRITENR ENTER COMMAND :
READ &COMM
/* */
IF &COMM = LP THEN GOTO LPONLY
IF &COMM = ALLB THEN GOTO ALLB
IF &COMM = LPB THEN GOTO LPB
/* */
/* ******************************************** */
/* RUN FORTRAN PROGRAM AND LP INTERACTIVELY */
```

```
/* ******************************************** */
 WRITENR ENTER NAME OF DATA FILE:
 READ &DATANAM
 IF &DATANAM=&STR() THEN SET &DATANAM=BIA.DATA
 /* */
 WRITENR ENTER NUMBER OF CRITERIA :
 READ &NUMCRIT
 /* */
 ALLOC FI(SYSPRINT) DA(*)
 /* */
 ALLOC FI(FT11F001) DA(LPIN.DATA) SHR
 /* */
 ALLOC FI(FT07F001) DA(&DATANAM) SHR
 /* EXECUTE FORTRAN PROGRAM */
 /* */
 ALLOC FI(FT08F001) DA(SETUP.DATA) SHR
 /* */
 /* CHECK FOR USING A CONSTRAINT FILE */
 /* */
 ASKCON: WRITE
 WRITENR DO YOU WISH TO USE AN ADDITIONAL CONSTRAINT FOR THE LP?
 READ &ANS
 /* */
 IF &ANS=YES THEN GOTO GETCON
 IF &ANS=NO THEN GOTO CALLIN
  ELSE DO
    WRITE MUST ANSWER "YES" OR "NO"
    GOTO ASKCON
 ENDO
 /* */
 /* */
 GETCON: WRITE
 WRITE ENTER NAME OF YOUR CONSTRAINT FILE (IF THE SAME AS YOUR
 WRITE DATA FILE JUST DEPRESS "RETURN" KEY)
 READ &CONNAME
 IF &CONNAME = &STR() THEN SET &CONNAME = SAME
 ELSE ALLOC FI(FT09F001) DA(&CONNAME) SHR
 /* */
 /* CALL FORTRAN PROGRAM TO INITILIZE SETUP.DATA WITH CONST */
 /* */
 CALL 'VG8H83H.BIA.LOAD(INITC)'
 GOTO SETCNT
 /* */
 CALLIN: CALL 'VG8H83H.BIA.LOAD(INIT)'
 /* */
 /* */
 SETCNT: SET &COUNT=1
 SET &NUMCRIT = &NUMCRIT+1
 SET &VAL = 0
 SET &LPCALL = 0
 /* */
 /* GO THROUGH LP LOOP AND SEE WHAT TO RUN */
```

```
/* */
DO WHILE &COUNT LE &NUMCRIT
/* */
/* EXECUTE FORTRAN PROGRAM TO INITIALIZE FILE FOR BIA7 PROGRAM *
/* */
   CALL 'VG8H83H.BIA.LOAD(INIT2)'
   /* */
   IF &COUNT < &NUMCRIT THEN DO
     WRITENR DO YOU WANT TO RUN THE LP FOR CRITERIA &COUNT :
     READ &ANS
     IF &ANS = NO THEN GOTO NXLP
     IF &ANS = SKIP THEN DO
      SET &COUNT = &NUMCRIT-1
      CALL 'VG8H83H.BIA.LOAD(INIT3)'
      GOTO NXLP
     ENDO
     /* */
     /* EXECUTE FORTRAN PROGRAM TO SET UP LP INPUT */
     /* */
     CALL 'VG8H83H.BIA.LOAD(BIA7)'
     /* */
     IF &LPCALL = 0 THEN SET &VAL = 1
     SET &LPCALL = 1
     /* */
     /* CALL IN LP CLIST */
     /* */
     EXEC RUNLP 'LPOUT&COUNT..DATA &VAL' &LIST
     ENDO
   /* */
   /* INITIAL SOLUTION FOR DATA */
   /* */
   ELSE DO
     /* */
     /* IF THERE IS ONLY 1 CRITERIA, NO NEED TO RUN INIT SOL */
     /* */
     IF &COUNT = 2 THEN GOTO ENDIT
     /* */
     WRITENR DO YOU WANT TO RUN THE LP FOR THE INITIAL SOLUTION
     READ &ANS
     IF &ANS = NO THEN GOTO NXLP
     /* */
    /* EXECUTE FORTRAN PROGRAM TO SET UP LP INPUT */
     /* */
     CALL 'VG8H83H.BIA.LOAD(BIA7)'
     /* */
     IF &LPCALL = 0 THEN SET &VAL = 1
     SET &LPCALL = 1
     /* */
     /* CALL LP CLIST */
     /* */
     EXEC RUNLP 'LPOUT&COUNT..DATA &VAL +
     PROG(MPSCL2.DATA)' &LIST
```

```
    ENDO
    /* */
    SET &VAL = Ø
    /* */
    /* SEE IF USER WANTS TO LOOK AT OUTPUT */
    /* */
    WRITE DO YOU WISH TO TAKE OVER CONTROL TO INVESTIGATE THE
    WRITE LP OUTPUT FILE - LPOUT&COUNT..DATA
    READ &ANS
    IF &ANS = YES THEN DO
      WRITE
      WRITE CONTROL IS BEING TRANSFERRED TO YOU   WHEN YOU HAVE
      WRITE FINISHED YOU CAN RETURN TO THIS SYSTEM BY ENTERING ONE
      WRITE OF THE FOLLOWING COMMANDS:
      WRITE
      WRITE   COMMAND                         MEANING
      WRITE
  WRITE    RUN    CONTINUE THE NORMAL PROCESSING CYCLE
  WRITE
  WRITE    RERUN  RUN THE LP AGAIN USING THE SAME INPUT
  WRITE           AND OUTPUT FILES (WITH MODIFICATIONS YOU
  WRITE           HAVE MADE TO THE INPUT FILE)
  WRITE
  WRITE    STOP   ABORT SYSTEM
  WRITE
   WRITE WHEN YOU SEE THE "READY" MESSAGE YOU HAVE CONTROL
  WRITE
      TERMIN RUN RERUN STOP
      /* CHECK RESPONSE */
      IF &SYSDLM = 2 THEN DO
        SET &VAL = 2
        GOTO RUNIT
      /* */
      ENDO
      /* */
      IF &SYSDLM = 3 THEN GOTO ENDIT
      /* */
    ENDO
    /* */
    /* CHECK FOR PRINTING OUTPUT AT PRINTER */
    /* */
    WRITE
    WRITE DO YOU WANT A HARDCOPY PRINTOUT OF THE LP OUTPUT?
    READ &ANS
    IF &ANS = YES THEN DO
    /* */
    /* SUBSTITUTE FILE NAME AND PRINTING LOCATION */
      WRITE ENTER DESCRIPTION ( MAX 3Ø CHARS ENCLOSED IN 'QUOTES')
      WRITE FOR IDENTIFYING LISTING
      READ &DESC
      /* */
      FREE DA(LPOUT&COUNT..DATA)
```

```
      /* */
      SET &DATE = &SYSDATE
      SET &TIME = &SYSTIME
      EDIT PRNT.CNTL
      C 10 9999 /???/LPOUT&COUNT..DATA/ALL
      C 10 9999 /###/&SITE/
      C 10 9999 /DESCRIPTION/&DESC/ALL
      C 10 9999 /DATERUN/&DATE/ALL
      C 10 9999 /TIMERUN/&TIME/ALL
      SUBMIT
      END NOSAVE
    ENDO
    /* */
    NXLP: SET &COUNT=&COUNT+1
    ENDO
/* */
GOTO ENDIT
/* */
/* END OF CYCLE WHEN EXECUTING FORTRAN PROGRAM */
/* */
/* */
/* ***************************************************** */
/* RUN LP ONLY INTERACTIVELY */
/* ***************************************************** */
/* ONLY RUNNING THE LP, WILL PROMPT FOR FILES */
/* */
LPONLY: WRITENR ENTER NAME OF LP INPUT FILE :
READ &NAMEINP
WRITENR ENTER NAME OF OUTPUT FILE :
READ &NAMEOUT
WRITENR ENTER NAME OF LP PROGRAM :
READ &PROG
IF &PROG = &STR() THEN SET &PROG = MPSCL.DATA
/* */
/* EXECUTE LP */
/* */
RUNIT2: +
EXEC RUNLP '&NAMEOUT 1 PROG(&PROG) INP(&NAMEINP)'
/* */
WRITE DO YOU WISH TO TAKE OVER CONTROL TO INVESTIGATE THE
WRITE LP OUTPUT FILE - &NAMEOUT
READ &ANS
IF &ANS = YES THEN DO
  WRITE
  WRITE CONTROL IS BEING TRANSFERRED TO YOU   WHEN YOU HAVE
  WRITE FINISHED YOU CAN RETURN TO THIS YSTEM BY ENTERING
  WRITE ONE OF THE FOLLOWING COMMANDS:
  WRITE
  WRITE   COMMAND                      MEANING
  WRITE
  WRITE    RUN               CONTINUE THE NORMAL PROCESSING CYCLE
  WRITE
```

```
  WRITE    RERUN           RUN THE LP AGAIN USING THE SAME INPUT
  WRITE                    AND OUTPUT FILES (WITH MODIFICATIONS
  WRITE                    YOU HAVE MADE TO THE INPUT FILE)
  WRITE
  WRITE   STOP             ABORT SYSTEM
  WRITE
  WRITE WHEN YOU SEE THE "READY" MESSAGE YOU HAVE CONTROL
  WRITE
  TERMIN RUN RERUN STOP
  /* CHECK RESPONSE */
  IF &SYSDLM = 2 THEN GOTO RUNIT2
  IF &SYSDLM = 3 THEN GOTO ENDIT
ENDO
/* */
WRITE
WRITE DO YOU WANT A HARDCOPY PRINTOUT OF THE LP OUTPUT?
READ &ANS
IF &ANS = YES THEN DO
  WRITE ENTER DESCRIPTION ( MAX 30 CHARS ENCLOSED IN 'QUOTES')
  WRITE FOR IDENTIFYING LISTING
  READ &DESC
  /* */
  FREE DA(&NAMEOUT)
  /* */
  SET &DATE = &SYSDATE
  SET &TIME = &SYSTIME
  EDIT PRNT.CNTL
  C 10 9999 /???/&NAMEOUT/ALL
  C 10 9999 /###/&SITE/
  C 10 9999 /DESCRIPTION/&DESC/ALL
  C 10 9999 /DATERUN/&DATE/ALL
  C 10 9999 /TIMERUN/&TIME/ALL
  SUBMIT
  END NOSAVE
ENDO
/* */
GOTO ENDIT
/* */
/* ****************************************** */
/*  RUN FORTRAN PROGRAM, BATCH LP RUN */
/* ****************************************** */
/* */
ALLB: WRITENR ENTER NAME OF DATA FILE:
READ &DATANAM
IF &DATANAM=&STR() THEN SET &DATANAM=BIA.DATA
/* */
ALLOC FI(FT11F001) DA(LPIN.DATA) SHR
/* */
ALLOC FI(FT07F001) DA(&DATANAM) SHR
ALLOC FI(FT08F001) DA(SETUP.DATA) SHR
/* */
/* */
```

```
/* CHECK FOR USING A CONSTRAINT FILE */
/* */
ASKC: WRITE
WRITENR DO YOU WISH TO USE AN ADDITIONAL CONSTRAINT FOR THE LP?
READ &ANS
/* */
IF &ANS=YES THEN GOTO GETCON2
IF &ANS=NO THEN GOTO CALLINB
 ELSE DO
   WRITE MUST ANSWER "YES" OR "NO"
   GOTO ASKC
ENDO
/* */
/* */
GETCON2: WRITE
WRITE ENTER NAME OF YOUR CONSTRAINT FILE (IF THE SAME AS YOUR
WRITE DATA FILE JUST DEPRESS "RETURN" KEY)
READ &CONNAME
IF &CONNAME = &STR() THEN SET &CONNAME = SAME
ELSE ALLOC FI(FT09F001) DA(&CONNAME) SHR
/* */
/* CALL FORTRAN PROGRAM TO INITILIZE SETUP.DATA WITH CONST */
/* */
CALL 'VG8H83H.BIA.LOAD(INITBC)'
GOTO CALLBIA
/* */
CALLINB: CALL 'VG8H83H.BIA.LOAD(INITB)'
CALLBIA: CALL 'VG8H83H.BIA.LOAD(BIA7)'
/* */
WRITENR ARE YOU RUNNING THE LP FOR THE INITIAL SOLUTION?
READ &ANS
/* */
IF &ANS = YES THEN SET &BATCHJ = 2
ELSE SET &BATCHJ = 1
/* */
GOTO BATCH
/* */
/* ************************************************** */
/* RUN LP PROGRAM AS A BATCH JOB */
/* ************************************************** */
 LPB: WRITENR ENTER NAME OF LP INPUT FILE :
READ &NAMEINP
WRITENR ENTER NAME OF LP PROGRAM :
READ &PROG
IF &PROG = &STR() THEN SET &PROG = MPSCL.DATA
/* */
/* ************************************************ */
/* EDIT JOBSTREAM FOR LP TO INSERT PROPER FILES */
/* ************************************************* */
/* */
```

```
BATCH: WRITE
WRITE   JOB CLASS     ACTION
WRITE       B        BATCH JOB SHOULD RUN NOW (DEFAULT)
WRITE       D        BATCH JOB WILL RUN OVERNIGHT (CHEAPER)
WRITE
WRITENR ENTER CLASS CODE FOR JOB :
READ &CLSS
/* */
IF &CLSS = &STR() THEN SET &CLSS = B
/* */
/* IF CLASS D, INCREASE BATCH SWITCH TO RUN BATCH JOBS 3 OR 4 */
   IF &CLSS = D THEN SET &BATCHJ = &BATCHJ + 2
/* */
/*  FREE ALL FILES */
/* */
FREEALL
/* */
/* DEPENDING ON CLASS CODE AND TYPE OF RUN (INIT SOL/CRITERIA */
/* SUBMIT THE PROPER BATCH JOB */
/* */
IF &BATCHJ = 4 THEN DO
   SUBMIT BATCH4.CNTL
   GOTO ENDIT
ENDO
IF &BATCHJ = 3 THEN DO
   SUBMIT BATCH3.CNTL
   GOTO ENDIT
ENDO
IF &BATCHJ = 2 THEN DO
   SUBMIT BATCH2.CNTL
ENDO
ELSE DO
   SUBMIT BATCH1.CNTL
ENDO
/* */
/* *********************************************** */
/* END OF PROCESSING. FREE ALL FILES */
/* *********************************************** */
/* */
ENDIT: WRITE
WRITE END OF BIA LP SYSTEM PROCESSING
WRITE
FREEALL
```

BIA7.FORT

```
C        BIA7.FORT
C
         COMMON ICON(13),ITYPE(13),VALC(13),ACON(13,325),IFILE
         DIMENSION ARRAY(13,325),COST(325)
C
   31    FORMAT(' ENTER NUMBER OF PROJECTS (ROWS)')
   32    FORMAT(I2)
   34    FORMAT(2I3,F10.2,3I3)
   35    FORMAT(I3,A1,F10.2)
   33    FORMAT(' ENTER NUMBER OF CRITERIA (COLUMNS)')
   41    FORMAT(' ENTER ROW ',I2)
   42    FORMAT(3(F2.0,1X))
   43    FORMAT(' ENTER COST')
   44    FORMAT(F2.0)
   52    FORMAT(' ENTER BUDGET')
C
  101    FORMAT('NAME',10X,'BIA')
  103    FORMAT('ROWS')
  104    FORMAT(' N',2X,'OBJ')
  106    FORMAT(' L',2X,'W',I3)
  111    FORMAT('COLUMNS')
  112    FORMAT(4X,'DEBE',6X,'''MARKER''',17X,'''INTORG''')
  114    FORMAT(4X,'X',I3,6X,'OBJ',7X,'-',F11.4,3X,'W',I3,7X,F11.5)
  116    FORMAT(4X,'X',I3,6X,'W',I3,11X,'1.00000')
  121    FORMAT(4X,'FINE',6X,'''MARKER''',17X,'''INTEND''')
  123    FORMAT('RHS')
  124    FORMAT(4X,'LHS',7X,'W',I3,6X,F12.5)
  126    FORMAT(4X,'LHS',7X,'W',I3,11X,'1.00000')
  131    FORMAT('BOUNDS')
  133    FORMAT(' UP INTB',6X,'X',I3,6X,F12.5)
  134    FORMAT('ENDATA')
  304    FORMAT(' N',2X,'OBJ',I3)
  314    FORMAT(4X,'X',I3,6X,'OBJ',I3,4X,'-',F12.5)
  324    FORMAT(4X,'LHS',7X,'W',I3,6X,F12.5)
  336    FORMAT(4X,'X',I3,6X,'W',I3,7X,F11.5)
C
C
C****READ IN CONTROL CARD FOR NUMBER OF ROWS & COLUMNS
C****THE AMOUNT OF MONEY TO SPEND AND THE COLUMN OF DATA
C****TO BE WRITTEN TO FILE LPIN.DATA
C
         READ (8,34) NUMROW,NUMCOL,XCOS,IPASS,ICCNT,NCCOL
C
C****CHECK FOR ADDING CONSTRAINTS TO THE LP INPUT
C
         IF (ICCNT.EQ.0) GO TO 40
C
C****READ IN CONSTRAINT INFO
C
```

```
      DO 30 I=1,ICCNT
      READ(8,35) ICON(I),ITYPE(I),VALC(I)
   30 CONTINUE
C
C****CHECK IF CONSTRAINT FILE AND DATA FILE THE SAME
C
      IF(NCCOL.EQ.0) GO TO 40
C
C****READ IN THE CONSTRAINT ARRAY
C
      DO 60 J=1,NUMROW
      READ(9,*) (ACON(I,J),I=1,NCCOL),DUM
   60 CONTINUE
C
   40 IFILE=11
C
C****READ IN THE ARRAY OF DATA
C
      DO 50 J=1,NUMROW
      READ(7,*) (ARRAY(I,J),I=1,NUMCOL),COST(J)
   50 CONTINUE
C
C****CHECK IF CONSTRAINTS BEING USED
C
      IF (ICCNT.EQ.0) GO TO 80
C
C****CHECK IF CONSTRAINT FILE AND DATA FILE THE SAME
C
      IF (NCCOL.NE.0) GO TO 80
C
C****MOVE DATA ARRAY TO CONSTRAINT ARRAY
C
      DO 75 J=1,NUMROW
      DO 70 I=1,NUMCOL
      ACON(I,J)=ARRAY(I,J)
   70 CONTINUE
   75 CONTINUE
C
C****CHECK IF NEED TO WRITE OUT FILE FOR INITIAL SOLUTION
C
   80 J=IPASS
      IF (IPASS.GT.NUMCOL) GO TO 250
C
C****WRITE OUT HEADER INFO FOR LP
C
      WRITE(IFILE,101)
      WRITE(IFILE,103)
      WRITE(IFILE,104)
C
C****WRITE OUT ROW NAMES
C
      IVAL2=NUMROW+1
```

```
      DO 100 I=1,IVAL2
      IVAL=I+100
      WRITE(IFILE,106) IVAL
  100 CONTINUE
C
C****CHECK FOR WRITING CONSTRAINTS
C
      IF (ICCNT.NE.0) CALL CONROW(ICCNT,IVAL2)
C
C****WRITE COLUMN HEADERS
C
      WRITE(IFILE.111)
      WRITE(IFILE,112)
C
C****WRITE COLUMN INFO
      IVAL2=NUMROW+101
C
      DO 120 I=1.NUMROW
      IVAL=I+100
      WRITE(IFILE.114) IVAL,ARRAY(J,I),IVAL2.COST(I)
      WRITE(IFILE,116) IVAL,IVAL
C
C****CHECK FOR WRITING CONSTRAINTS
C
      IF (ICCNT.NE.0) CALL CONCOL(ICCNT,IVAL2,IVAL.I)
C
  120 CONTINUE
C
C****WRITE END OF COLUMN INFO
C
      WRITE(IFILE.121)
C
C****WRITE RIGHT HAND SIDE INFO
C
      WRITE(IFILE.123)
      WRITE(IFILE,124) IVAL2,XCOS
C
C****CHECK FOR WRITING CONSTRAINTS
C
      IF (ICCNT.NE.0) CALL CONRHS(ICCNT,IVAL2)
C
      DO 130 I=1.NUMROW
      IVAL=I+100
      WRITE(IFILE.126) IVAL
  130 CONTINUE
C
C****BOUNDS INFO
C
      WRITE(IFILE.131)
C
      DO 140 I=1.NUMROW
      IVAL=I+100
```

```
          WRITE(IFILE,133) IVAL,XCOS
    140   CONTINUE
C
           WRITE(IFILE,134)
    200   CONTINUE
          GO TO 500
C
C****WRITE OUT INITIAL GP CRITERIA
C
C****WRITE OUT HEADER INFO FOR LP
C
    250   CONTINUE
C
          WRITE(IFILE.101)
          WRITE(IFILE,103)
C
          DO 300 I=1.NUMCOL
          IVAL=I+100
          WRITE(IFILE.304) IVAL
    300   CONTINUE
C
C****WRITE OUT ROW NAMES
C
          IVAL2=NUMROW+1
          DO 310 I=1,IVAL2
          IVAL=I+100
          WRITE(IFILE,106) IVAL
    310   CONTINUE
C
C****CHECK FOR WRITING CONSTRAINTS
C
          IF (ICCNT.NE.0) CALL CONROW(ICCNT,IVAL2)
C
C****WRITE OUT COLUMN HEADERS
C
          WRITE(IFILE.111)
          WRITE(IFILE,112)
C
C****WRITE OUT COLUMN INFO
C
          IVAL3=NUMROW+101
          DO 400 I=1,NUMROW
          IVAL=I+100
          DO 330 J=1,NUMCOL
          IVAL2=J+100
          WRITE(IFILE,314) IVAL.IVAL2.ARRAY(J,I)
    330   CONTINUE
C
C****WRITE OUT COST
C
          WRITE(IFILE.336) IVAL,IVAL3.COST(I)
          WRITE(IFILE,116) IVAL,IVAL
```

```
C
C****CHECK FOR WRITING CONSTRAINTS
C
      IF (ICCNT.NE.0) CALL CONCOL(ICCNT,IVAL3,IVAL,I)
C
  400 CONTINUE
C
C****WRITE END OF COLUMN INFO
C
      WRITE(IFILE,121)
C
C****WRITE RIGHT HAND SIDE INFO
C
      WRITE(IFILE,123)
      WRITE(IFILE,324) IVAL3,XCOS
C
C****CHECK FOR WRITING CONSTRAINTS
C
      IF (ICCNT.NE.0) CALL CONRHS(ICCNT,IVAL3)
C
      DO 410 I=1,NUMROW
      IVAL=I+100
      WRITE(IFILE,126) IVAL
  410 CONTINUE
C
C****BOUNDS INFO
C
      WRITE(IFILE,131)
C
      DO 420 I=1,NUMROW
      IVAL=I+100
      WRITE(IFILE,133) IVAL,XCOS
  420 CONTINUE
C
       WRITE(IFILE,134)
  500 CONTINUE
      STOP
      END
C*******************************************************
C
      SUBROUTINE CONROW(ICCNT,IVAL2)
C
      COMMON ICON(13),ITYPE(13),VALC(13),ACON(13,325),IFILE
C
  101 FORMAT(' ',A1,2X,'W',I3)
C
      DO 100 I=1,ICCNT
      IVAL=IVAL2+I+100
      WRITE(IFILE,101) ITYPE(I),IVAL
  100 CONTINUE
C
      RETURN
```

```
      END
C
C****************************************************************
C
      SUBROUTINE CONCOL(ICCNT,IVAL2,IVAL,I)
C
      COMMON ICON(13),ITYPE(13),VALC(13),ACON(13,325),IFILE
C
  101 FORMAT(4X,'X',I3,6X,'W',I3,7X,F11.5)
C
      DO 100 J=1,ICCNT
      IVAL3=IVAL2+J
      K=ICON(J)
      WRITE(IFILE,101) IVAL,IVAL3,ACON(K,I)
  100 CONTINUE
C
      RETURN
      END
C
C****************************************************************
C
     SUBROUTINE CONRHS(ICCNT,IVAL2)
C
      COMMON ICON(13),ITYPE(13),VALC(13),ACON(13,325),IFILE
C
  101 FORMAT(4X,'LHS',7X,'W',I3,6X,F12.5)
C
      DO 100 I=1,ICCNT
      IVAL3=IVAL2+I
      WRITE(IFILE,101) IVAL3,VALC(I)
  100 CONTINUE
C
      RETURN
      END
```

RUNLP.CLIST

```
PROC 2 OUT FTIME PROG(MPSCL.DATA) INP(LPIN.DATA)
CONTROL END(ENDO) NOMSG
IF &FTIME = 1 THEN DO
FREE FI(SYSIN)
ALLOC FI(SYSIN) DA(&PROG) SHR
ALLOC FI(SCRATCH1) SPACE(25 25) BLOCK(4000)
ALLOC FI(SCRATCH2) SPACE(25 25) BLOCK(4000)
ALLOC FI(SCRATCH3) SPACE(25 25) BLOCK(4000)
ALLOC FI(SCRATCH4) SPACE(25 25) BLOCK(4000)
ALLOC FI(SYSMLCP) SPACE(25 25) BLOCK(4000)
ATTR POUT RECFM(F A) LRECL(133) BLKSIZE(133)
ENDO
RUNIT: FREE FI(SYSPRINT)
DEL &OUT
ALLOC FI(SYSPRINT) DA(&OUT) SPACE(30 20) T USING(POUT) NEW
WRITE SETTING UP FILES FOR LP
CALL 'SYS1.MPSX16.LOADLIB(DPLCOMP)'
ALLOC FI(PROBFILE) SPACE (30 30) BLOCK(4000)
ALLOC FI(MATRIX1) SPACE(25 25) BLOCK(4000)
ALLOC FI(MATRIX2) SPACE(25 25) BLOCK(4000)
ALLOC FI(ETA1) SPACE(25 25) BLOCK(4000)
ALLOC FI(ETA2) SPACE(25 25) BLOCK(4000)
ALLOC FI(MIXWORK) SPACE(90 60) BLOCK(4000)
FREE FI(SYSIN)
ALLOC FI(SYSIN) DA(&INP)
WRITE BEGINNING LP
CALL 'SYS1.MPSX16.LOADLIB(DPLEXEC)'
FREE FI(PROBFILE MATRIX1 MATRIX2 ETA1 ETA2 MIXWORK)
WRITE FINISHED LP
WRITE
```

INIT.FORT

```
C     INIT.FORT
C
   31  FORMAT(' ENTER NUMBER OF PROJECTS (ROWS)')
   33  FORMAT(' ENTER NUMBER OF CRITERIA (COLUMNS)')
   52  FORMAT(' ENTER BUDGET')
C
C
       WRITE(6,31)
       READ(5,*) NUMROW
       WRITE(6,33)
       READ(5,*) NUMCOL
C
C
       WRITE(6,52)
       READ(5,*) XCOS
       IPASS=0
       ICNT=0
       ICVAL=0
       WRITE(8,34) NUMROW.NUMCOL.XCOS.IPASS,ICNT,ICVAL
   34  FORMAT(2I3,F10.2,3I3)
       STOP
       END
```

INITC.FORT

```
C      INITC.FORT
C
        DIMENSION ICON(13),ITYPE(13),VAL(13)
C
        DATA IG,IL,IN1,IN2/'G','L','NO','N'/
        DATA IANS/'YES'/
C
    31  FORMAT(' ENTER NUMBER OF PROJECTS (ROWS) IN YOUR DATA ARRAY'
    33  FORMAT(' ENTER NUMBER OF CRITERIA (COLUMNS)')
    34  FORMAT(2I3,F10.2,3I3)
    35  FORMAT(I3,A1,F10.2)
    52  FORMAT(' ENTER BUDGET')
    61  FORMAT(' IN THE FILE YOU ARE USING FOR YOUR CONSTRAINTS.',
      1 ' HOW MANY CRITERIA (COLUMNS) ARE THERE')
    62  FORMAT(' OF THESE ',I3,' CRITERIA, ENTER THE COLUMN ',
      1 'WHICH IS TO BE A CONSTRAINT')
    63  FORMAT(' IS THIS A "GREATER THAN" CONSTRAINT?')
    64  FORMAT(' ENTER THE CONSTRAINT VALUE FOR COLUMN ',I3)
    65  FORMAT(' DO YOU WANT TO ALSO USE ANOTHER COLUMN ',
      1 'AS A CONSTRAINT')
    66  FORMAT(' ENTER THE COLUMN NUMBER')
    68  FORMAT(' IF YOUR CONSTRAINT FILE IS ALSO YOUR DATA FILE',
      1 ' ENTER 0')
    71  FORMAT(A2)
    72  FORMAT(A3)
C
C
        WRITE(6,31)
        READ(5,*) NUMROW
        WRITE(6,33)
        READ(5,*) NUMCOL
C
C
        WRITE(6,52)
        READ(5,*) XCOS
        IPASS=0
        ICNT=1
        WRITE(6,61)
        WRITE(6,68)
        READ(5.*) ICVAL
C
C****LOOP THROUGH AND GET CONSTRAINT INFO
C
        DO 200 I=1.20
        IF (I.NE.1) GO TO 100
C
        IVAL=ICVAL
        IF(IVAL.EQ.0) IVAL=NUMCOL
        WRITE(6.62) IVAL
```

```
        READ(5,*) ICON(I)
        GO TO 150
C
  100   WRITE(6,65)
        READ(5,71) IANS
        IF (IANS.EQ.IN1) GO TO 300
        IF (IANS.EQ.IN2) GO TO 300
C
        WRITE(6,66)
        READ(5,*) ICON(I)
        ICNT=ICNT+1
C
  150   WRITE(6,63)
        ITYPE(I)=IG
        READ(5,72) IANS
        IF (IANS.EQ.IN1) ITYPE(I)=IL
        IF (IANS.EQ.IN2) ITYPE(I)=IL
C
        WRITE(6,64) ICON(I)
        READ(5,*) VAL(I)
  200   CONTINUE
C
  300   WRITE(8,34) NUMROW,NUMCOL,XCOS,IPASS,ICNT,ICVAL
C
C****WRITE OUT CONSTRAIN INFO
C
        DO 350 I=1,ICNT
        WRITE(8,35) ICON(I),ITYPE(I),VAL(I)
  350   CONTINUE
        STOP
        END
```

INITB.FORT

```
C     INITB.FORT
C
   31 FORMAT(' ENTER NUMBER OF PROJECTS (ROWS)')
   33 FORMAT(' ENTER NUMBER OF CRITERIA (COLUMNS)')
   34 FORMAT(2I3,F10.2,3I3)
   52 FORMAT(' ENTER BUDGET')
   53 FORMAT(' ENTER NUMBER OF THE CRITERION (1 TO ',I2,')')
   55 FORMAT(' TO BE RUN OR THE')
   54 FORMAT(' NUMBER ',I2,' TO RUN THE INITIAL SOLUTION')
C
C
      WRITE(6,31)
      READ(5,*) NUMROW
      WRITE(6,33)
      READ(5,*) NUMCOL
C
C
      WRITE(6,52)
      READ(5,*) XCOS
      WRITE(6,53) NUMCOL
      WRITE(6,55)
      NC=NUMCOL+1
      WRITE(6,54) NC
      READ(5,*) IPASS
      ICNT=0
      ICVAL=0
      WRITE(8,34) NUMROW,NUMCOL,XCOS,IPASS,ICNT,ICVAL
      STOP
      END
```

INITBC.FORT

```
C      INITBC.FORT
C
       DIMENSION ICON(13),ITYPE(13),VAL(13)
C
       DATA IG,IL,IN1,IN2/'G','L','NO','N'/
       DATA IANS/'YES'/
C
   31  FORMAT(' ENTER NUMBER OF PROJECTS (ROWS) IN YOUR DATA ARRAY')
   33  FORMAT(' ENTER NUMBER OF CRITERIA (COLUMNS)')
   34  FORMAT(2I3,F10.2,3I3)
   35  FORMAT(I3,A1,F10.2)
   52  FORMAT(' ENTER BUDGET')
   53  FORMAT(' ENTER NUMBER OF THE CRITERION (1 TO ',I2,')')
   55  FORMAT(' TO BE RUN OR THE')
   54  FORMAT(' NUMBER ',I2,' TO RUN THE INITIAL SOLUTION')
   61  FORMAT(' IN THE FILE YOU ARE USING FOR YOUR CONSTRAINTS,',
     1 ' HOW MANY CRITERIA (COLUMNS) ARE THERE')
   62  FORMAT(' OF THESE ',I3,' CRITERIA, ENTER THE COLUMN ',
     1 'WHICH IS TO BE A CONSTRAINT')
   63  FORMAT(' IS THIS A "GREATER THAN" CONSTRAINT?')
   64  FORMAT(' ENTER THE CONSTRAINT VALUE FOR COLUMN ',I3)
   65  FORMAT(' DO YOU WANT TO ALSO USE ANOTHER COLUMN ',
     1 'AS A CONSTRAINT')
   66  FORMAT(' ENTER THE COLUMN NUMBER')
   68  FORMAT(' IF YOUR CONSTRAINT FILE IS ALSO YOUR DATA FILE',
     1 ' ENTER 0')
   71  FORMAT(A2)
   72  FORMAT(A3)
C
C
       WRITE(6,31)
       READ(5,*) NUMROW
       WRITE(6,33)
       READ(5,*) NUMCOL
C
C
       WRITE(6,52)
       READ(5,*) XCOS
       WRITE(6,53) NUMCOL
       WRITE(6,55)
       NC=NUMCOL+1
       WRITE(6,54) NC
       READ(5,*) IPASS
       ICNT=1
       WRITE(6,61)
       WRITE(6,68)
       READ(5,*) ICVAL
C
C****LOOP THROUGH AND GET CONSTRAINT INFO
```

```
C
      DO 200 I=1.20
      IF (I.NE.1) GO TO 100
C
      IVAL=ICVAL
      IF(IVAL.EQ.0) IVAL=NUMCOL
      WRITE(6,62) IVAL
      READ(5,*) ICON(I)
      GO TO 150
C
  100 WRITE(6,65)
      READ(5,71) IANS
      IF (IANS.EQ.IN1) GO TO 300
      IF (IANS.EQ.IN2) GO TO 300
C
      WRITE(6,66)
      READ(5.*) ICON(I)
      ICNT=ICNT+1
C
  150 WRITE(6,63)
      ITYPE(I)=IG
      READ(5,72) IANS
      IF (IANS.EQ.IN1) ITYPE(I)=IL
      IF (IANS.EQ.IN2) ITYPE(I)=IL
C
      WRITE(6,64) ICON(I)
      READ(5,*) VAL(I)
  200 CONTINUE
C
  300 WRITE(8,34) NUMROW.NUMCOL,XCOS,IPASS,ICNT,ICVAL
C
C****WRITE OUT CONSTRAIN INFO
C
      DO 350 I=1.ICNT
      WRITE(8,35) ICON(I),ITYPE(I).VAL(I)
  350 CONTINUE
      STOP
      END
```

INIT2.FORT

```
C      INIT2.FORT
C
        DIMENSION ICON(13),ITYPE(13),VALC(13)
   34   FORMAT(2I3,F10.2,3I3)
   35   FORMAT(I3.A1.F10.2)
C
        READ (8,34) NUMROW.NUMCOL.XCOS.IPASS.ICCNT,NCCOL
C
C****UPDATE COUNTER FOR NUMBER OF PASSES
C
        IPASS=IPASS+1
C
C****CHECK ON CONSTRAINTS
C
        IF (ICCNT.EQ.0) GO TO 200
C
        DO 100 I=1.ICCNT
        READ(8,35) ICON(I),ITYPE(I).VALC(I)
  100   CONTINUE
C
  200   REWIND 8
        WRITE(8,34) NUMROW,NUMCOL.XCOS.IPASS.ICCNT,NCCOL
C
C****CHECK FOR WRITING CONSTRAINTS BACK OUT
C
        IF (ICCNT.EO.0) GO TO 400
C
        DO 300 I=1.ICCNT
        WRITE(8,35) ICON(I),ITYPE(I).VALC(I)
  300   CONTINUE
C
  400   CONTINUE
C
        STOP
        END
```

INIT3.FORT

```
C      INIT3.FORT
C
       DIMENSION ICON(13),ITYPE(13),VALC(13)
    34 FORMAT(2I3,F1Ø.2,3I3)
    35 FORMAT(I3.A1.F1Ø.2)
C
       READ (8,34) NUMROW,NUMCOL.XCOS,IPASS,ICCNT,NCCOL
C
C****SKIP REST OF CRITERIA SO SET COUNTER TO NUMBER OF COLS
C
C****CHECK ON CONSTRAINTS
C
       IF (ICCNT.EO.Ø) GO TO 2ØØ
C
       DO 1ØØ I=1.ICCNT
       READ(8,35) ICON(I),ITYPE(I).VALC(I)
   1ØØ CONTINUE
C
   2ØØ REWIND 8
       WRITE(8,34) NUMROW,NUMCOL.XCOS.NUMCOL,ICCNT,NCCOL
C
C****CHECK FOR WRITING CONSTRAINTS BACK OUT
C
       IF (ICCNT.EQ.Ø) GO TO 4ØØ
C
       DO 3ØØ I=1.ICCNT
       WRITE(8,35) ICON(I),ITYPE(I).VALC(I)
   3ØØ CONTINUE
C
   4ØØ CONTINUE
C
       STOP
       END
```

MPSCL.DATA

```
PROGRAM
INITIALZ
MOVE(XPBNAME,'SIMPLEX')
MOVE(XDATA,'BIA')
CONVERT
BCDOUT
SETUP('BOUND','INTB','MIN')
MOVE(XOBJ,'OBJ')
MOVE(XRHS.'LHS')
CRASH
PRIMAL
OPTIMIX
EXIT
PEND
```

MPSCL2.DATA

```
PROGRAM
INITIALZ
MOVE(XPBNAME,'SIMPLEX')
MOVE(XDATA,'BIA')
CONVERT
BCDOUT
SETUP('BOUND'.'INTB','MAX')
MOVE(XOBJ,'OBJ1Ø1')
MOVE(XRHS.'LHS')
CRASH
PRIMAL
OPTIMIX
EXIT
PEND
```

BATCH1.DATA

```
//W01160D7 JOB (WP7120D01.D869,5,20),DEASON.CLASS=B
/*ROUTE PRINT N5R190
//*  ***********************************************
//*  CRITERIA SOLUTION USING MPSCL.DATA
//*  ***********************************************
//STEP1 EXEC PGM=DPLCOMP,REGION=500K
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//SYSIN DD DSN=W01160D.MPSCL.DATA,DISP=SHR
//SCRATCH1 DD DSN=&&SCR1,DISP=(NEW,PASS),UNIT=SYSDA,
//   SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH2 DD DSN=&&SCR2,DISP=(NEW,PASS),UNIT=SYSDA,
//   SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH3 DD DSN=&&SCR3,DISP=(NEW,PASS),UNIT=SYSDA,
//   SPACE=(TRK,(25,25)),DCB=BLKSIZE=4000
//SCRATCH4 DD DSN=&&SCR4,DISP=(NEW,PASS),UNIT=SYSDA,
//   SPACE=(TRK,(25,25)),DCB=BLKSIZE=4000
//SYSMLCP DD DSN=&&SYSM,DISP=(NEW,PASS),UNIT=SYSDA,
//   SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
/*
//STEP2  EXEC PGM=DPLEXEC,REGION=500K,TIME=4
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//PROBFILE DD DSN=&&PROB,DISP=(NEW,DELETE),UNIT=SYSDA,
//   SPACE=(TRK,(60,30)),DCB=BLKSIZE=4000
//SCRATCH1 DD DSN=&&SCR1.DISP=(OLD,DELETE)
//SCRATCH2 DD DSN=&&SCR2,DISP=(OLD,DELETE)
//SCRATCH3 DD DSN=&&SCR3.DISP=(OLD,DELETE)
//SCRATCH4 DD DSN=&&SCR4,DISP=(OLD,DELETE)
//SYSMLCP DD DSN=&&SYSM,DISP=(OLD,DELETE)
//MATRIX1  DD DSN=&&MAT1,DISP=(NEW,DELETE),UNIT=SYSDA,
//   SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MATRIX2  DD DSN=&&MAT2,DISP=(NEW,DELETE),UNIT=SYSDA,
//   SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA1  DD DSN=&&ETA1,DISP=(NEW,DELETE),UNIT=SYSDA,
//   SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA2  DD DSN=&&ETA2,DISP=(NEW,DELETE),UNIT=SYSDA,
//   SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MIXWORK  DD DSN=&&MIXW,DISP=(NEW,DELETE),UNIT=SYSDA,
//   SPACE=(TRK,(90.90)),DCB=BLKSIZE=4000
//SYSIN DD DSN=W01160D.LPIN.DATA,DISP=SHR
/*
```

BATCH2.CNTL

```
//W01160D7 JOB (WP7120D01.D869.5,20),DEASON.CLASS=B
/*ROUTE PRINT N5R190
//*   ********************************************
//*   INITIAL SOLUTION USING MPSCL2.DATA
//*   ********************************************
//STEP1 EXEC PGM=DPLCOMP,REGION=500K
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//SYSIN DD DSN=W01160D.MPSCL2.DATA,DISP=SHR
//SCRATCH1 DD DSN=&&SCR1,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH2 DD DSN=&&SCR2,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH3 DD DSN=&&SCR3,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH4 DD DSN=&&SCR4,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SYSMLCP DD DSN=&&SYSM,DISP=(NEW,PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
/*
//STEP2  EXEC PGM=DPLEXEC,REGION=500K,TIME=4
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//PROBFILE DD DSN=&&PROB,DISP=(NEW.DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(60,30)),DCB=BLKSIZE=4000
//SCRATCH1 DD DSN=&&SCR1,DISP=(OLD,DELETE)
//SCRATCH2 DD DSN=&&SCR2,DISP=(OLD,DELETE)
//SCRATCH3 DD DSN=&&SCR3,DISP=(OLD,DELETE)
//SCRATCH4 DD DSN=&&SCR4,DISP=(OLD,DELETE)
//SYSMLCP DD DSN=&&SYSM,DISP=(OLD,DELETE)
//MATRIX1  DD DSN=&&MAT1,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MATRIX2  DD DSN=&&MAT2,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA1  DD DSN=&&ETA1,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA2  DD DSN=&&ETA2,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MIXWORK  DD DSN=&&MIXW,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(90.90)),DCB=BLKSIZE=4000
//SYSIN DD DSN=W01160D.LPIN.DATA,DISP=SHR
/*
```

BATCH3.CNTL

```
//W01160D7 JOB (WP7120D01.D869.5,20),DEASON.CLASS=D
/*ROUTE PRINT N5R190
//*  ********************************************
//*  CRITERIA SOLUTION USING MPSCL.DATA
//*  ********************************************
//STEP1 EXEC PGM=DPLCOMP,REGION=500K
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//SYSIN DD DSN=W01160D.MPSCL.DATA,DISP=SHR3
//SCRATCH1 DD DSN=&&SCR1,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH2 DD DSN=&&SCR2,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH3 DD DSN=&&SCR3,DISP=(NEW,PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH4 DD DSN=&&SCR4,DISP=(NEW,PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SYSMLCP DD DSN=&&SYSM,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
/*
//STEP2  EXEC PGM=DPLEXEC,REGION=500K,TIME=4
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//PROBFILE DD DSN=&&PROB,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK.(60,30)),DCB=BLKSIZE=4000
//SCRATCH1 DD DSN=&&SCR1,DISP=(OLD,DELETE)
//SCRATCH2 DD DSN=&&SCR2,DISP=(OLD,DELETE)
//SCRATCH3 DD DSN=&&SCR3.DISP=(OLD,DELETE)
//SCRATCH4 DD DSN=&&SCR4,DISP=(OLD,DELETE)
//SYSMLCP DD DSN=&&SYSM,DISP=(OLD,DELETE)
//MATRIX1  DD DSN=&&MAT1,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MATRIX2  DD DSN=&&MAT2,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA1  DD DSN=&&ETA1,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA2  DD DSN=&&ETA2,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MIXWORK  DD DSN=&&MIXW,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(90.90)),DCB=BLKSIZE=4000
//SYSIN DD DSN=W01160D.LPIN.DATA,DISP=SHR
/*
```

BATCH4.CNTL

```
//W01160D7 JOB (WP7120D01.D869.5,20),DEASON,CLASS=D
/*ROUTE PRINT N5R190
//*  ********************************************
//*  INITIAL SOLUTION USING MPSCL2.DATA
//*  ********************************************
//STEP1 EXEC PGM=DPLCOMP,REGION=500K
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//SYSIN DD DSN=W01160D.MPSCL2.DATA,DISP=SHR
//SCRATCH1 DD DSN=&&SCR1,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH2 DD DSN=&&SCR2,DISP=(NEW,PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH3 DD DSN=&&SCR3,DISP=(NEW,PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SCRATCH4 DD DSN=&&SCR4,DISP=(NEW.PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
//SYSMLCP DD DSN=&&SYSM,DISP=(NEW,PASS),UNIT=SYSDA,
//    SPACE=(TRK,(25.25)),DCB=BLKSIZE=4000
/*
//STEP2  EXEC PGM=DPLEXEC,REGION=500K,TIME=4
//STEPLIB DD DSN=SYS1.MPSX16.LOADLIB,DISP=SHR
//SYSPRINT DD SYSOUT=A
//PROBFILE DD DSN=&&PROB,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(60,30)),DCB=BLKSIZE=4000
//SCRATCH1 DD DSN=&&SCR1,DISP=(OLD,DELETE)
//SCRATCH2 DD DSN=&&SCR2,DISP=(OLD,DELETE)
//SCRATCH3 DD DSN=&&SCR3.DISP=(OLD,DELETE)
//SCRATCH4 DD DSN=&&SCR4,DISP=(OLD,DELETE)
//SYSMLCP DD DSN=&&SYSM,DISP=(OLD,DELETE)
//MATRIX1  DD DSN=&&MAT1,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MATRIX2  DD DSN=&&MAT2,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA1  DD DSN=&&ETA1,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//ETA2  DD DSN=&&ETA2,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(30.30)),DCB=BLKSIZE=4000
//MIXWORK  DD DSN=&&MIXW,DISP=(NEW,DELETE),UNIT=SYSDA,
//    SPACE=(TRK,(90.90)),DCB=BLKSIZE=4000
//SYSIN DD DSN=W01160D.LPIN.DATA,DISP=SHR
/*
```

FORT.CNTL

```
00010 //VG8H83H1 JOB (840531000.H869.5,5),HARMS.CLASS=A,NOTIFY=VG8H83H
00020 /*ROUTE  PRINT RMT14
00030 //STEP1  EXEC FORTXLIB,PROG=BIA7,MLIB='VG8H83H.BIA.LOAD'
00050 //FORT.SYSIN DD DSN=VG8H83H.BIA7.FORT,DISP=SHR
00060 /*
00070 //
```

PRNT.CNTL

```
//W01160D5 JOB (WP7120D01.D869.5.20),DEASON.CLASS=B
/*ROUTE PRINT ###
//* TIME: TIMERUN
//* DATE: DATERUN
//* DESCRIPTION
//STEP1 EXEC PGM=IEBPTPCH
//SYSPRINT DD  SYSOUT=A
//SYSUT1 DD DSN=W01160D.???,DISP=SHR
//SYSUT2 DD SYSOUT=A,DCB=BLKSIZE=133
//SYSIN  DD *
    PRINT  PREFORM=A
    TITLE ITEM=('DESCRIPTION',30)
/*
```

APPENDIX E

Listing of Separable Irrigation and Power Divisions

This appendix contains a listing of geographically separate divisions of BIA irrigation and power projects. Although the various divisions may not be totally independent hydrologically (more than one may be served by a common main canal, or some may use return flows from others), the lands served in each division are distinct geographically and can be considered independent for purposes of analysis. That is, calculations of crop production, numbers of people served, and so on can be made within each division with no overlap.

Divisions marked with an "x" under the "new construction" column heading are in need of additional funding for the construction of new facilities in order to complete the unit to planned capacity. That is, new construction is required to serve irrigable acreage that is planned under existing plans or designation reports, but which are not currently served; to build new storage or power generation facilities; or to serve new power customers. Divisions with no mark under "new construction" are complete. Divisions marked with an "x" under "rehabilitation and betterment" are in need of funding to bring the facilites to a fully operational state.

Entries under the "reference" column provide information on the most significant source document used to determine whether each division may be treated as a geographically and operationally separate unit. In addition, most of the indicated references provide detailed information on the units planned for construction or rehabilitation.

Aberdeen Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Standing Rock	Fort Yates	x		(210, p. 2-5)
Lower Brule	Grass Rope	x		(258, p. 1)

Albuquerque Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Nambe	Nambe	x	x	(211, p. 48)
Picuris	Picuris	x	x	(183, p. 204)
Pojoaque	Pojoaque	x	x	(211, p. 51)
San Ildefonso	Pojoaque Unit	x	x	(211, p. 54)
	Rio Grande Unit	x	x	(211, p. 54)
San Juan	San Juan	x	x	(211, p. 62)
Santa Clara	Santa Clara	x	x	(211, p. 58)
Taos	Taos	x	x	(273, p. 29)
Tesuque	Tesuque	x	x	(211, p. 45)
Cochiti	Cochiti	x	x	(221, p. 14)
Isleta	Isleta	x	x	(221, p. 12)
Sandia	Sandia	x	x	(221, p. 11)
San Felipe	San Felipe	x	x	(221, p. 13)
Santa Ana	Santa Ana	x	x	(221, . 9)
Santo Domingo	Santo Domingo	x	x	(256, p. 10)
Acoma	Acoma	x	x	(183, p. 163)
Jemez	Jemez	x	x	(257, p. iv)
Laguna	Laguna	x	x	(273, p. 29)
Zia	Zia	x	x	(257, p. iv)
Jicarilla	Dulce	x	x	(222, p. 13)
	John Mills	x	x	(222, p. 13)
	La Jara	x	x	(222, p. 13)
	Martinez	x	x	(222, p. 13)
	Enbem	x	x	(222, p. 13)
Mescalero	Tularosa Valley	x	x	(223, p. 1)
	Three Rivers	x	x	(223, p. 1)
	Maruche	x	x	(223, p. 1)
	Cherokee Bill	x	x	(223, p. 1)
Zuni	Nutria	x	x	(253, p. i)
	Pescado	x	x	(253, p. i)
	Zuni	x	x	(253, p. i)
Southern Ute	Ceanaboo Ditch	x	x	(219, p. 10)
	La Boca	x	x	(219, p. 10)

Albuquerque Area (continued)

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
	Severo	x	x	(219, p. 10)
	Dr. Morrison Ditch	x	x	(219, p. 10)
	Pine River	x	x	(219, p. 10)
	Florida	x	x	(256, p. A-12)
	Mancos	x	x	(220, p. 1c)
	Ismay Draw	x	x	(220, p. 1c)

Billings Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Blackfeet	Two Medicine	x	x	(225, p. 78)
	Badger Fisher	x	x	(225, p. 78)
	Birch Creek (Piegan)	x	x	(225, p. 78)
Crow	Pryor	x	x	(224, p. 2-1)
	Agency	x	x	(224, p. 2-1)
	Reno	x	x	(224, p. 2-1)
	Big Horn	x	x	(224, p. 2-1)
	Soap Creek	x	x	(224, p. 2-1)
	Lodge Grass 1	x	x	(224, p. 2-1)
	Lodge Grass 2	x	x	(224, p. 2-1)
	Forty Mile	x	x	(224, p. 2-1)
	Upper Little Horn #2	x	x	(213, p. IV.2)
Fort Belknap	Milk	x	x	(215, p. 7-22)
	White Bear	x	x	(215, p. 7-22)
	Three Mile	x	x	(215, p. 7-23)
	Peoples Creek	x		(215, p. 7-23)
Fort Peck	Frazier-Wolf Point	x	x	(216, p. 6-19)
	Wiota	x	x	(216, p. 6-19)
N. Cheyenne	Rosebud Creek	x	x	(214, p. IV.2)
	Lame Bear Creek	x	x	(214, p. IV.2)
	Muddy Creek	x	x	(214, p. IV.2)
	Birney Canal	x	x	(214, p. IV.2)
	Tongue River	x	x	(214, p. IV.2)
	Pumpsites	x	x	(214, p. IV.2)
Wind River	Little Wind	x	x	(218, p. V.10)
	Upper Wind	x	x	(218, p. V.10)
	Coolidge	x	x	(218, p. V.10)
	Johnstown	x	x	(218, p. V.10)
	Le Clair Riverton	x	x	(218, p. V.10)
	Left Hand	x	x	(218, p. V.10)
Rocky Boys	Rocky Boys	x	x	(217, p. 7-10)

Navajo Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Navajo	Hogback	x	x	(273, p. 34)
	NIIP Block 6	x		(226, p. I-3)
	NIIP Block 7	x		(226, p. I-3)
	NIIP Block 8	x		(226, p. I-3)
	NIIP Block 9	x		(226, p. I-3)
	NIIP Block 10	x		(226, p. I-3)
	NIIP Block 11	x		(226, p. I-3)

Phoenix Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Kaibab	Kaibab	x		(273, p. 30)
Gila River	San Tan Canal	x	x	(76, p. 13)
	South Side Canal	x	x	(76, p. 13)
	North Side Canal	x	x	(76, p. 13)
	Pima Lateral	x	x	(76, p. 13)
	Casa Blanca Canal	x	x	(76, p. 13)
	San Carlos Power	x	x	(230, p. I-3)
	Joint Works		x	(76, p. 11)
	Gila Crossing	x	x	(273, p. 32)
	Maricopa Colony		x	(273, p. 32)
Ak Chin	Ak Chin	x	x	(16, p. 32)
Fort McDowell	Fort McDowell	x		(174, p. V-5)
Salt River	Salt River		x	(231, p. 72)
Colorado River	Colorado River Irr	x		(228, p. 10)
	Colorado River Power	x	x	(229, App. B)
Fort Yuma	Fort Yuma		x	(273, p. 33)
San Carlos	San Carlos	x	x	(238, p. IV-13)
Fort Apache	Fort Apache	x	x	(240, p. 14)
Papago	Chuichu		x	(244, p. 1)
	San Xavier	x	x	(186, p. 8)
	Vaiva Vo	x	x	(239, p. 10)
Camp Verde	Camp Verde		x	(238, p. IV-15)
Havasupai	Havasupai		x	(231, p. 44)
Uintah and Ouray	Uintah	x	x	(233, p. iii)
Uncompahgre	Uncompahgre	x	x	(273, p. 31)
Skull Valley	Skull Valley	x	x	(231, p. 135)
Duck Valley	Duck Valley	x	x	(232, p. 18)
	Blue Creek	x		(232, p. 24)
	Mary's Creek	x		(232, p. 24)

Phoenix Area (continued)

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Goshute	Georgetta		x	(237, p. 11)
	Probert and Snively		x	(237, p. 11)
	Old Indian		x	(237, p. 11)
Te Moak	South Fork		x	(236, p. 21)
Duckwater	Duckwater		x	(235, p. 14)
Odgers Ranch	Odgers Ranch		x	(273, p. 31)
Fort McDermitt	Fort McDermitt Reserve		x	(231, p. 104)
	Hern Ranch		x	(231, p. 104)
	Giacometto Ranch		x	(231, p. 104)
Fallon	Fallon	x	x	(231, p. 102)
Moapa	Moapa		x	(253, p. i)
Pyramid Lake	Wadsworth	x	x	(275, p. 45)
	Nixon	x	x	(275, p. 45)
Washoe	Washoe Ranch		x	(231, p. 126)
Yomba	Yomba		x	(231, p. 131)
Yerington	Campbell Ranch	x	x	(231, p. 129)
Summitt Lake	Summitt Lake		x	(231, p. 123)
Walker River	Walker River		x	(227, p. 7)
Cocopah	Cocopah	x	x	(231, p. 10)
Yuma Homesteads	Yuma Homesteads	x	x	(273, p. 32)

Portland Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Yakima	Wapato-Satus		x	(243, App. A)
	Ahtanum		x	(204, p. i)
	Toppenish- Simcoe		x	(244, p. 66)
	Mabton		x	(245, p. 4)
	White Swan	x	x	(248, p. 3)
	Wapato Add'l Works		x	(241, p. i)
Fort Hall	Fort Hall		x	(246, p. vi)
	Michaud		x	(246, p. vi)
	Minor Units (Ross Fork, Lincoln Creek, Bannock Creek)		x	(242, p. ii)
Colville	East Omak	x	x	(254, p. 47)
	North Monse	x	x	(254, p. 47)
	South Monse	x	x	(254, p. 47)
	Blue Bottle Flat	x	x	(254, p. 47)

Portland Area (continued)

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Colville	Grape	x	x	(254, p. 47)
	Goose Flat	x	x	(254, p. 47)
	South Nespelem	x	x	(254, p. 47)
	North Nespelem	x	x	(254, p. 47)
	Inchelium	x	x	(254, p. 47)
	Sanpoil	x	x	(254, p. 47)
	Swawilla Basin	x	x	(254, p. 47)
Warm Springs	Warm Springs	x	x	(247, App. 1)
	Mill Creek	x	x	(247, App. 1)
Spokane	Spokane	x	x	(255, p. 27)
Flathead	Mission Valley		x	(212, p. I-3)
	Camas Division		x	(212, p. I-3)
	Jocko Division		x	(212, p. I-3)
	Flathead Power	x	x	(212, p. 1)

Sacramento Area

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Augustine	Coachella Valley	x	x	(273, p. 33)
Big Pine	Big Pine	x	x	(273, p. 33)
Bishop	Bishop	x	x	(273, p. 33)
Ft. Independence	Ft. Independence	x	x	(273, p. 33)
Lone Pine	Lone Pine	x	x	(273, p. 33)
Colusia	Colusia	x	x	(273, p. 33)
Fort Bidwell	Fort Bidwell	x	x	(273, p. 33)
Rumsey	Rumsey	x	x	(273, p. 33)
Santa Rosa	Santa Rosa	x	x	(273, p. 33)
Tule River	Tule River	x	x	(273, p. 33)
Tuolumne	Tuolumne	x	x	(273, p. 33)
XL Ranch	System 1	x	x	(273, p. 33)
	System 2	x	x	(273, p. 33)
	System 3	x	x	(273, p. 33)
	System 4	x	x	(273, p. 33)
	System 5	x	x	(273, p. 33)
	System 6	x	x	(273, p. 33)
Hoopa	Campbell Field	x	x	(249, p. 11)
	Soctish Field	x	x	(249, p. 9)
	Agency Field	x	x	(249, p. 10)
	Matilton Field	x	x	(249, p. 10)
	Hostler Field	x	x	(249, p. 9)
	Norton Field	x	x	(249, p. 8)

Sacramento Area (continued)

Reservation	Division Name	New Construction	Rehabilitation and Betterment	Reference
Hoopa	Mescat Field	x	x	(249, p. 8)
Pala	Pala	x	x	(273, p. 33)
Rincon	Rincon	x	x	(273, p. 33)
La Jolla	La Jolla	x	x	(273, p. 33)
Morongo	Morongo	x	x	(250, p. I-1)
Pauma	Puama	x	x	(273, p. 33)

APPENDIX F

Decision Support System Input Data

This appendix contains input data used in the test implementation of the decision support system described in Chapter 7. Each data element a_{ij} represents the contribution to objective j resulting from construction of project division x_i. A complete discussion of the data base, including assumptions made and sources of potential data error, are contained in Chapter 6.

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Blackfeet Const	10990	29	47	40	0	464	470	320	0	1697	0	9.092
Blackfeet R&B	0	55	0	122	0	53	0	59	0	0	43600	2.579
Crow Const	5426	7	33	33	0	95	330	224	0	527	0	3.178
Crow R&B	0	18	0	148	0	15	0	60	0	0	42600	0.676
Ft Belknap Const	2818	67	0	3	0	54	0	0	0	151	0	0.919
Ft Belknap R&B	0	244	0	16	0	10	0	0	0	0	8200	1.024
Ft Peck Const	3049	29	41	17	0	136	410	40	0	353	0	2.082
Ft Peck R&B	0	5	0	102	0	22	0	21	0	0	6400	0.321
N Cheyenne Const	2100	42	25	0	0	210	250	0	0	301	0	1.716
N Cheyenne R&B	0	24	0	0	0	7	0	0	0	0	1710	0.545
Wind River Const	10275	108	19	162	0	328	190	246	0	4828	0	25.033
Wind River R&B	0	205	0	526	0	39	0	40	0	0	3800	5.789
Rocky Boys Const	262	0	0	0	52	0	0	0	13	15	0	0.075
Rocky Boys R&B	0	0	0	0	91	0	0	0	3	0	500	0.033
Nambe Const	480	0	0	0	48	0	0	0	72	30	0	0.586
Nambe R&B	0	0	0	0	26	0	0	0	2	0	800	0.370
Picuris Const	135	0	0	0	15	0	0	0	23	27	0	0.229
Picuris R&B	0	0	0	0	9	0	0	0	1	0	250	0.240
Pojoaque Const	165	0	0	0	33	0	0	0	12	37	0	0.208
Pojoaque R&B	0	0	0	0	4	0	0	0	0	0	60	0.115
San Ildefonso Const	659	0	0	40	54	0	0	14	30	234	0	1.322
San Ildefonso R&B	0	0	0	3	12	0	0	0	0	0	400	0.400
San Juan Const	1200	0	0	0	38	0	0	0	90	845	0	4.309
San Juan R&B	0	0	0	0	25	0	0	0	4	0	2400	1.200
Santa Clara Const	453	0	0	14	29	0	0	6	24	495	0	2.553
Santa Clara R&B	0	0	0	50	50	0	0	1	2	0	1500	0.550
Taos Const	4897	0	0	0	408	0	0	0	367	783	0	4.018
Taos R&B	0	0	0	0	89	0	0	0	6	0	3300	1.620
Tesuque Const	773	0	0	0	193	0	0	0	58	141	0	0.734
Tesuque R&B	0	0	0	0	7	0	0	0	0	0	75	0.420

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Cochiti Const	848	0	0	0	8	0	0	0	64	177	0	0.895
Cochiti R&B	0	0	0	0	8	0	0	0	4	0	2600	0.126
Isleta Const	1502	0	0	0	54	0	0	0	113	558	0	2.837
Isleta R&B	0	0	0	0	165	0	0	0	14	0	13700	0.483
Sandia Const	1541	0	0	0	22	0	0	0	116	475	0	2.394
Sandia R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
San Felipe Const	2321	0	0	0	68	0	0	0	174	572	0	2.916
San Felipe R&B	0	0	0	0	49	0	0	0	8	0	5000	0.744
Santa Ana Const	21	0	0	0	1	0	0	0	2	139	0	0.695
Santa Ana R&B	0	0	0	0	14	0	0	0	6	0	3400	0.371
Santo Domingo Cons	1227	0	0	0	27	0	0	0	92	459	0	2.355
Santo Domingo R&B	0	0	0	0	53	0	0	0	12	0	7100	1.345
Acoma Const	522	0	0	0	52	0	0	0	39	540	0	2.782
Acoma R&B	0	0	0	0	184	0	0	0	9	0	5400	0.788
Jemez Const	277	0	0	0	14	0	0	0	21	263	0	1.366
Jemez R&B	0	0	0	0	91	0	0	0	6	0	5500	0.617
Laguna Const	1521	0	0	0	169	0	0	0	114	530	0	2.715
Laguna R&B	0	0	0	0	186	0	0	0	8	0	5100	0.876
Zia Const	234	0	0	0	13	0	0	0	18	96	0	0.512
Zia R&B	0	0	0	0	29	0	0	0	2	0	1500	0.020
Jicarilla Const	43	0	0	0	1	0	0	0	3	175	0	0.881
Jicarilla R&B	0	0	0	0	5	0	0	0	1	0	400	0.095
Mescalero Const	40	0	0	0	1	0	0	0	3	20	0	0.103
Mescalero R&B	0	0	0	0	12	0	0	0	2	0	1200	0.916
Zuni Const	2946	75	15	0	0	295	150	0	0	1500	0	31.306
Zuni R&B	0	0	0	0	0	41	0	0	0	0	24700	1.264
Southern Ute Const	1059	219	0	0	0	95	0	0	0	59	0	0.377
Southern Ute R&B	0	260	0	0	0	55	0	0	0	0	35800	1.281
Ute Mountain Const	7700	48	24	0	0	693	240	0	0	1100	0	6.572
Ute Mountain R&B	0	5	0	0	0	2	0	0	0	0	900	0.066

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Kaibab Const	45	0	0	0	9	0	0	0	1	100	0	0.830
Kaibab R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
San Carlos Irr Cn	36042	405	225	45	0	9720	2250	720	0	2000	0	56.740
San Carlos Irr R&B	0	163	0	18	0	1304	0	144	0	0	68600	20.000
San Carlos Pwr Cn	0	0	0	0	0	0	0	0	0	0	0	14.500
San Carlos Pwr R&B	0	0	0	0	0	0	0	0	0	0	0	5.450
Ak Chin Const	18000	112	56	0	0	4480	560	0	0	500	0	84.000
Ak Chin R&B	0	13	0	0	0	312	0	0	0	0	4000	0.200
Ft McDowell Const	600	15	0	0	0	2	0	0	0	150	0	0.905
Ft McDowell R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Salt River Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Salt River R&B	0	0	0	250	0	0	0	465	0	0	11600	10.300
Colo River Irr Cn	30575	28	89	150	0	2167	890	7740	0	5000	0	47.000
Colo River Irr R&B	0	72	0	376	0	647	0	129	0	0	292600	21.000
Colo River Pwr Cn	0	0	0	0	0	0	0	0	0	0	0	7.100
Colo River Pwr R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Fort Yuma Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Fort Yuma R&B	0	12	0	65	0	62	0	325	0	0	23200	16.000
San Carlos Res Cn	1681	21	10	0	0	126	100	0	0	300	0	1.763
San Carlos Res R&B	0	8	0	0	0	13	0	0	0	0	2000	1.600
Fort Apache Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Fort Apache R&B	0	0	0	0	490	0	0	0	0	10	8700	2.271
Chuichu Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Chuichu R&B	0	4	0	0	0	0	0	0	0	0	5000	0.750
San Xavier Const	0	0	0	0	0	0	0	0	0	0	0	0.000
San Xavier R&B	0	23	0	0	0	0	0	0	0	0	3500	0.500
Camp Verde Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Camp Verde R&B	0	1	0	0	20	3	0	0	1	0	600	0.098
Havasupai Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Havasupai R&B	0	0	0	0	20	0	0	0	1	0	500	0.050

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Uintah Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Uintah R&B	18795	146	38	103	0	876	380	309	0	1000	74900	26.058
Utah Misc Const	6521	65	0	88	0	390	0	264	0	1800	0	10.051
Utah Misc R&B	0	25	0	38	0	6	0	5	0	0	3400	0.520
Uncompahgre Const	18186	177	114	278	0	2124	1140	1668	0	433	0	23.097
Uncompahgre R&B	0	17	0	26	0	8	0	6	0	0	7000	0.690
Skull Valley Const	6022	150	0	0	50	405	0	0	135	890	0	4.943
Skull Valley R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Duck Valley Const	998	6	3	0	0	144	30	0	0	100	0	4.919
Duck Valley R&B	0	69	0	0	0	88	0	0	0	0	22000	2.330
Goshute Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Goshute R&B	508	0	0	0	66	0	0	0	84	10	1300	0.335
South Fork Const	0	0	0	0	0	0	0	0	0	0	0	0.000
South Fork R&B	974	24	0	1	0	38	0	0	0	25	6200	3.715
Duckwater Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Duckwater R&B	970	24	0	0	2	38	0	0	0	25	1900	1.499
Odgers Ranch Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Odgers Ranch R&B	350	24	0	0	0	30	0	0	0	10	1200	0.310
Ft McDermitt Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Ft McDermitt R&B	0	75	0	0	0	53	0	0	0	0	7100	0.650
Fallon Const	2677	268	0	0	0	401	0	0	0	1000	0	6.905
Fallon R&B	0	220	0	0	0	6	0	0	0	0	4400	2.640
Moapa Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Moapa R&B	0	108	0	0	0	9	0	0	0	0	1200	0.089
Pyramid Lake Const	2108	53	10	0	0	136	100	0	0	380	0	2.223
Pyramid Lake R&B	0	0	0	0	0	22	0	0	0	0	2200	0.500
Washoe Ranch Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Washoe Ranch R&B	0	48	0	0	0	14	0	0	0	0	1000	0.157
Yomba Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Yomba R&B	0	44	0	0	0	18	0	0	0	0	7000	0.150

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Campbell Ranch Cn	0	0	0	0	0	0	0	0	0	0	0	0.000
Campbell Ranch R&B	0	21	0	0	0	10	0	0	0	0	2100	0.275
Summit Lake Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Summit Lake R&B	0	0	0	1	0	0	0	1	0	0	800	0.040
Walker River Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Walker River R&B	0	133	0	1	200	50	0	0	18	0	5600	4.252
Vaiva Vo Const	720	880	3	0	0	144	30	0	0	200	0	1.360
Vaiva Vo R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Gila Crossing Cn	1993	10	10	15	0	239	100	239	0	570	0	3.458
Gila Crossing R&B	0	5	0	8	0	20	0	15	0	0	3000	1.900
Maricopa Colony Cn	0	0	0	0	0	0	0	0	0	0	0	0.000
Maricopa Colony R&B	0	48	0	0	0	66	0	0	0	0	3900	0.600
Cocopah Const	1347	0	5	45	0	0	50	337	0	400	0	2.040
Cocopah R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Yuma Homestead Cn	35	0	0	50	0	0	0	9	0	10	0	0.070
Yuma Homestead R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Yakima Addl Works Cn	0	0	0	0	0	0	0	0	0	0	0	0.000
Yakima Addl Works R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Wapato-Satus Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Wapato-Satus R&B	0	203	0	789	0	407	0	631	0	0	200700	60.600
Ahtahum Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Ahtahum R&B	0	5	0	40	0	9	0	32	0	0	7200	2.025
Toppenish-Simcoe Cn	0	0	0	0	0	0	0	0	0	0	0	0.000
Toppenish-Simcoe R&B	0	18	0	7	0	35	0	5	0	0	10900	1.230
Klickitat Const	30000	188	94	187	0	2250	940	1200	0	1000	0	160.000
Klickitat R&B	0	0	0	0	0	0	0	0	0	0	0	0.000
Michaud Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Michaud R&B	0	250	0	250	0	62	0	31	0	0	64400	8.388
Fort Hall Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Fort Hall R&B	0	580	0	580	0	142	0	71	0	0	144500	25.000

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Flathead Irr Const	4856	36	296	23	0	207	2960	66	0	2000	0	12.408
Flathead Irr R&B	0	9	0	138	0	4	0	34	0	0	71600	20.000
Flathead Power Const	0	0	10	0	0	0	0	0	0	0	0	5.000
Flathead Power R&B	0	0	0	0	0	0	0	0	0	0	0	10.000
Coachella Const	4264	0	5	53	0	0	50	213	0	500	0	3.995
Coachella R&B	1961	0	2	25	0	0	20	98	0	100	500	1.450
Big Pine Const	59	6	0	0	0	4	0	0	2	15	0	0.104
Big Pine R&B	130	13	0	0	13	10	0	0	5	10	300	0.151
Bishop Const	148	15	0	0	15	8	0	0	8	30	0	0.232
Bishop R&B	0	0	0	0	145	0	0	0	13	0	2200	0.585
Fort Ind Const	85	0	0	0	17	0	0	0	11	10	0	0.115
Fort Ind R&B	0	0	0	0	26	0	0	0	2	0	200	0.100
Lone Pine Const	77	0	0	0	15	0	0	0	8	10	0	0.098
Lone Pine R&B	0	0	0	0	32	0	0	0	8	0	500	0.072
Colusia Const	118	0	0	0	24	0	0	0	12	10	0	0.083
Colusia R&B	0	0	0	0	20	0	0	0	1	0	300	0.010
Fort Bidwell Const	72	0	0	0	15	0	0	0	9	10	0	0.054
Fort Bidwell R&B	0	0	0	0	46	0	0	0	6	0	700	0.068
Rumsey Const	0	0	0	0	0	0	0	0	0	0	0	0.000
Rumsey R&B	0	0	0	0	13	0	0	0	2	0	200	0.010
Santa Rosa Const	55	0	0	0	11	0	0	0	7	10	0	0.044
Santa Rosa R&B	0	0	0	0	11	0	0	0	3	0	150	0.033
Tule River Const	135	0	0	0	27	0	0	0	17	20	0	0.162
Tule River R&B	0	0	0	0	10	0	0	0	1	0	50	0.006
Tuolomne Const	15	0	0	0	8	0	0	0	1	5	0	0.021
Tuolomne R&B	0	0	0	0	18	0	0	0	1	0	100	0.021
XL Ranch Const	600	14	0	0	25	55	0	0	6	75	0	0.480
XL Ranch R&B	0	18	0	0	33	18	0	0	3	0	2400	0.200
Hoopa Valley Const	257	5	0	0	29	20	0	0	7	25	0	0.200
Hoopa Valley R&B	0	25	0	0	40	25	0	0	5	0	3600	0.533

Division	OBJ 1	OBJ 2	OBJ 3	OBJ 4	OBJ 5	OBJ 6	OBJ 7	OBJ 8	OBJ 9	OBJ 10	OBJ 11	Cost
Pala Const	4278	100	20	0	0	856	200	0	0	250	0	2.996
Pala R&B	508	13	0	0	0	102	0	0	0	0	350	0.333
Rincon Const	3199	80	15	0	0	960	150	0	0	200	0	2.239
Rincon R&B	343	9	0	0	0	103	0	0	0	0	250	0.247
La Jolla Const	1334	12	5	0	67	200	50	0	67	100	0	0.573
La Jolla R&B	100	0	0	0	5	0	0	0	20	0	0	0.045
Morongo Const	813	0	0	0	163	0	0	0	163	100	0	2.722
Morongo R&B	412	0	0	0	28	0	0	0	87	0	400	0.812
Pauma Const	132	0	0	0	26	0	0	0	20	10	0	0.090
Pauma R&B	75	0	0	0	20	0	0	0	12	0	100	0.026
Hogback Const	3946	2	5	0	234	60	50	0	709	300	0	6.343
Hogback R&B	0	14	0	0	437	88	0	0	164	0	59900	0.807
Navajo Const	60630	10000	100	0	0	4547	1000	0	0	5000	0	418.388
Navajo R&B	0	0	0	0	0	0	0	0	0	0	0	0.000

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