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IIASA Working Paper

WP-85-059

September 1985

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INTERACTIVE DECISION ANALYSIS IN ENERGY PLANNING AND POLICY ASSESSMENT

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PREFACE

In recent years, there has been considerable fruitful collaboration between the System and Decision Sciences (SDS) Program and the Energy Project at IIASA. This paper gives an overview of this joint work, which involves the use of methodological tools developed in SDS to analyze decision situations based on models constructed in the Energy Project.

The paper starts with a study of the use of the earliest version of DIDASS in conjunction with the energy supply model MESSAGE. It then describes how construction of more advanced energy models such as MESSAGE II, SEMA (an Austrian energy model), and GATE (a model of gas trade in Europe) took place in parallel with the development of an interactive multiple-criteria LP-solver (IMM), which represents a first step towards the integration of modeling and optimization processes in the analysis of complex decision situations.

We hope that such collaboration will continue to provide a driving force for advances in different areas of IIASA research.

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INTERACTIVE DECISION ANALYSIS IN ENERGY PLANNING AND POLICY ASSESSMENT

M. Grauer, S. Messner and M. Strubegger

1. INTRODUCTION

The explosive growth in the market prices of various forms of energy (especially of oil) over the last decade has made the question of future energy supplies a major political issue in almost all countries of the world. Decisions concerning energy supply can have far-reaching consequences, influencing, among other things, the quality of the environment, the state of the economy (balance of trade deficit, unemployment), the level of dependence on foreign energy sources, general standard of living and the national distribution of costs and benefits. All of these factors should be considered in energy planning and policy assessment – the main objectives of this process are discussed in Section 2.

Analytic models may be used to help decision makers to cope with the wide range of issues related to the energy problem. Energy models have been developed for planning purposes at the regional, national and international levels; their scope ranges from engineering models of different energy conversion technologies, through sectoral models dealing with the demand and/or supply of particular fuels and models encompassing the entire energy system, to models describing the energy system as an integral part of the economy. A survey of these energy models is given in Section 3. Section 4 presents a multicriteria energy analysis based on a specific energy model (the energy supply model MESSAGE developed at IIASA) and the reference point optimization method. The case studies presented in Sections 4 and 5 demonstrate how tradeoffs between different, not directly comparable objectives can be identified and quantified in a dynamic, interactive procedure. Section 5 describes an interactive system for the analysis of energy strategies. This is based on an extended version of MESSAGE and a multiple-criteria decision support system (DIDASS) developed at IIASA. Thus, interactive multiple-criteria analysis can be used to help decision makers evaluate efficient alternatives and if possible achieve a satisfactory compromise between conflicting strategic goals.

2. MAIN AIMS IN ENERGY PLANNING

When analyzing the future development of an energy system it is necessary (i) to consider a number of quantifiable objectives, (ii) to take into account non-quantifiable objectives and (iii) to study the time dependence of these objectives and thus the interplay between them over time. A detailed discussion of the types of objectives that can be included in an analytic model and those that resist quantification is given in [1].

We shall take the situation in The Netherlands as an example. The social impacts of decisions linked with energy research and development in this country are discussed in [2]; the associated objectives are structured hierarchically, as shown in Figure 1. Although this structure is based on the Dutch situation the objectives are generally valid and include many crucial criteria such as impact on balance of payments, effects on employment and environmental aspects.

Energy R&D should help to achieve a well-balanced national energy economy and to consolidate the ability of Dutch industry to compete on both home and foreign markets					
Thus, the aims of energy R & D should be					
To diversify and secure energy supply by:	To increase energy efficiency by:	To increase the social acceptability of new energy systems by:	To create innovative industrial activity by:	To facilitate long-term energy management by:	To promote high-level scientific activity by:
• minimizing strategic risks	• improving extraction, conversion, distribution, and consumption technologies	• adapting modern energy systems to demands related to public health, safety & environmental protection	• urgent updating of technical know-how and implementation of modern technology	• achieving a sustainable society	• long-term industrial development
• studying short- & long-term availability of supplies	• development of high-yield technologies	• awareness of pressure groups pro & con	• exploiting advantages related to the Dutch energy position and industry	• funding basic R&D or research aimed at a breakthrough	• creating and maintaining scientific "cutting edges"
• studying technological & economic feasibility of supply options	• reduction of energy demand	• studying problems faced by public authorities	• studying commercial feasibility	• addressing problems connected with the depletion of finite high-quality energy sources	• exploiting specific features of Dutch R&D
• studying the flexibility & adaptability of existing & new facilities	• utilization of residues		• studying the impact on employment	• management of uncertainty in the long-term development of energy prices	• promoting international interest in results
• studying the impact on the balance of payments			• studying the impact on other developments in science and industry		

Figure 1. Hierarchy of main objectives of energy R&D in The Netherlands (based on [2]).

The case studies presented in Sections 4 and 5 take factors (i)–(iii) into account by using methodology derived from the paradigm of satisficing decision making, which makes it possible to combine the "hard" information obtained from analytic energy models with "soft" information on, for example, the social or political impacts of particular alternatives. The "soft" information is incorporated by involving the decision maker in an *interactive* dialogue with the computerized decision support system: the decision process develops as an adaptive learning procedure driven by the decision maker. A more detailed description of the achievement scalarizing approach used in this system and some of its applications is given in [3].

3. A SURVEY OF ENERGY MODELS

The development of energy models requires the use of theoretical and analytical methods from several disciplines: engineering, econometrics, operations research, and computer sciences. The reasons for this lie in the history of energy modeling, which reaches back some twenty years to the 1960s. Although efforts to develop energy models began well before the first oil crisis in 1973, it was growing awareness of the energy problem caused by this event that brought about an explosion in energy modeling.

The energy models developed in the sixties focussed mainly upon the supply and demand of a single energy form or fuel such as electricity, oil or natural gas. Faced with the complex problem of optimal allocation of crude oil and oil products between different sources, refineries and demand centers, the petroleum companies developed large allocation models, as well as models of the refining process [4]. The electricity utilities also used sectoral models with some success. Their models evaluate the optimal strategy for expanding a power plant system to meet an increasing demand for electricity. They determine the technology mix and plant installation program that achieves minimum overall cost (i.e., capital, fuel and operating costs). This multiple-criteria problem is usually solved as a single-objective problem by assigning weights (using a discount rate) to the different criteria (i.e., the types of costs to be minimized).

All of the energy models mentioned above focus on the supply side: they look for the "best" way to satisfy an assumed energy demand. Energy demand is an exogenous input to these models and is often provided by econometric demand models which estimate energy or fuel demand as a function of energy prices and other determinants such as population, economic growth, etc.

A major criticism of sectoral, single-fuel models is that they treat the development of the sector or fuel in question in isolation from the rest of the energy and economic system, thereby ignoring the fact that there are many different ways to satisfy demands for, say, space heat, industrial process heat and transportation. A sectoral, single-fuel model cannot adequately describe the interfuel substitution caused by changing energy prices, technological development or environmental considerations.

The need to take these factors into account was the main reason for the development of models which describe the flow of energy from different primary energy sources through various conversion processes to meet different energy requirements. Work on these *energy system models* began in the early 1970s. The energy reference system shown in Figure 2 illustrates the structure of such an energy system model.

Most energy system models are based on network representations and the energy balance approach. Using a network that describes the flows from resources (coal, oil, gas, nuclear power, solar power) to various demand sectors (industrial, transportation, commercial, household) as a simple accounting framework, it is possible to simulate and evaluate different ways of satisfying an estimated increase in demand in each of the major end-use sectors. The results provide information about primary energy consumption, required conversion capacity, etc. This type of model may also be extended to consider environmental aspects, for example, by taking into account the effects of sulfur dioxide (SO_2) emissions from power plants.

In addition to the development of network accounting models, work on a series of optimizing models of energy systems was initiated at the beginning of the 1970s. These models were designed to determine the optimal allocation of resources, conversion technologies and end-use technologies using a network

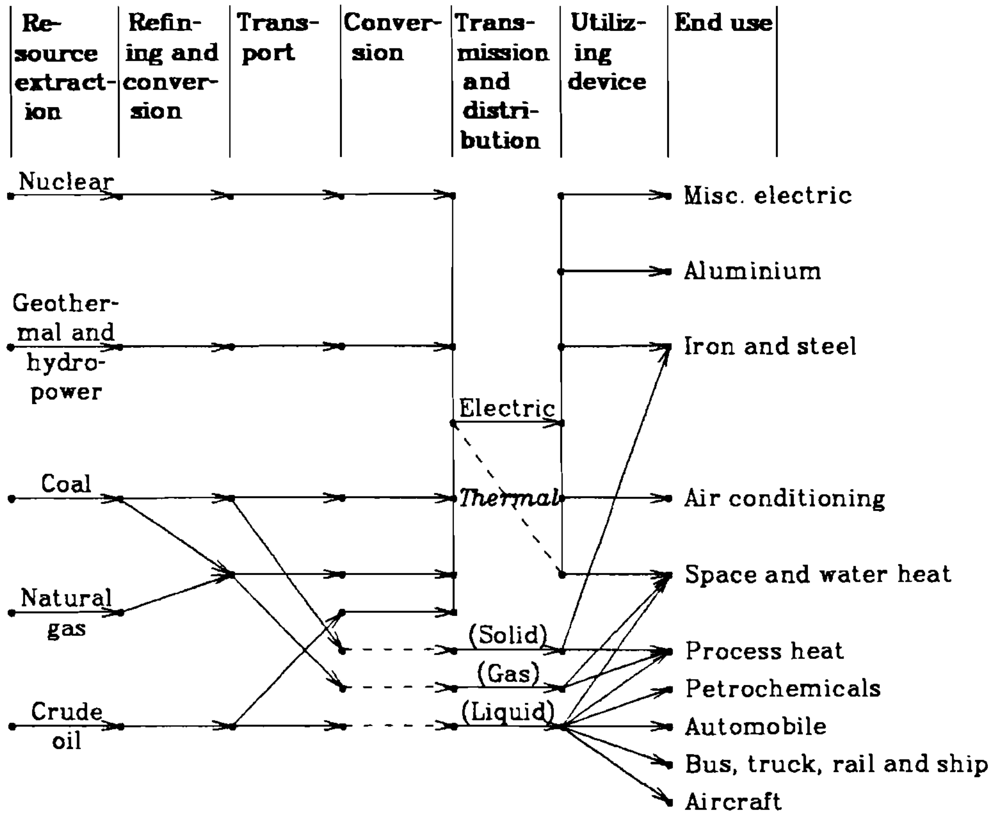

Figure 2. Energy reference system [5].

representation of the energy system. The models are either static, with the optimization process seeking to minimize costs for a single target year, or they are quasi-dynamic, minimizing the present value of the total costs over the whole planning horizon.

Accounting and optimization models of the types described above focus on the technical structure of the energy system and usually take the energy demand as an exogenous input. Thus, they do not fully reflect consumer reaction to changing energy prices or the influence of rising energy prices and limited supply on the economy and thus on industrial energy use. Most of the more recent energy modeling work is concerned with the interactions between energy, the economy and the environment. Linear programming techniques have been used far more than other mathematical programming methods in this type of work because of their capacity for solving large problems.

A number of energy models based on input–output techniques, the system dynamics approach or the methods of game theory have also been developed.

Table 1 lists several well-known energy models, together with the methodology used and their area of application.

4. A CASE STUDY IN MULTIPLE-CRITERIA ENERGY STRATEGY EVALUATION

This section describes an experiment based on the achievement scalarizing approach to multicriteria analysis, and the energy supply model MESSAGE [6]. In its original form, MESSAGE is a dynamic linear programming model (see Table 1) with the single objective of minimizing the total discounted costs of meeting a set of energy demands over a given time horizon. The experiment described in detail in [9] shows that it is possible to consider more than one objective and thus to study the interplay between costs and other factors such

Table 1. A survey of energy models (based on [4], [7] and [8]).

		MODEL	METHODOLOGY	APPLICATION
ENERGY SYSTEM MODELS		BESOM (Brookhaven)	Linear optimization	Evaluation of energy technologies for US R&D policy.
ENERGY SYSTEM MODELS		EFOM (Grenoble)	Linear optimization	Originally built to develop energy scenarios for France. Now used within the EEC set of models for policy assessment.
ENERGY SYSTEM MODELS		MARKAL (Brookhaven/ Jülich)	Linear optimization	Optimization of end-use and supply side. Applied to 15 countries of the IEA for evaluation of new and conservation technologies.
ENERGY SYSTEM MODELS		MESSAGE (IIASA)	Linear optimization	Applied to 7 world regions in the context of IIASA's set of models.
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	ETA–MACRO (Stanford Univ.)	Non-linear optimization, informal econometric	Studies of nuclear and alternative energy systems in the US.
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	PILOT (Stanford Univ.)	Dynamic linear optimization	Exploration of energy and economic growth in the US.
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	Soviet Union	Dynamic linear optimization	Study of the interconnected balanced growth of energy and the economy in the Soviet Union.
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	SRI (Stanford Res. Inst.)	Process representation, informal econometric	Analysis of US synfuels strategy.
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	HUDSON–JORGENSON	Econometric	Long-term energy and economic growth analysis of the US. Taxing policy in the US.
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	ESPM (Bechtel Co.)	Accounting	Framework for energy supply planning and accounting of industrial, capital, labor and material requirements. Applied to the US and developing countries (Peru, Egypt, Indonesia).
ENERGY–ECONOMY MODELS	INTEGRATED MODELS	PIES (Project Independence Evaluation System)	Process representation, linear optimization, econometric	Analysis of alternative strategies for the national energy plan of the US.
ENERGY–ECONOMY MODELS	MODEL SETS	DRI–BROOKHAVEN [combination of Hudson–Jorgenson and BESOM models]	Linear optimization, econometric	Studies of economic impact of alternative energy futures in the US.
ENERGY–ECONOMY MODELS	MODEL SETS	EEC (Brussels) [combination of macro-economic growth, energy demand, input–output and energy supply models]	Linear optimization, econometric	Application to member countries of the European Communities for Energy System Studies.
ENERGY–ECONOMY MODELS	MODEL SETS	IIASA (Laxenburg) [combination of macro-economic, energy demand, energy supply and energy impact models]	Linear optimization, econometric	Applied to studies of the energy/economy growth of 7 world regions. Investigations of energy strategy impacts.
ENERGY–ECONOMY MODELS	MODEL SETS	Zencap (Zurich) [combination of I/O and energy technology models]	Optimization, econometric	Applied to studies of the relationship between the energy technology potential and the economic system in the FRG.

as import dependence, the need to develop infrastructure, and so on. The main purpose of the case study described below is to illustrate the methodology; the data used in the MESSAGE run serve only as examples and the policy implications of the results are therefore not discussed.

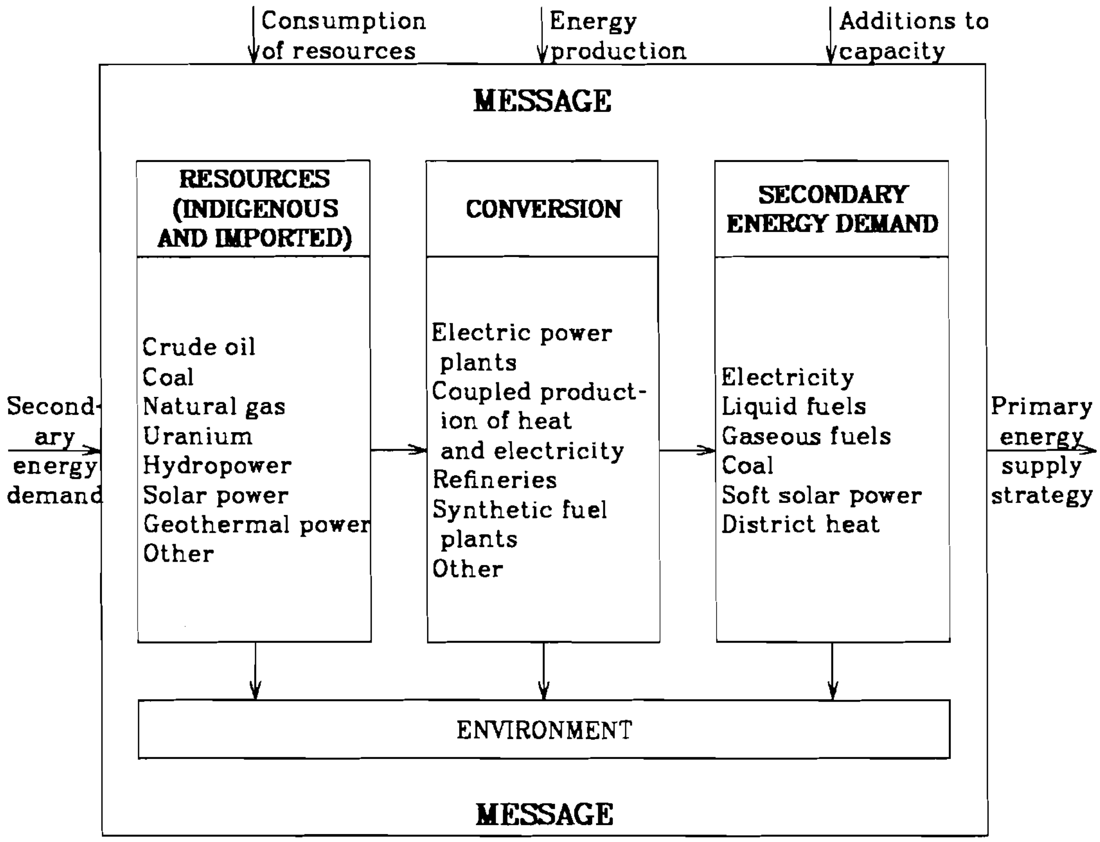

Figure 3. Structure of the energy supply model MESSAGE.

4.1. The Energy Supply Model MESSAGE: Problem Formulation

We used the energy supply model MESSAGE in conjunction with the reference point optimization approach to study energy supply policies for the countries of the European Economic Community (EEC) [9] over the period 1980–2030. The main aim of this model is to meet the predicted demand for secondary energy by manipulating the vector of annual consumption of resources, the vector of energy production, and the vector of annual increases in energy-producing capacity. The feasible set is determined mainly by strategies for the supply of primary energy resources involving a variety of possible technologies (see Figure 3).

The resulting problem can be formulated as a standard dynamic linear program. The general form of the *state equation* is:

$$y(t+1) = \sum_{i=1}^{\nu} \bar{A}(t-n_i)y(t-n_i) + \sum_{j=1}^{\mu} \bar{B}(t-m_j)u(t-m_j), \quad t=0,1,\ldots,T-1 \qquad (1)$$

where

y is a vector of state variables

u is a vector of control variables

$\bar{A}, \bar{B}$ are matrices of input data,

$(n_1, \ldots, n_\nu), (m_1, \ldots, m_\mu)$ are sets of integers which characterize time lags in state and/or control variables

T is the length of the planning period (50 years in 5-year steps, i.e., $T = 11$).

Examples of equations of this type in the energy supply model are:

Capacities of Technologies:

$$c(t) = c(t-1) + 5z(t) - 5z(t-6), \quad t = 1,2,\ldots,11$$

where

c is a vector describing the capacities of the different technologies

z is a vector describing annual additions to capacity

$t-6$ reflects a 30-year service life.

Resource Balances:

$$s(t) = s(t-1) - 5r(t), \quad t = 1,2,\ldots,11$$

where

s is a vector of reserves (stocks) of primary energy carriers or synthetic fuels

r is a vector describing the annual consumption of primary energy carriers or synthetic fuels.

The general form of the *inequality constraints* is:

$$\bar{G}(t)y(t) + \bar{D}(t)u(t) \leq f(t), \quad t = 0,1,\ldots,T \tag{2}$$

where

$\bar{G}, \bar{D}$ are matrices of input data

f is a vector of input data.

Examples of constraints of type (2) are given below.

Demand/Supply Balance:

$$Dx(t) \geq d(t) + H(t), \quad t = 1,2,\ldots,11$$

where

D is a matrix describing supply/demand paths

x is a vector of annual supply activities

d is a vector of annual secondary energy demands (exogenous inputs)

H is a matrix of coefficients reflecting secondary energy inputs to technologies.

Capacity Utilization:

$$B_i x(t) \leq c(t), \quad i = 1,2,\ldots,n, \quad t = 1,2,\ldots,11$$

where

B_i are matrices defining load regions and the availability of technologies in each load region $i = 1,2,\ldots,n$ (input data).

Build-Up Constraint:

$$\sum_{i \in I_1} z_i(t) \le GUB(t), \quad t = 1,2,\ldots,11$$

where

GUB is a vector of absolute upper limits (input data)

I_1 is a subset of the set of technologies.

Resource Consumption:

$$Gr(t) \ge Q_1 x(t) + Q_2 z(t) - Q_3 z(t-6), \quad t = 1,2,\ldots,11$$

where

G is a binary matrix which aggregates resource categories

Q_1, Q_2, Q_3 are matrices of parameters describing the specific consumption of resources by conversion technologies (input data).

Resource Extraction:

$$G_1 r(t) \le p(t), \quad t = 1,2,\ldots,11$$

where

G_1 is a matrix which aggregates indigenous resource categories (input data)

p is a vector of annual production limits for each type of resource (exogenous inputs).

The general form of the ***bounds*** is:

$$L(t) \le \begin{bmatrix} u(t) \\ y(t) \end{bmatrix} \le U(t), \quad t = 0,1,\ldots,T \tag{3}$$

where

U is a vector of upper bounds

L is a vector of lower bounds.

The ***planning period*** (T) is fixed and the initial state of the energy system is also given:

$$y(0) = y^0 \quad . \tag{4}$$

The ***performance function*** in the ***scalar case*** has the general form:

$$J(u) = (a(T), y(T)) + \sum_{t=0}^{T-1} \left\{ (a(t), y(t)) + (b(t), u(t)) \right\} \tag{5}$$

where a and b are input vectors.

MESSAGE was originally run with the following scalar objective function, which minimizes the total discounted costs of energy supply:

$$J(u(t)) = \sum_{t=1}^{T} \left\{ \beta_1(t)(\alpha_1(t), x(t)) + \beta_2(t)(\alpha_2(t), z(t)) + \beta_3(t)(\alpha_3(t), r(t)) \right\} \rightarrow \min \tag{6}$$

where

$T = 11$

$J(u(t)) = J(x(t), z(t), r(t))$

$x(t)$ is a vector of energy production

$z(t)$ is a vector describing the annual increase in energy-producing capacity

$r(t)$ is a vector describing the annual consumption of primary energy carriers or synthetic fuels

β_i are discount factors

α_i are vectors containing annual cost coefficients.

To demonstrate the qualitatively new character of the multiple-criteria analysis we decided not to simply minimize a single aggregated function at the end of the planning period (as represented by (6)) but to "minimize" the trajectory of certain criteria of interest. As a test we considered the problem of simultaneous minimization of the undiscounted costs $J_{\text{cost}}(t)$, the amount of coal extracted $r_{\text{coal}}(t)$, and the volume of oil imported $r_{\text{oil}}(t)$ in each time period. This leads to the following vector of 33 criteria:

$$\begin{bmatrix} J_{\text{cost}}(t)\,;\ t = 1,2,\ldots,11 \\ r_{\text{coal}}(t)\,;\ t = 1,2,\ldots,11 \\ r_{\text{oil}}(t)\,;\ t = 1,2,\ldots,11 \end{bmatrix} \tag{7}$$

where

$$J_{\text{cost}}(t) = \left\{ (\alpha_1(t), x(t)) + (\alpha_2(t), z(t)) + (\alpha_3(t), r(t)) \right\} .$$

Here $r_{\text{coal}}(t)$ and $r_{\text{oil}}(t)$ are subvectors of the vector $r(t)$.

The minimization of vector (7) under constraints (1)–(4) reflects a wish to minimize both current costs and the use of fossil fuels in the production of energy. Our approach to this multiple-criteria problem is based on a methodology derived from the paradigm of satisficing decision making and linear programming techniques. The mathematical background to this approach (based on aspiration formation and the concept of scalarizing functions) is outlined in the next section.

4.2. The Achievement Scalarizing Function Approach

In satisficing decision making it is assumed [10] that people set up aspiration levels for various outcomes of interest, modify them as they accumulate more information, and then make decisions that satisfy or come close to these aspiration levels. Many of the methods of multiobjective analysis, such as the displaced ideal point approach [11] and goal programming [12] have more or less consciously adopted this approach. A generalized method that combines the satisficing and aspiration level concepts with mathematical optimization techniques was proposed by Wierzbicki [13, 14]. This approach concentrates on the construction of modified utility functions (called achievement functions) which express the utility or disutility of attaining or not attaining given aspiration levels. We will now describe the problem and explain the mathematical basis of the method.

Let $E_0 \subset E$ be the set of admissible decisions or alternatives to be evaluated and G be a (linear topological) space of objectives, performance indices, or outcomes. Assume that a mapping $Q: E_0 \rightarrow G$ which assigns a numerical value to the consequences of each alternative is given, and let $Q_0 = Q(E_0)$ denote the set of attainable objectives. Assume that there is a natural inequality (a partial preordering) in G; to simplify the presentation, we shall suppose that the preordering is transitive and can be expressed by a *positive cone* (any closed, convex, proper cone) $D \subsetneq G$:

$$q_1, q_2 \in G, \; q_1 \leq q_2 \Leftrightarrow q_2 - q_1 \in D \; . \tag{8}$$

The corresponding *strong partial preordering* is given by

$$q_1, q_2 \in G, \; q_1 < q_2 \Leftrightarrow q_2 - q_1 \in \tilde{D} \overset{\mathrm{df}}{=} D \setminus (D \cap -D) \; . \tag{9}$$

If the cone D has a nonempty interior $\mathring{D}$, it is also possible to introduce *strict partial preordering*:

$$q_1, q_2 \in G, \; q_1 \ll q_2 \Leftrightarrow q_2 - q_1 \in \mathring{D} \; . \tag{10}$$

Suppose that we wish to maximize all objectives (gains, etc.). A generalized Pareto (nondominated) objective $\hat{q}$ is then a D-*maximal element* of Q_0:

$$\hat{q} \in Q_0 \text{ is D-maximal} \Leftrightarrow Q_0 \cap (\hat{q} + \tilde{D}) = \phi \; . \tag{11}$$

A slightly weaker definition, which includes a few points that are not nondominated, is that of *weak* D-maximal elements:

$$\hat{q} \in Q_0 \text{ is weakly D-maximal} \Leftrightarrow Q_0 \cap (\hat{q} + \mathring{D}) = \phi \; . \tag{12}$$

For a normed space G, we can also have a stronger definition (D_ε*-maximality*) which does not include all nondominated points:

$$\hat{q} \in Q_0 \text{ is } D_\varepsilon\text{-maximal} \Leftrightarrow Q_0 \cap (\hat{q} - \tilde{D}_\varepsilon) = \phi \; , \tag{13}$$

where D_ε is an ε-conical neighborhood of D:

$$D_\varepsilon \overset{\mathrm{df}}{=} \left\{ q \in G : \mathrm{dist}(q, D) < \varepsilon \|q\| \right\} ; \; \tilde{D}_\varepsilon \overset{\mathrm{df}}{=} D_\varepsilon \setminus (D_\varepsilon \cap -D_\varepsilon) \tag{14}$$

and

$$\mathrm{dist}(q, D) = \inf_{\tilde{q} \in D} \|q - \tilde{q}\|$$

is implied by the norm of the space G.

If the space G is normed, we can define an *achievement scalarizing function* (often shortened to *achievement function*) $s : G \to R^1$, where s is assumed to satisfy either (15) and (17) below (the order representation case) or (16) and (18) below (the order approximation case). Thus, an achievement function should be

(a) *strictly order-preserving* : for all $\bar{q} \in G$, all $q_1, q_2 \in Q_0$:

$$q_1 \ll q_2 \Rightarrow s(q_1 - \bar{q}) < s(q_2 - \bar{q}) \; , \tag{15}$$

or, if possible, *strongly order-preserving*: for all $\bar{q} \in G$, all $q_1, q_2 \in Q_0$:

$$q_1 < q_2 \Rightarrow s(q_1 - \bar{q}) < s(q_2 - \bar{q}) \; , \tag{16}$$

where strong order preservation implies strict order preservation.

(b) *order-representing*:

$$S_0 \overset{\text{df}}{=} \left\{ q \in G : s(q - \bar{q}) \geq 0 \right\} = \bar{q} + D \,;\; s(0) = 0 \,, \tag{17}$$

or, at least, *order-approximating* for some small $\varepsilon > 0$,

$$\bar{q} + D \subset S_0 \overset{\text{df}}{=} \left\{ q \in G : s(q - \bar{q}) \geq 0 \right\} \subseteq \bar{q} + D_\varepsilon \,;\; s(0) = 0 \,, \tag{18}$$

where, clearly, order representation implies order approximation.

We see that the achievement function s is taken to be a function of the difference $q - \bar{q}$, where $q = Q(x)$, $x \in E_0$ is an attainable objective but $\bar{q} \in G$ is an *arbitrary* aspiration level, which is *not constrained* to Q_0, nor otherwise constrained. Moreover, an achievement function is usually constructed such that, if $\bar{q} \notin Q_0 - D$, then maximization of $s(q - \bar{q})$ over $q \in Q_0$ represents minimization of the distance between $\bar{q} + D$ and Q_0 ; if $\bar{q} \in Q_0 - D$, then maximization of $s(q - \bar{q})$ represents allocation of the surplus $q - \bar{q} \in D$.

Using the above definition of an achievement scalarizing function we shall now show how this approach may be used to minimize the vector of criteria (7) subject to (1)–(4). To do this we have to construct an achievement functional with $G = L^2[0,T]$ and $D = \{ q \in L^2[0;T] : q(t) \geq 0 \text{ on } [0;T] \}$:

$$s(q - \bar{q}) = \int_0^T \left\{ [q(t) - \bar{q}(t)]^2 - s[\bar{q}(t) - q(t)]_+^2 \right\} dt \tag{19}$$

where $q(t)$ is the criteria vector (7) and $\bar{q}(t)$ is the vector of reference trajectories for these criteria.

The implementation of this approach in the Dynamic Interactive Decision Analysis and Support System (DIDASS) developed at IIASA is described in more detail in [3,9,15].

Here we shall give only a short overview of the use of this approach for multiple-criteria analysis in energy planning and policy assessment.

4.3. Implementation and Computational Aspects

The software for the energy supply model MESSAGE has been combined with the DIDASS package for linear multiple-criteria reference point optimization to produce a system capable of solving the problem described above. The combined structure of the energy model and the multiple-criteria software is given in Figure 4. This figure also illustrates how a model (e.g., the energy supply model) may be used in conjunction with an interactive multiple-criteria analysis procedure. The left-hand side of Figure 4 gives the usual stages in a computer run of MESSAGE. In the combined case, however, the MPS format input file must be prepared according to the formulation of the multiple-criteria problem: for large models such as MESSAGE, the original matrix generator (Matrix Gener. I) must be altered (Matrix Gener. II) to modify the MPS input file in this way.

The right-hand side of Figure 4 illustrates the multiple-criteria optimization procedure. This begins with an interactive "editor" (LPMOD) which is used to define the trajectories of the various criteria and to manipulate the reference trajectories and scaling factors. In the next step, the preprocessor (LPMULTI in Figure 4) converts the prepared MPS format input file into its single-criterion equivalent (19). This single-criterion problem is solved using the MINOS system [16]. A postprocessor (LPSOL in Figure 4) extracts selected

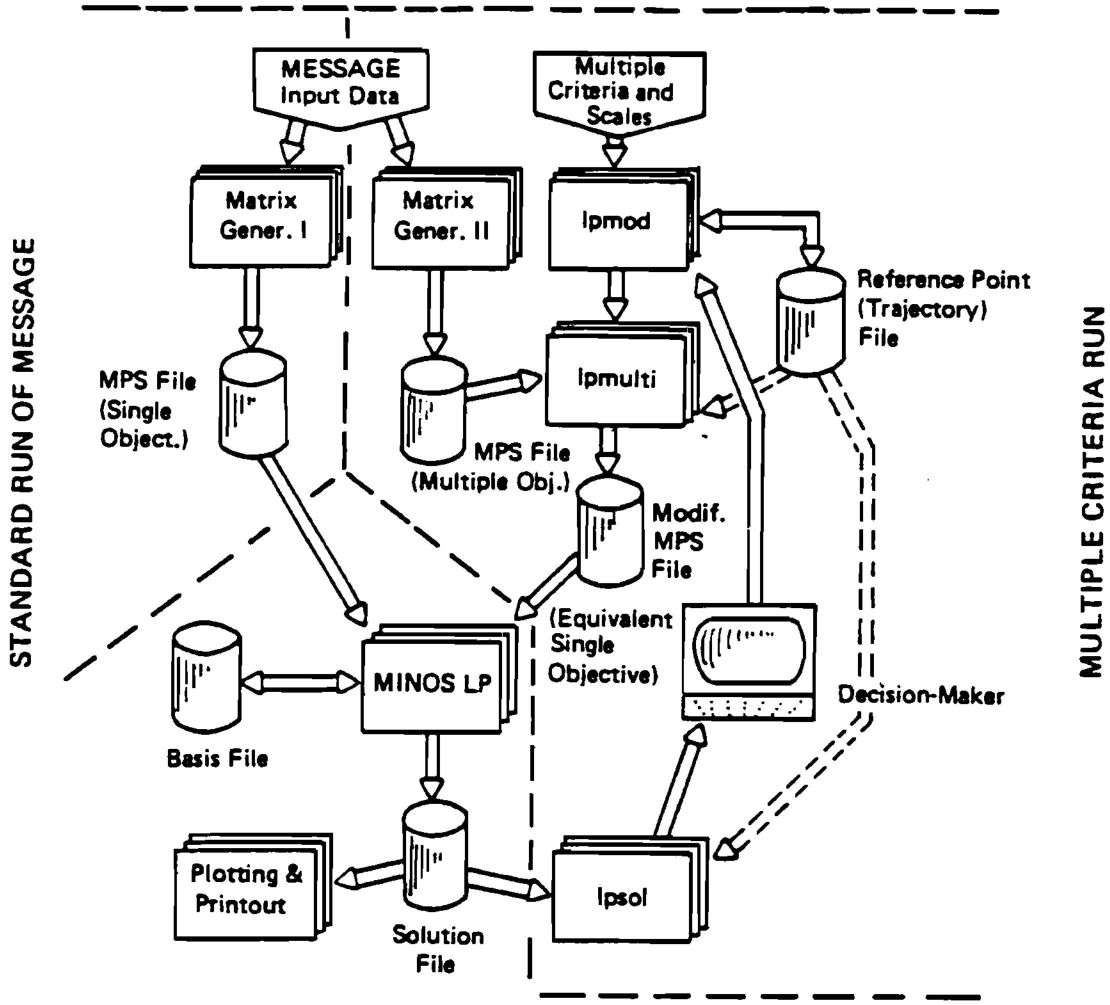

Figure 4. The combined structure of the energy supply model MESSAGE and the DIDASS package.

information from the LP system output file, computes the values of the objectives and displays the information to the decision maker. Figure 5 shows the results obtained if the problem is to minimize the use of imported oil and indigenous coal in energy production (to save them as feedstocks for other industries), while at the same time minimizing investment in the energy sector. The decision maker can then change the reference trajectories on the basis of this information, on the basis of his assessment of the nonquantifiable impacts, and possibly on the basis of experience gained in previous sessions, thus generating new efficient energy supply strategies which he can analyze in future iterations.

5. AN INTEGRATED PROGRAMMING PACKAGE FOR MULTIPLE-OBJECTIVE DECISION MAKING

The links between the energy supply model and DIDASS have been changed from those shown in Figure 4 in order to create a truly interactive decision support system based on the reference trajectory optimization approach described in the previous sections. The system developed so far will be described in some detail, and we shall then present two applications and one ongoing project in which this approach has been adopted. It has been shown to be a powerful tool

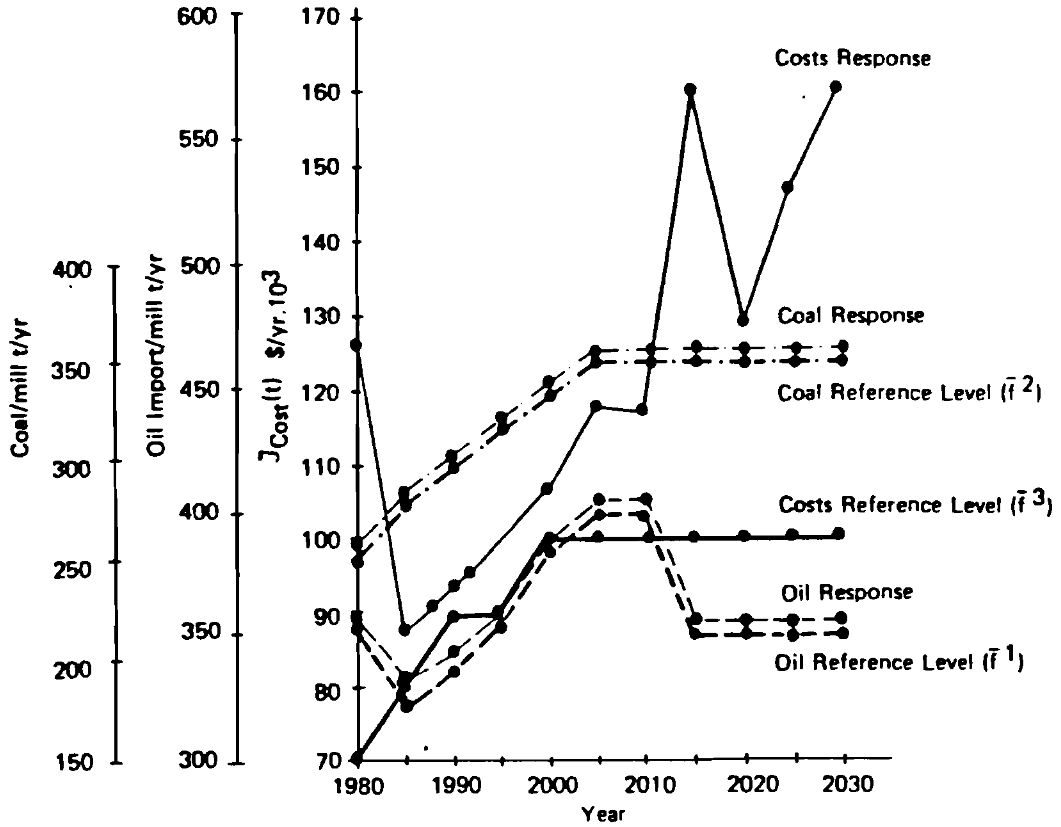

Figure 5. Reference trajectories (objectives) for imported oil supply, indigenous coal supply, and cost.

for finding acceptable solutions to problems in which conflicting objectives play an important role.

5.1 The Model Set

The set of models is based on the dynamic linear programming model MESSAGE II, which is an extended version of MESSAGE. The codes used in this interactive model system are MXG (the matrix generator of MESSAGE II), an interactive linear programming solver based on MINOS, and CAP (the post-processing program of MESSAGE II), which allows interactive evaluation of model results. All these codes are implemented on the VAX 11/780 at IIASA and are accessible via telecommunications networks.

5.1.1 The Model MESSAGE II

MESSAGE II is an extended version of the model MESSAGE described in the previous section. The main differences between MESSAGE II and its predecessor are the following:

- MESSAGE II allows modeling of the entire energy chain, from resource extraction via central conversion (e.g., electricity, district heat), energy transmission and distribution to on-site conversion (e.g., heating systems) and hence to ultimate consumption (e.g., as heat, light, motive power). This classifies it as an energy systems model (see Section 3).

- MESSAGE II permits variable period lengths.
- MESSAGE II can incorporate demand elasticity functions, so the model can react to changing energy prices.
- MESSAGE II allows user-defined constraints: the user can incorporate any additional factors influencing the development of the energy system, such as pollution control, restrictions on the use of resources other than energy (e.g., water, steel) or fixed import shares.
- Depending on the LP-solver used, MESSAGE II can cope with mixed integer programming and a non-linear objective function.

In addition, MESSAGE II supports conventional multiobjective optimization. That is, variables other than those directly related to the costs of the energy system (such as equation (6) in Section 4) can be included in the objective function and weighted accordingly. Such variables could be used to penalize pollution or other activities. For a more detailed description see the *User's Guide to the Matrix Generator of MESSAGE II* [17].

5.1.2 Adaptation of MESSAGE II to the Reference Point Optimization Method

In order to avoid the rather time-consuming procedure of problem formulation as described in the previous section (generation of a matrix by MESSAGE, generation of additional information by LPMOD and restructuring of the matrix by the pre-processor LPMULTI), MESSAGE II was extended so that the restructuring step could be omitted. All constraints and variables necessary for the reference trajectory optimization approach are generated during the matrix generation step, using dummy variables for the reference trajectories and scaling factors. The correct values are then entered during the next step, as described below.

5.1.3 The Interactive LP-solver IMM

The interactive LP-solver is based on MINOS. The routines described in [18] were added and others (Driver, Minos) extended to call various additional routines so that the necessary matrix manipulations can be performed (see Figure 6).

After the matrix has been read successfully, the user can enter the reference trajectories. These take the form of a vector of targets for each objective, and can be inserted into the matrix directly. If the "utopia" trajectories are not known for all goal trajectories the user has to supply scaling factors (as in LPMOD). However, as it is useful to know the "utopia" and "nadir" trajectories, and hence the range for decisions, the model makes it possible to calculate these values. The "utopia" and "nadir" trajectories are calculated by optimizing a weighted single objective for each time step of each trajectory. The weights are set to 1 for the trajectory being optimized, to 1000 for the current time step, and to 0.001 for the other trajectories. Then the best (utopia trajectory) and the worst (nadir trajectory) values are determined for each element. The user is then presented with the range of possible values and the solution of the dynamic problem for each objective (i.e., each trajectory is optimized over the whole time horizon). Once the reference trajectory has been defined, the scaling factors are calculated as the inverse of the distance between the reference trajectory and the corresponding "utopia" trajectory (see Figure 7 for a two-dimensional static example). This procedure avoids the arbitrary setting of scaling factors.

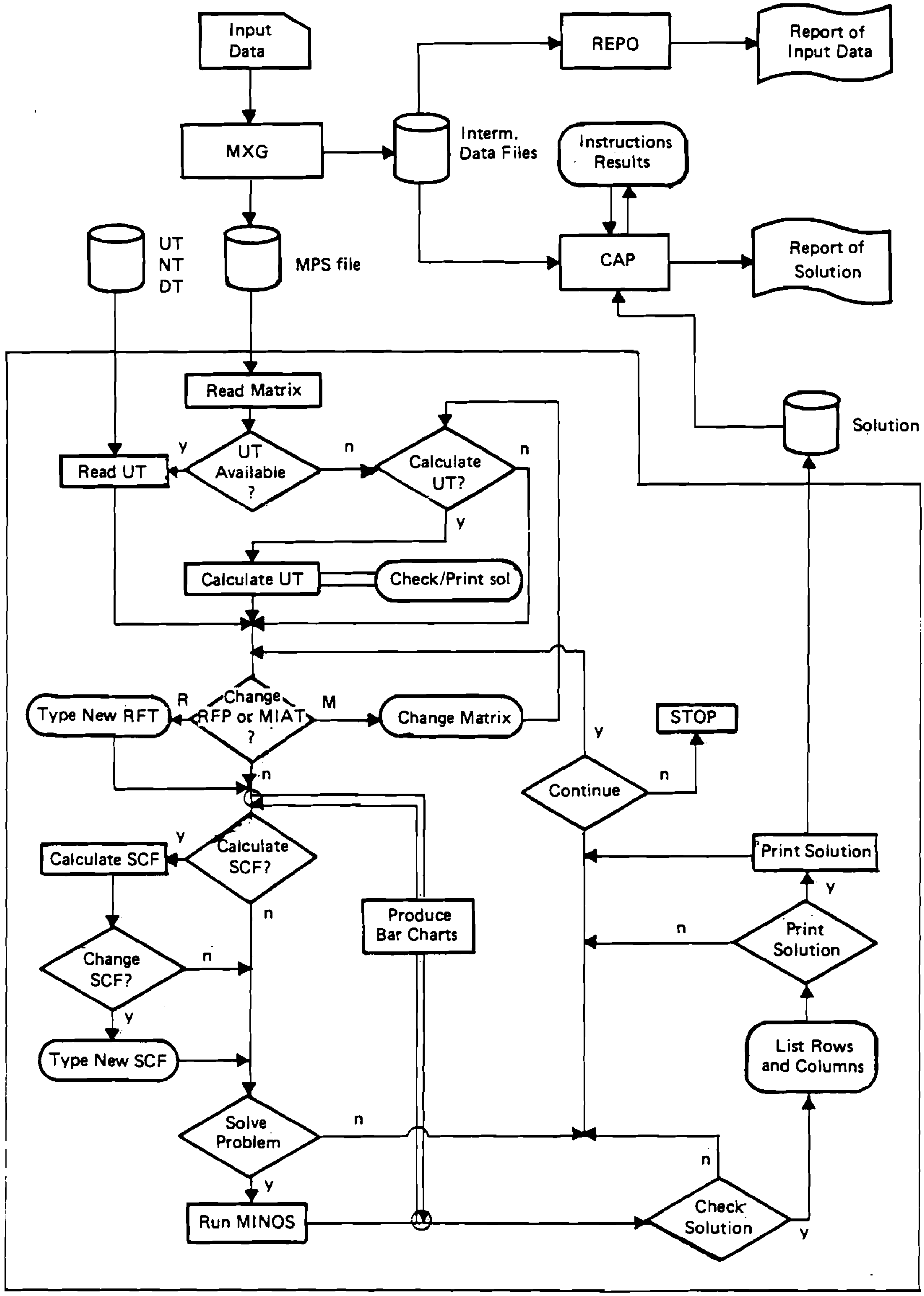

Figure 6. The interactive solver (IMM).

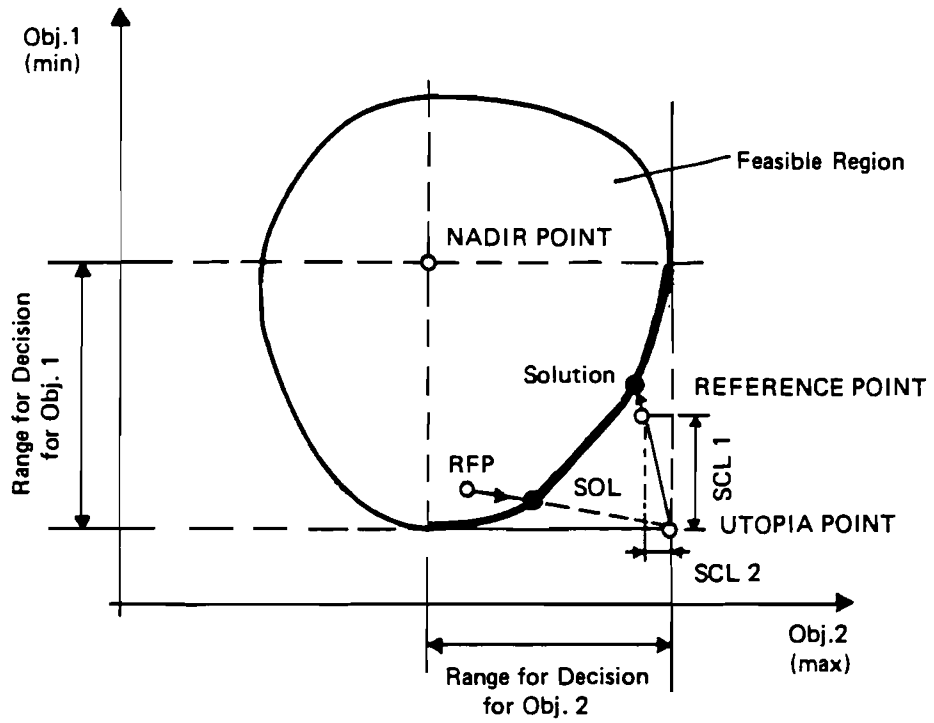

Figure 7. An example of a static problem with two objectives.

The actual problem is then solved by optimizing the single-criterion equivalent, an objective defined by the reference trajectories and scaling factors. The present result can then be compared with those obtained during earlier iterations, and the solution analyzed. In addition the user may access the values of all constraints and variables interactively. If a detailed analysis of the results is required, the solution can be printed and processed using the post-processing program CAP [19].

Based on the analysis of the solution, the user may now change the reference trajectories and solve the resulting new problem. The user also has access to the matrix and can alter any element, bound or right-hand side interactively. In most cases recalculation of the "utopia" trajectories is then necessary.

The interactive procedure outlined above has the great advantage of reducing the amount of time (in many cases by a factor of 100) otherwise necessary for input/output operations. This reduction of the time between defining the reference trajectories and investigating the solution makes this approach even more attractive. In addition, the machine-independent interface to the user was improved by introducing an option which displays bar charts for the different trajectories.

5.2 Applications

The following sections present some applications of the procedure outlined above. The first describes an application to a model of the Austrian energy supply system, while the second deals with a gas trade model for Europe. Finally, current attempts to develop an energy/economy interaction model for Austria are presented.

5.2.1 SEMA: An Energy Model for Austria

The energy model described here is a relatively aggregated representation of the present Austrian energy supply system and its possible future development. The simplifications were mainly concerned with end-use, where, for example, the different temperature requirements for industrial heat were ignored and the demand for liquid fuel for transportation was supplied by a fixed mix of gasoline and diesel oil. Figure 8 shows the representation of the energy system studied. This model covers the years from 1980 to 2000, with a resolution of four years up to 1992 and eight years thereafter. The results of this model will then be used as guidelines in another, more disaggregated, model* that takes cost minimization as the decision criterion.

At present four trajectories are defined: minimization of costs for the central conversion system; minimization of the costs related to consumption of energy; minimization of energy imports; and minimization of SO_2 emissions.

The results of the model show a strong correlation between the goals of SO_2 reduction and import reduction. Both drive the model towards increased use of hydroelectricity and to unconventional technologies, such as deep gas drilling or solar heating systems – this, of course, results in a higher cost trajectory. On the other hand, the goal of cost reduction limits this tendency and, instead of switching completely to such energy production systems, meets the SO_2 reduction criterion by the installation of pollution abatement equipment, such as scrubbers or fluidized bed combustion power stations.

5.2.2 GATE: A Gas Trade Model for Europe

The question addressed by this model is: How do different strategies in the various European regions influence the gas trade between these regions and with the rest of the world? To answer this question, Europe was divided into four regions, namely North, Central, South, and East. Three gas exporting regions are also considered: the USSR, the Norwegian North Sea gas fields, and North Africa. In this context North Africa is just a synonym for the rest of the world, since projects such as a gas pipeline from the Middle East or LNG imports from any conceivable exporter could be included in this part of the model. Figure 9 shows the existing and possible gas links between these seven regions.

Each of the four European regions is then represented in a framework similar to that shown in Figure 8, taking into account regional differences where necessary (see [20] for a more detailed description). The gas exporters are, in the case of the USSR and North Africa, represented using supply elasticity functions. In the case of the North Sea, the gas supply options are modeled explicitly as drilling technologies and gas reserves in different cost categories. Different representations were used because of the different amounts of gas available from each supplier. While the reserves in the USSR and North Africa are essentially infinite (in relation to the anticipated gas consumption in Europe over the next 50 years), the North Sea reserves are limited and more difficult to extract.

Three trajectories, or decision criteria, are specified for each of the four European regions: maximization of energy use in the household sector, minimization of total costs and minimization of SO_2 emissions. For the USSR the objective is assumed to be to maximize hard currency income while minimizing the amount of gas exported; for the North Sea and North Africa an objective of simple revenue maximization was assumed.

*Currently under development.

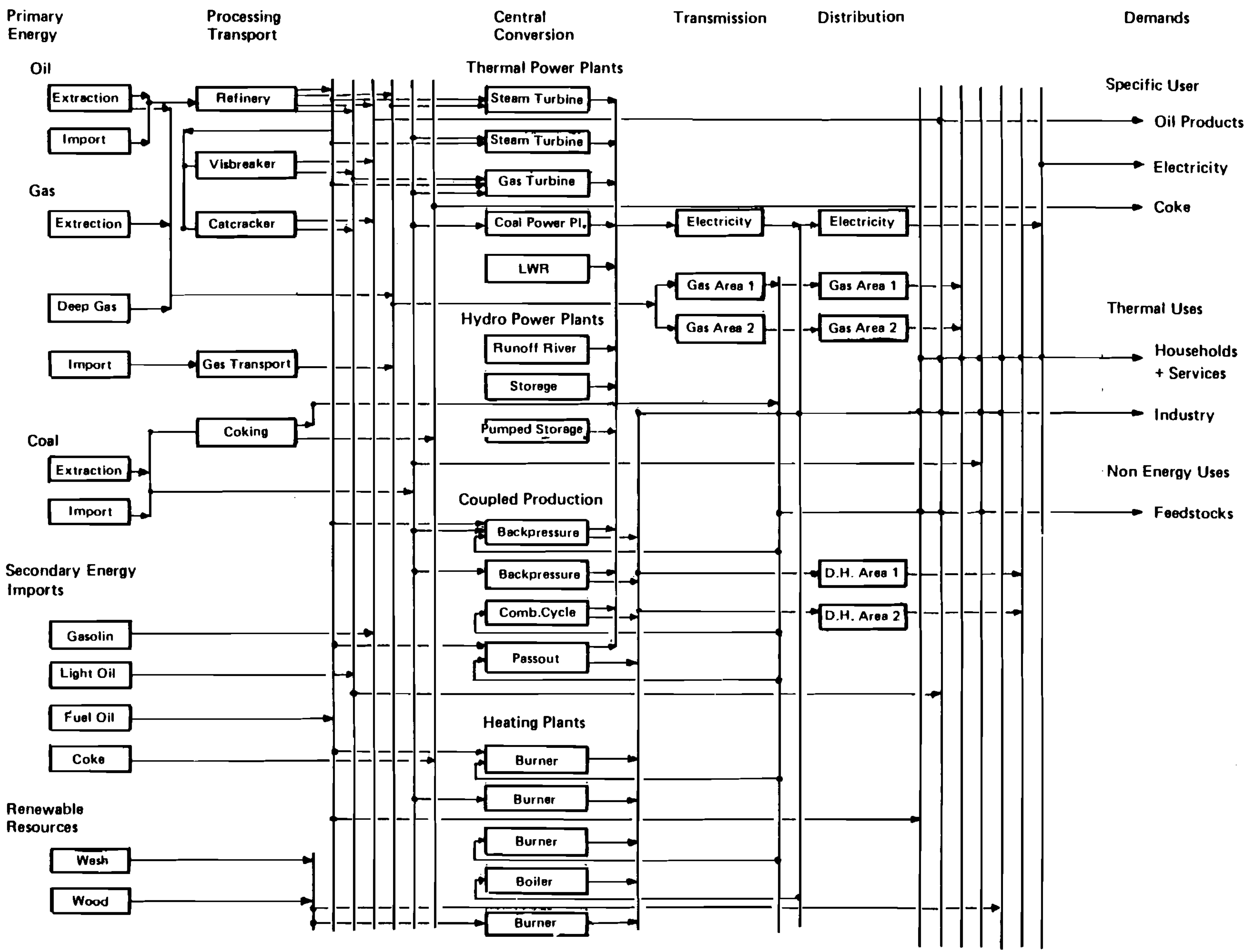

Figure 8. The SEMA energy system.

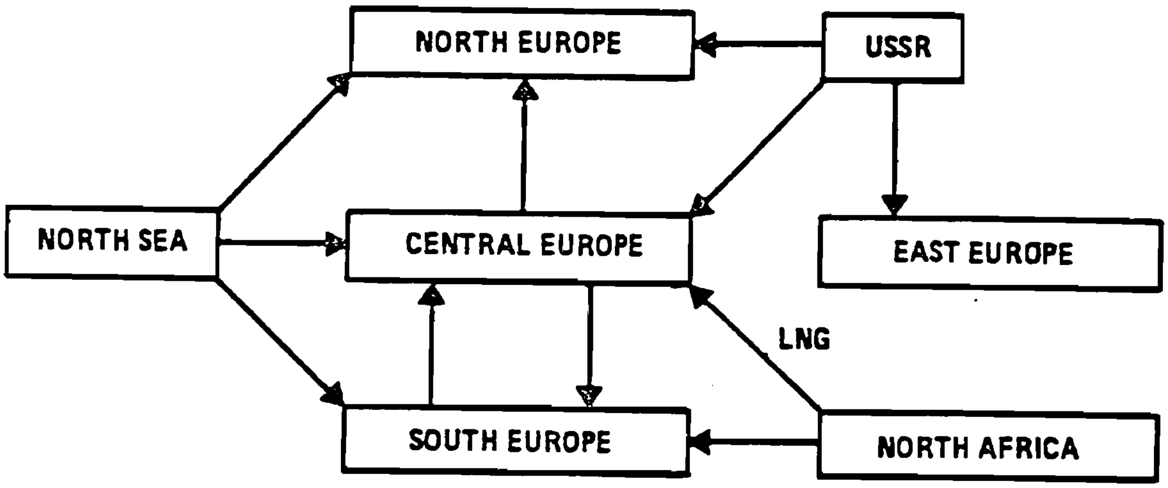

Figure 9. Possible gas flows in GATE.

An earlier version of this model was used during a meeting on gas issues at IIASA in Spring 1984. It proved to be an interesting tool for the experts, who used it to investigate the effects of their ideas about energy prices, emission standards, etc. on the pattern of gas trade in Europe.

5.2.3 Energy/Economy Interactions: The Case of Austria

The energy/economy model described below is currently being developed to investigate options for the future development of the Austrian economy. Although the model is not yet complete, we include a preliminary description to demonstrate the capabilities of our approach.

The model consists of four modules running in sequence. These are:

- a dynamic input/output (I/O) model, based on the vintage production theory
- a dynamic energy supply model (SEMA, as described above)
- an econometric consumer demand model
- an interactive taxing and monetary redistribution accounting framework.

The I/O and energy modules are contained in a common linear programming model, in which the industrial energy demand is determined from the activity of each of the economic sectors considered in the I/O model. The energy demand is expressed as useful energy needed per unit of output produced. In turn, the energy model demands capital and intermediate goods from the rest of the economy. Thus each of the technologies included in the energy model must contain information about the structure of investment for new installations. The investment and intermediate goods needed by the rest of the economy are endogenously determined in the I/O model.

Each of the economic sectors is represented by its intermediate and investment demands as well as by other indicators (e.g., labor demand, emissions, value-added produced, or a minimum demand for imported goods). The different economic sectors are not represented as one activity but as a number of different activities having different investment, primary and/or intermediate input structures. This leads to an I/O matrix with more columns than rows. The mix of options actually used depends on the particular objectives considered. As proposed by the vintage production theory (putty–clay hypothesis), the input structure of each installation is kept constant for the entire lifetime of the installation. This hypothesis is not, of course, valid for the variable factors of production, such as labor and intermediate consumption of goods and services, but holds for the relation between these factors. The overall economic structure varies over time due to the changing mix of options offered and the varying utilization of the different installations.

The final demand for the goods and services included in the model is determined exogenously. From the model results one can determine the average and marginal prices for all goods and services as well as the total GNP produced. With this information, and assumptions on government expenditure and exports, it is possible to determine the household income. An econometric model (e.g., a linear expenditure model, or translog functions) can then be used to estimate the final private demand for the chosen consumption sectors. Using a bridge matrix, these demands may be transformed into demands for goods and services as defined in the I/O model.

These three parts of the model are then solved iteratively until an equilibrium between demand and supply is obtained.

The I/O and energy modules are solved using the reference trajectory optimization approach as described above. This means that the objectives of different decision makers can be taken into account. These objectives could include environmental criteria (reduction of emissions), producers' interests (cost minimization, minimization of labor force, etc.), political issues (balance of imports and exports, employment rate, etc.) and private interests (increasing income and thus the consumption of goods and services).

The other modules provide interactive assistance in defining different strategies for taxation, monetary redistribution and the like. The consumption module may be a specific model, or the demand for the various commodities could be given completely exogenously in order to investigate the effects of different behavioral expectations.

This model is clearly a useful tool for decision making. It requires different decision makers to agree to a common framework which can then be used to arrive at a common proposal for the future development of the economy. As with all models, it should not be seen as a crystal ball for forecasting the future, but rather as a tool for investigating various alternatives and determining the conditional expectations of possible future events.

6. SOME UNRESOLVED ISSUES AND POSSIBLE DIRECTIONS FOR FUTURE RESEARCH

The aim of this paper was to demonstrate the need to use the techniques of interactive multiple-criteria analysis in energy planning and policy assessment. We shall now consider a number of ways in which current work in this area could usefully develop.

Future energy modeling research should concentrate on linking the models with the rest of the economy, and especially with the environment. The corresponding decision analysis would then have a broader basis. Some attempts to move in this direction are discussed in Section 5.2.

We have discussed here only situations with a single decision maker. However, the decision-making process often involves several individuals or groups (see Section 5.2.2), so that the problem of multiple decision makers with different criteria should be studied.

The efficient use of decision support tools is greatly dependent on the user/computer interface. The use of high-resolution graphics, for example, can often improve the decision maker's appreciation of the problem. Further work on the user interface could also help to bridge the gap between the decision maker (planner) and his policy analysts.

The treatment of uncertainty and risk in decision-making situations is another subject which deserves more attention. In view of the fact that there is considerable uncertainty in many of the key parameters which influence current decision making, e.g., economic growth, oil (fuel) prices, consumer behavior, air pollution, etc., there is clearly a need to have some means of identifying efficient and "robust" policies. This would require further research in the field of interactive multiple-criteria analysis under uncertainty.

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