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FOREWORD

This Research Report reprints the September 1980 issue of *Behavioral Science,* which was devoted entirely to research done under the auspices of the International Institute for Applied Systems Analysis. This issue is the second one of this sort to appear, since the May 1979 issue of this journal was also devoted to IIASA work.

We are greatly indebted to James Grier Miller, the Editor of *Behavioral Science,* for suggesting and organizing these special issues and devoting space to them, to Larry W. Dybala, its Managing Editor, for helping with the arrangements for bringing them to completion, and to the General Systems Science Foundation, the copyright holder, for permission to reproduce this special issue as an IIASA Research Report.

ROGER LEVIEN
Director

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SYSTEMS ANALYSIS IN AN INTERNATIONAL SETTING: RECENT PROGRESS AND FUTURE PROSPECTS[1]

by Roger E. Levien[2]

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After discussing the current reporting on two mature IIASA research activities, those on global energy and interregional migration, this introduction describes the four main themes foreseen as motivating IIASA's future work: global transition, national interdependence, regional integration, and the craft of systems analysis. After mentioning the backgrounds of the papers in this issue, some items of general interest are listed.

IN 1979 THE International Institute for Applied Systems Analysis and the editors of this journal collaborated in preparing the special May 1979 issue of *Behavioral Science* devoted to IIASA's work. My introduction (Levien, 1979) described the history of the Institute and the status of its work at that time. The intervening 16 months have seen a continuing evolution of the work of this eight-year-old Institute; several lines of research have come to completion, some new ones have been opened up, and others have made significant progress toward their goals. The six papers in this special issue sample some of this progress; this introduction mentions some recent highlights and sketches a brief perspective of future work.

NOTABLE RECENT REPORTS

The Energy Program

The Energy Program, IIASA's most ambitious research activity so far, has completed a major report on its geographically comprehensive, long-term examination of the global energy system, which was described briefly in the earlier special issue of *Behavioral Science* (Häfele & Sassin, 1979).

The program asked this question: Is it technically and economically feasible to provide, in the year 2030 (when the global population will have doubled to about eight billion persons), sufficient energy to support global economic development to improve the well-being of the populace of developing countries while maintaining living standards in the developed countries?

The current global primary energy consumption for 4.4 billion persons is about 8.8 terawatt-years per year (TWyr/yr—a terawatt being 10^{12} watts, 30 quads, or equivalent to about one billion tons of coal). According to the Energy Program's scenarios, with a doubled population and moderate economic development, as well as considerable energy conservation in developed countries, the global primary energy demand in 2030 is likely to reach between 22 TWyr/yr and 35 TWyr/yr, between 2.5- and 4-times current consumption.

By drawing on all available energy sources—conventional and unconventional fossil fuels, solar energy, renewables, and nuclear energy—the Energy Program has concluded that "it could be done," that is, the prospective energy demand could be satisfied.

The analysis that led to this conclusion is presented in two books, an extensive technical report (Energy Systems Program Group, 1981a) and a shorter account for the general reader (Energy Systems Program Group, 1981b); both will appear early in 1981.

Human settlements and services

A second line of research, of quite a different character, has also reached a stage of comprehensive documentation: The Hu-

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man Settlements and Services Area's comparisons of interregional migration in the 17 nations having IIASA National Member Organizations (NMOs) are now appearing. This work marks the first time that analysts or analytical groups in so many countries have carried out studies of patterns of internal migration using a common theoretical and computational framework (Rogers & Willekens, 1978a; 1978b). These 17 analyses are being published as IIASA research reports. (For the early items in the series, see Rees, 1979; Rikkinen, 1979; Andersson & Holmberg, 1980; Mohs, 1980; Drewe, 1980; Termote, 1980; Koch & Gatzweiler, 1980; Soboleva, 1980; Bies & Tekse, 1980; and Sauberer, 1980.) They will eventually be summarized as chapters of one of three volumes in the *International Series on Applied Systems Analysis* (published by Wiley: Chichester, England); the other volumes will document the theory and computer programs. Together these publications establish the validity and practicality of the theoretical and computational tools for multistate demography developed at IIASA by Rogers and his colleagues.

Other research

Many other research activities have reported their findings in books, journal articles, and research reports since May 1979. A complete listing of 1979 publications is available from IIASA's Publications Department upon request, as is the Institute's 1979 Annual Report.

THEMES FOR FUTURE RESEARCH

The Institute is required by its charter to convene a conference every few years to serve as "the major forum for providing broad scientific and technical advice to the Council and the Director; for encouraging the programs of the Institute and linking them with the research efforts of other national and international institutions; and for fostering understanding of the work of the Institute." IIASA Conference '80, the second of these conferences, was held in May 1980 in the newly completed conference area of Schloss Laxenburg.

The theater and dining halls built during the reign of Maria Theresia (1740–1780) have been beautifully restored and reconstructed by the Austrian authorities to provide an elegant but completely modern site for scientific conferences of up to 350 persons. It is also available for use by organizations other than IIASA.

IIASA Conference '80 inaugurated this new facility, and provided an opportunity to review the progress of the Institute since the first such conference was held in May 1976, and to discuss the Institute's plans for its future. In the coming years, as I reported to the Conference, the Institute expects to devote its attention to problems falling within four themes.

Global transition

We are now roughly halfway through the 300-year period from 1800 to 2100 during which the global population will increase ten-fold, from a stable level of somewhat less than one billion persons to a potentially stable level of roughly ten billion persons. This increase, and the consequent shift in the distribution of global population toward the developing countries and the cities, is the underlying driving force of the "global problematique." As a consequence, over the coming decades all of the world's support systems—those providing energy, food, industrial products, materials, water—will be subject to severe shifts and stresses as the distribution of demand and supply alters. Are there feasible paths or strategies that will enable the world to achieve, late in the next century, a system that will support ten billion persons in a way that is sustainable, equitable, and resilient?

IIASA has investigated the global energy system with this basic question in mind; it is in the middle of a similar study of the global food system. In coming years it will undertake studies of other global systems and their interactions.

National interdependence

While the driving forces of change are global and know no political boundaries, nations are still the highest level of true political authority and action. Each nation must chart its course, in cooperation or competition with other nations, toward the society it seeks. Yet, to an ever increasing extent, the choices of individual nations are constrained by and affect those of other nations, so that autonomy and autarky have become unrealistic goals. In the presence of this high degree of interdependence, ways must be developed for national decision makers to understand and respond to the external forces that affect their possibilities so strongly, and processes must be designed by which nations can concert their actions in the interest of all. IIASA has studied agricultural, energy, and general economic policies on the national scale in the context of interdependence, and will extend its studies to other sectors. It will also develop its work on questions of fair division and allocation of common property resources, which can provide a theoretical underpinning for international collaboration.

Regional integration

The impacts of global change and national interaction are felt directly at the places where high-level policies and decisions are generally implemented—the subnational regions. They are also the points where the need for coordinated action in different sectors is most evident, although generally not evidenced. Thus, at the regional scale, there is a close linkage among the agricultural, human-settlement, water-supply, urban, industrial, and environmental systems, for example—even though in most regions there is little or no ability to plan for or achieve integrated development.

Effective and equitable uses of the world's resources, as well as the need to increase regional well-being, require that techniques for integrated regional development be advanced. IIASA has been developing such tools and testing them in a series of case-study regions; in the future, this work will be extended to a wider range of regions and new techniques will be added.

The craft of systems analysis

The three themes I have just discussed provide the motivation and framework for most of IIASA's applied analyses. Through them we seek to contribute to understanding the problems they encompass and to design strategies to alleviate or overcome them.

However, there is a fourth theme to which the Institute devotes attention: to advance the methods and practices by which these problems are addressed.

The activity of applying scientific and technical knowledge and procedures to assist in the process of decision and policy making has many of the characteristics of a craft: Its goal is to produce a useful product; it relies heavily on the skill, judgment, and experience of the practitioner; it draws on knowledge from many fields; and it has a repertoire of practical tools and procedures. This craft is a relatively new one; indeed, its application to problems of global importance is quite recent. Too, its levels of achievement in various contexts and uses vary widely.

From its early days, IIASA has sought to gather and distil the lessons of systems analysis as learned by its scattered practitioners, to review these lessons critically, and to disseminate them widely by a variety of means: The *International Series on Applied Systems Analysis*, mentioned earlier, has published eight books so far and some two dozen additional volumes are in preparation; a three-volume *Handbook of Applied Systems Analysis* is in preparation, with the first volume in draft form; and other papers on the craft of systems analysis appear from time to time. In order to strengthen and broaden the international basis for applied systems analysis, this work will be continued and extended in coming years.

THIS SPECIAL ISSUE

The six articles in this special issue of *Behavioral Science* reflect the diversity of disciplines, nationalities, and topics that enrich the Institute. The authors come from seven nations and at least as many disciplines. Their concerns include energy, food, health, and regional policy, as well as developing tools from decision analysis, game theory, and optimization that can contribute to improved policy and decision making. Two of the articles have international authorship, but all of them report on aspects of larger studies that engage international teams. The work reported was done between the end of 1977 and late 1979.

Parikh and Srinivasan's article on "Food and Energy Choices for India" was completed as part of our Food and Agriculture Program, for which Parikh has developed an Indian agricultural policy model. This paper investigates the important interactions between energy and food policies in an era of high and rising oil prices.

The paper by Thomas and her collaborators on the accuracy of policy makers' perceptions of public beliefs about nuclear energy arose from a joint project between IIASA's Energy Program and the International Atomic Energy Agency.The project explored aspects of risk estimation, assessment, and management and their relations to energy policy.

The paper by Andersson and Mantsinen was written as part of IIASA's work on regional development. The paper by Seo reflects the interest of the System and Decision Science (SDS) Area in improving methods for making complex decisions. Nurminski, a mathematician in the SDS Area, collaborated with Hughes from the Human Settlements and Services Area and Royston from the United Kingdom Department of Health and Social Security in applying new techniques of nondifferential optimization to planning health care.

OTHER ITEMS

Recently IIASA has begun to issue publications in two new forms. The first, *Executive Reports*, convey the results of IIASA work to decision makers, as well as other interested general readers. They complement our existing *Research Reports*, which are addressed primarily to the scientific and technical community. The second is a quarterly journal, *IIASA Reports*, which will disseminate the results of IIASA work to a wide audience on a regular basis.

The last year has also seen some further steps toward making Laxenburg, where IIASA is located in Schloss Laxenburg, into an "international science city." The Austrian Institute for International Affairs (AIIA) and, of special interest to readers of this journal, the International Federation for Systems Research (IFSR) established headquarters in Laxenburg in 1979, joining the International Federation of Automatic Control (IFAC), which came to Laxenburg in 1978. The IFSR has three member societies, of which the Society for General Systems Research is one.

This second special issue of *Behavioral Science* devoted to IIASA work reflects the close relation that is developing between IIASA and the broad systems research community that this journal represents. We look forward to strengthening this communality further in coming years.

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NUCLEAR ENERGY: THE ACCURACY OF POLICY MAKERS' PERCEPTIONS OF PUBLIC BELIEFS[1]

by Kerry Thomas, Elisabeth Swaton, Martin Fishbein, and Harry J. Otway

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The primary purpose of this study is to make an empirical test of how accurate a group of policy makers were in their assessment of the beliefs and attitudes of the public with regard to the use of nuclear energy. The 40 respondents were senior Austrian civil servants responsible for energy matters. The questionnaire used was the same as that employed earlier to measure the attitudes and underlying beliefs of 224 persons selected as a stratified sample of the Austrian public and two subsets of this sample, the 48 most PRO and 47 most CON the use of nuclear energy. The policy makers completed this questionnaire twice: once with respect to their own positions and, on the second occasion, in the *role* of a typical member of the Austrian public who was either PRO or CON the use of nuclear energy. This experimental design also permitted comparisons between the policy makers' own positions and those of the general public.

Public attitudes toward the use of nuclear energy were found, using factor analysis, to be based upon four underlying dimensions of belief: psychological (anxiety-inducing) risks; economic/technical benefits; sociopolitical implications; and environmental/physical risks. The policy makers' own attitudes were found to be significantly more favorable than those of the total public sample; this was primarily because the policy makers' beliefs about psychological risks made a significantly smaller negative contribution to attitude, and their beliefs about environmental risks made a significantly larger positive contribution.

The policy makers were able to shift their own (personal) responses in the directions indicated by their role-play assignments to reproduce accurately the overall attitudes of the PRO and CON groups on this controversial topic, although there was a tendency to overestimate the positive attitudes of the PRO nuclear public. In terms of the underlying belief dimensions, however, there was a significant failure to recognize the extent to which issues of psychological significance contribute negatively to the attitudes of both PRO and CON public groups. The policy makers underestimated the negative value both groups assigned to these risks as well as the extent to which the public believed that nuclear energy would lead to such risks.

KEY WORDS: society, decision making, nuclear energy, policy making.

INTRODUCTION

ISSUES OF technological policy are increasingly attracting public attention, a good example being plans for nuclear energy programs. Experts responsible for making policy recommendations, and government itself, have been forced by events to take notice of public attitudes and opinions. The motivations for wishing to take public attitudes into account in policy decisions will depend very much upon the particular political system involved; such a discussion is beyond the scope of this report. For our purpose we will assume that the aim is to formulate socially viable technological policies, where viability refers not only to an ethically acceptable level of public risk, but also to social acceptability. This requires knowledge of what the relevant public attitudes are as well as an understanding of the belief and value systems which underlie these attitudes. A simple "head-count" of those in favor of (PRO) and those against (CON) a particular technological issue is not sufficient; the policies selected, and even the processes by which they are evolved, must be responsive to the real concerns of the public if a broad base of support is to be found.

The particular aspect of policy we have

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addressed in this report is the role of nuclear energy in the Austrian economy. During the course of this research the Austrian nuclear energy program became an issue of considerable importance. As Austria's first nuclear power plant (at Zwentendorf, near Vienna) approached completion, the government organized a series of public debates aimed at opening up discussions on energy issues. These debates, held during late 1976 and early 1977, had the effect of polarizing opinions, and clarified the aims of the anti-nuclear lobby, namely to prevent completion and operation of the Zwentendorf plant (Hirsch, 1977). At a national referendum held in November 1978, the Austrian electorate decided that the Zwentendorf plant should not be brought into operation. The study reported here was carried out in the period between the public debates and the referendum (late 1977 and early 1978), although the data reported for the public sample were collected before the information campaign.

The aims of the present research were as follows: first, to examine the beliefs and attitudes toward the use of nuclear energy held by a group of senior government officials in Austria (referred to throughout this report as "policy makers") who were in a position to make policy recommendations to decision makers at ministerial level, and to compare these beliefs and attitudes with those of a sample of the general public, second, to examine the degree of accuracy with which the policy makers perceived the public's beliefs and attitudes on the topic of nuclear energy. The policy makers and the members of the general public responded to the same questionnaire, allowing direct comparisons to be made. (Detailed reports on the beliefs and attitudes, with respect to the use of nuclear energy, of the sample of the Austrian public can be found in Otway and Fishbein (1977), and in Otway, Maurer, and Thomas (1978). An extension of this research to a comparison of beliefs about five different energy sources can be found in Thomas, Maurer, Fishbein, Otway, Hinkle, and Simpson (1980). The design of the questionnaire was largely based upon a pilot study reported by Otway and Fishbein (1976).) The policy makers' perceptions of the viewpoints of the general public were examined by having the policy makers respond to the questionnaire on a second occasion, this time in the role of a typical (i.e., not an active extremist) member of the public in favor of (or against) the use of nuclear energy. Half of the policy makers responded in each role condition. A comparison of the in-role responses with those of the public sample gave an indication of how accurately public beliefs were reproduced. The in-role responses also provided a basis for assessing the policy makers' perceptions of the issues underlying the public response to nuclear energy.

THE ATTITUDE APPROACH

The particular attitude model used in this study is that developed by Fishbein and his associates (for a summary, see Fishbein & Ajzen, 1975). Since this model has been described in some detail elsewhere, we will only summarize the main points that are relevant to the procedures and findings described in this report.

1. Attitude is defined as the overall judgment about an object in terms of favorableness or unfavorableness, where "object" refers to any discriminable aspect of the individual's world.

2. Attitude is based on the beliefs an individual holds about an attitude object. The strength of each such belief is treated as a subjective probability judgment that the attitude object is associated with some characteristic or attribute.

3. At any given time an attitude is determined by the sum, over the salient beliefs, of evaluations of the attributes, each evaluation being weighted by the strength of the belief (i.e., the subjective probability that the attitude object is characterized by that attribute).

4. The way in which evaluations and belief strengths are combined to estimate attitude can be stated formally:

$$A_o \approx \sum_i^n b_i e_i,$$

where

A_o=the attitude toward the object o;
b_i=the strength of the belief which links the attitude object to attribute i;
e_i=the evaluation of attribute i;

n=the number of salient beliefs, i.e., those currently within the span of attention.

Two methods were used to measure attitude: a direct method using the semantic differential technique of Osgood, Suci, and Tannenbaum (1957), and an indirect method based on respondents' beliefs and attribute evaluations (using the formula of point 4 above). The semantic differential measure of attitude was used as the criterion to validate the set of beliefs by correlating the direct and indirect (i.e., belief-based) measures of attitude.

The beliefs used in the present study were selected on the basis of previous research (Otway & Fishbein, 1976), a literature survey, and open-ended elicitations. The 39 belief items relating the use of nuclear energy to a series of possible attributes and consequences are listed in Table 1.

METHOD

Samples

The sample of policy makers consisted of 40 senior civil servants specializing in energy matters; 34 of the respondents were male, 6 were female. This group of 40 people represented virtually all of the ministry staff in this category who were in duty at the time of the survey; only one person refused to participate. About five weeks after the respondents had completed the questionnaire for the first time, expressing their personal points of view, they were randomly assigned to one of the two role-play subgroups (i.e., playing the role of a typical Austrian citizen in favor of or against the use of nuclear energy) to obtain estimates of the policy makers' perceptions of the beliefs and attitudes of members of the public. Only 35 of the original group of 40 were available for the role-play part of the study (N = 17 for the PRO-role, and N = 18 for the CON-role).

The sample of the Austrian general public with which the policy makers were compared was a stratified sample controlled for geographic location (Vienna, provincial capital, and rural), sex, age, and education. The number of usable interviews was 224. Details of the sample can be found in a report by Thomas, Maurer, Fishbein, Otway, Hinkle, and Simpson (1980). Two subgroups, in favor of or against the use of nuclear energy, were selected from the public sample using the semantic differential measure of attitude as the criterion; the 48 respondents most favorable to the use of nuclear energy were termed the PUBPRO group, and the 47 least favorable the PUBCON group (see Fig. 1).

Questionnaire

The questionnaire used to measure the policy makers' responses (personal and in-role) consisted of the same items employed in the study of the Austrian public (Otway & Fishbein, 1977). The questionnaire was originally designed in English, and then translated into German by the experimenters prior to use.

Apart from the demographic information, the questionnaire measured the following variables:

Attribute evaluation. For each of the 39 beliefs the evaluation of the attribute was measured using a 7-point (+3 to −3) scale with the end-points labeled with the adjective pair good/bad. For example,

Increasing the standard of living

GOOD :—:—:—:—:—:—:—: BAD.

Belief Strength. Belief statements were presented in propositional form (as shown below) and the respondents were asked to judge the "truth" of each statement on a 7-point (+3 to −3) scale, where the end points were labeled likely/unlikely. For example,

The use of nuclear energy leads to an increase in the standard of living

LIKELY :—:—:—:—:—:—:—: UNLIKELY.

Although belief strength is conceptualized here as a subjective probability, the measurement procedure described above does not meet certain strict requirements of probability theory. In keeping with most earlier research using Fishbein's attitude model, the beliefs are *not* treated as a partitioned event space, in which the probabilities assigned to each attribute would have to sum to 1; furthermore, in order to permit measurement of belief and disbelief, a bi-

TABLE 1

THE ORIGINAL SET OF BELIEFS ABOUT THE USE OF NUCLEAR ENERGY AND THE FOUR BELIEF DIMENSIONS DERIVED FROM FACTOR ANALYSIS

Belief dimension	Belief item
Factor I: Psychological risks	* Means exposing myself to risk without my consent. * Leads to accidents which affect large numbers of people at the same time. * Means exposing myself to a risk which I cannot control. * Is a threat to mankind. * Is risky. Leads to hazards caused by material failure; has a delayed effect on health; increases the rate of mortality; leads to change in man's genetic make-up; leads to hazards by human failure.
Factor II: Economic and technical benefits	* Increases the standard of living. * Increases Austrian economic development. * Provides good economic value. * Increases my nation's prestige. * Leads to new forms of industrial development. Leads to technical "spin-offs;" increases employment; increases the development of methodologies for medical treatment; reduces the need to conserve energy; symbolizes the industrial way of life; satisfies the energy need in the decades ahead; decreases dependence on fossil fuels; increases the extent to which society is consumer-oriented.
Factor III: Sociopolitical risks	* Leads to rigorous physical security measures. * Produces noxious waste products. * Leads to the diffusion of knowledge that facilitates the construction of weapons by additional countries. * Leads to dependence on small groups of highly specialized experts. * Leads to transporting dangerous substances. Increases the likelihood that a technology is misused in a destructive way by terrorist groups; gives political power to big industrial enterprises.
Factor IV: Environmental and physical risks	* Does exhaust our natural resources. * Increases occupational accidents. * Leads to water pollution. * Leads to air pollution. * Makes Austria economically dependent upon other countries. Leads to a long-term modification of the climate.
Miscellaneous: Beliefs not loading on any factor	Involves a technology that I can understand; leads to the formation of groups advocating extreme political positions; leads to a police state.

* Beliefs used to represent the factor.

polar scale is used which makes it possible to encompass the probability that nuclear energy *is* or *is not* associated with the attribute in question.

Direct measure of attitude toward the "use of nuclear energy." This was measured using the semantic differential technique (Osgood, Suci, & Tannenbaum, 1957). The attitude object ("use of nuclear energy") was rated on a series of 7-point (+3 to −3) scales with the end points labeled with adjective pairs such as good/bad, harmful/beneficial.

PREDICTION OF ATTITUDE FROM BELIEFS AND ATTRIBUTE EVALUATIONS

In the earlier study of the Austrian public it was found that respondents' attitudes toward nuclear energy could be accurately estimated from a consideration of beliefs linking the use of nuclear energy with each of the 39 attributes and the evaluations of these attributes. The correlation between estimated attitudes and the same attitudes as measured by the semantic differential was 0.63. Given the validity of the attitude model in that application, a factor analysis of belief-strength scores was used to explore the underlying dimensions which characterized the thinking of the public with respect to the use of nuclear energy. (Factor analysis is a generic term for a set of linear, parametric statistical methods which identify the minimum number of independent dimensions needed to account for the variance in a larger set of intercorrelated variables. The method used here was that of principal components analysis, followed by varimax rotation. This technique produces underlying dimensions which are independent, i.e., orthogonal factors.) This factor analysis produced a clear factor structure relating the use of nuclear energy to four belief dimensions (see Table 1):

Psychological risks
Economic/technical benefits
Sociopolitical risks
Environmental/physical risks.

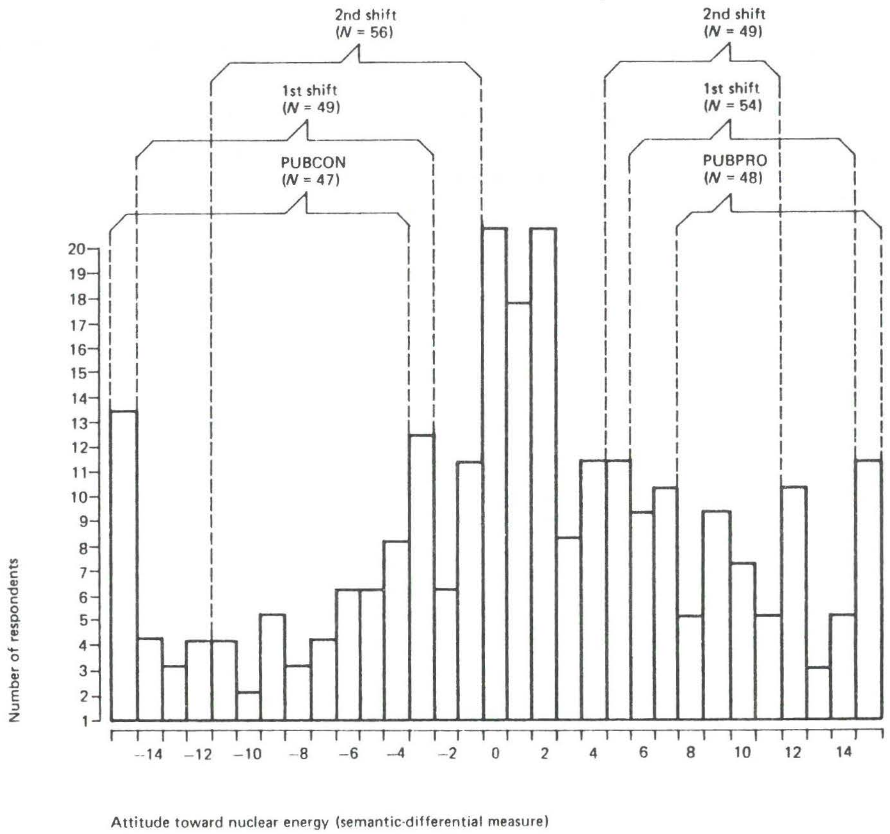

FIG. 1. Public subgroups selected for comparison with in-role responses of the policy makers.

Prediction of public attitudes from underlying belief dimensions

The factor analysis suggested that four major issues underlie public attitudes toward nuclear energy. Therefore, the five attributes which loaded highest on each belief dimension were used to calculate "factor-summaries" representative of each dimension. In each case the five belief strengths were summed ($\sum_{i=1}^{5} b_i$), as were the corresponding attribute evaluations ($\sum_{i=1}^{5} e_i$). These two sums were then multiplied in line with the attitude model used, to give an index of the contribution of that belief to overall attitude $[(\sum_{i=1}^{5} b_i) \times (\sum_{i=1}^{5} e_i)]$. To test the validity of reducing the 39 original attributes to 20 attributes (5 per dimension) an estimate of attitude based on a sum of these four factor-summary products was correlated with the direct (semantic differential) measure of attitude. The correlation coefficient was $r = 0.66$, as compared with $r = 0.63$ when all 39 attributes were used.

Prediction of the policy makers' own attitudes

In the case of the policy makers' own attitudes it was found that the correlation between the semantic differential measure of attitude and the attitude estimates based upon all 39 attributes was 0.89. Although it is possible that the higher correlation for this particular sample, as compared with the sample of the general public, could indicate the policy makers' higher level of education and familiarity with the topic, it is more likely that the difference in correlation merely reflects the fact that on the semantic differential the policy makers were asked to indicate their attitudes toward "the *use* of nuclear energy" while the public, due to an error in the wording of the questionnaire, were asked to indicate their attitudes toward "nuclear energy." Since the wording of the belief statements referred to "the *use* of nuclear energy," the semantic differential attitude of the public sample did not correspond precisely to the beliefs measured.

While it would have been desirable to perform a factor analysis of the policy makers' belief scores, the number of respondents ($N = 40$) was too small to obtain meaningful results for a set of 39 beliefs. Therefore, the factor structure obtained from the public sample was also used to summarize the policy makers' data. On calculating "factor-summaries" (as described above) for the policy makers, a correlation of 0.85 between this estimated attitude measure and the direct (semantic-differential) measure was found. This indicated the validity of using the reduced belief set; in the remainder of this report only the factor-summary indices will be considered.

COMPARISON OF POLICY MAKERS AND THE AUSTRIAN GENERAL PUBLIC

The first question of interest was the extent to which the policy makers' own beliefs and attitudes correspond with those of the general public. As expected, the attitudes of the policy makers toward the use of nuclear energy were significantly more favorable than those of the total public sample. This was true for both the direct (semantic differential) measure of attitude and the estimates based on the model. (Semantic differential scores could range from +15 to −15; the policy makers' mean score was 7.9, and the public mean score was 1.3. Recall, however, that policy makers evaluated "the use of nuclear energy" while the public evaluated "nuclear energy." This problem is avoided when estimates based on the model are considered, since all beliefs were about the *use* of nuclear energy. These latter scores could range from +900 to −900; the policy makers' mean score here was 30.6, and that of the public was −97.8.)

To investigate what underlies these differences, an analysis of variance (ANOVA) was calculated. The ANOVA design contrasted the policy makers and the public with respect to all four belief dimensions using the three factor-summary indices: belief strength, attribute evaluation, and their product (i.e., contribution to attitude, $[(\sum_{i=1}^{5} b_i) \times (\sum_{i=1}^{5} e_i)]$ as dependent variables. The two main effects (comparisons between the policy makers and the public, and comparisons between the four belief dimensions) and the 2-way interactions were statistically significant for all three dependent variables, with the single exception of the main-effect comparison between the attribute evaluations of the policy makers and the public.

Table 2 shows the mean values of the factor-summary indices for the policy makers and for the total public sample. It can be seen that the main differences in overall attitudes were due to different contributions from the psychological-risk and environmental/physical-risk dimensions. The former dimension made an appreciable negative contribution to the public's attitudes but only a small negative contribution to the policy makers' attitudes. In contrast, environmental-risk issues made a large positive contribution to the policy makers' attitudes. (The positive contribution to attitude made by a risk dimension is due to the belief that the use of nuclear energy will *not* lead to negatively valued risks. This double negative results in a positive contribution to attitude.) The policy makers and the public were in general agreement concerning economic/technical benefits and sociopolitical risks.

When these differences in contributions to overall attitude were analyzed in terms of the underlying beliefs and attribute evaluations they were found to be more closely related to differences in belief strengths than to differences in attribute evaluations. There were significant differences in the policy makers' and the public's beliefs about psychological risks and environmental/physical risks, although both agreed that the use of nuclear energy would lead to economic/technical benefits and to sociopolitical risks. It is interesting to note that the policy makers and the public agreed in their negative evaluations of sociopolitical risks and environmental/physical risks, but that the policy makers made

TABLE 2
MEAN VALUES OF ATTRIBUTE EVALUATIONS AND BELIEF STRENGTHS: POLICY MAKERS AND TOTAL PUBLIC SAMPLE.

Belief dimension	Mean attribute evaluation (range = ±15)		Mean belief strength (range = ±15)		Mean contribution to attitude (range = ± 225)	
	Policy makers	Public	Policy makers	Public	Policy makers	Public
Psychological risks	−8.4	−10.1*	0.7	8.6**	−9.9	−94.7**
Economic/technical benefits	5.7	7.4*	4.2	5.5	39.7	45.7
Sociopolitical risks	−4.3	−5.0	9.8	10.9	−45.0	−56.8
Environmental/physical risks	−8.8	−9.9	−4.9	−1.0**	45.8	8.0**

* Difference significant, $p < 0.05$.
** Difference significant, $p < 0.01$.

less unfavorable evaluations of psychological risks and less favorable evaluations of economic/technical benefits.

In summary, the policy makers were significantly more favorable toward the use of nuclear energy than were the general public. This was primarily because the policy makers did not associate the use of nuclear energy with psychological risks, and believed that the use of nuclear energy would not lead to environmental/physical risks; in contrast, the public strongly believed that the use of nuclear energy would lead to psychological risks, and were less certain that it would not cause environmental damage.

COMPARISON OF POLICY MAKERS' OWN AND ROLE-PLAY RESPONSES

The ultimate goal of this study was to examine the profiles of attribute evaluations and beliefs which the policy makers perceived as being typical of members of the general public who were in favor of or against the use of nuclear energy. However, before making a direct comparison between these perceptions (the role-play responses) and the actual findings for the general public, it is instructive to examine these role-play responses in relation to the policy makers' own personal positions.

The overall effects of playing ROLEPRO and ROLECON are reflected in measures of attitude estimated from the sum of the evaluation × belief-strength products over the four belief dimensions. Analysis of variance showed that both group membership (ROLEPRO/ROLECON) and role-play (SELF/ROLE) had a significant main effect on this measure of attitude, and the interaction between these variables was also significant. Examination of the mean values of attitude in the four cells of Table 3 clarifies the interaction effect. It can be seen that in the SELF condition there was no significant difference in attitude between the two groups. This is evidence that the policy makers were randomly assigned to ROLEPRO and ROLECON groups. (The difference in mean attitude is nevertheless larger than might be expected. It can be attributed to the chance placement of two individuals with initial viewpoints which were strongly CON in the ROLECON group.) When responding in-role, the differences in attitude between those playing PRO and CON were significant. Further, since the policy makers' own attitudes were more favorable than those of the public, the change in attitude from personal position to role response was greater for the ROLECON group than for the ROLEPRO group.

Analysis of variance was also used to make a detailed comparison between the policy makers' own responses and those they made in-role. The ANOVA design was 2 × 2 × 4 (ROLEPRO/ROLECON × SELF/ROLE × 4 BELIEF DIMENSIONS) using the same three dependent variables as before. All the main effects were statistically significant with the exception of the compari-

TABLE 3
MEAN VALUES* OF BELIEF-BASED ATTITUDE OF POLICY MAKERS IN SELF AND ROLE CONDITIONS.

	SELF ($N = 35$)	ROLE ($N = 35$)
ROLEPRO ($N = 17$)	52.6	163.9*
ROLECON ($N = 18$)	9.8	−259.4†
	NS	†

* Range of values = ±900.
** Difference significant, $p < 0.05$.
† Difference significant, $p < 0.01$.
NS, Difference nonsignificant.

son between attribute evaluations in the SELF and ROLE conditions. More important for this discussion, however, were the significant two-way interactions between ROLEPRO/ROLECON and SELF/ROLE for all three dependent variables, and a significant three-way interaction (ROLEPRO/ROLECON × SELF/ROLE × 4 BELIEF DIMENSIONS) for the belief-strength measure. The statistical significance of these interactions permits a detailed *a posteriori* comparison of the mean values of the dependent variables in all the cells of the ANOVA design. These mean values are shown in Table 4.

Looking first at the contribution to overall attitude of each belief dimension, it can be seen that there are no significant differences in the SELF responses of the ROLEPRO and ROLECON groups. When responding in-role, the ROLEPRO group tended to shift in a positive direction on all belief dimensions, but not significantly so. However, the net effect of these nonsignificant shifts on each of the four belief dimensions had a significant cumulative effect on overall attitude. For the ROLECON group, the shift from SELF to ROLE response was in the negative direction, and was significant on all four belief dimensions.

Although both the ROLEPRO and ROLECON groups shifted their evaluations of risks and benefits in the direction appropriate to their assigned roles, none of these changes were significant. Therefore the different contributions to attitude in the SELF and ROLE conditions were primarily due to in-role shifts in belief strengths as opposed to attribute evaluations. In the ROLEPRO group the SELF to ROLE response shifts were small but nonsignificant, but in the ROLECON group the shifts on three of the belief dimensions were statistically significant. The policy makers assigned to play the CON role shifted their own beliefs with respect to psychological risks, environmental risks, and economic/technical benefits; however, there was no significant shift in their beliefs about sociopolitical risks.

Basis for role-play response shifts

The results discussed above show that the policy makers were able to take a PRO or CON role and to shift their own responses in directions appropriate to the roles they were assigned. In virtually every case (the only exception being beliefs about sociopolitical implications) there were significant differences between responses in the PRO and CON roles. However, for the PRO role, these responses were not significantly different from the policy makers' own personal positions. In the CON role the differences between SELF and ROLE responses were significant for three of the belief dimensions.

Given these differences in response shift in PRO and CON role conditions, it is worth exploring whether the policy makers made their in-role responses essentially in terms of their own positions or independently of

TABLE 4
MEAN VALUES OF ATTRIBUTE EVALUATIONS AND BELIEF STRENGTHS: POLICY MAKERS IN SELF AND ROLE CONDITIONS.

Belief dimension		Mean attribute evaluation (range = ±15)		Mean belief strength (range = ±15)		Mean contribution to attitude (range = ±225)	
		SELF	ROLE	SELF	ROLE	SELF	ROLE
Psychological risk	ROLEPRO	−8.7	7.4NS	−0.1	−1.7NS	4.2	32.1NS
	ROLECON	−8.2	−10.1NS	1.3	11.5**	−23.1	−130.8*
		NS	*	NS	**	NS	**
Economic/technical benefits	ROLEPRO	5.5	9.7NS	3.7	6.2NS	39.1	83.4NS
	ROLECON	5.8	2.6NS	4.7	−1.8**	40.1	−5.6*
		NS	*	NS	**	NS	**
Sociopolitical risk	ROLEPRO	−3.8	−2.0NS	8.9	8.6NS	−38.9	−7.7NS
	ROLECON	−4.7	−6.7NS	10.6	11.9NS	−50.8	−80.6*
		NS	*	NS	NS	NS	**
Environmental/physical risk	ROLEPRO	−8.5	−6.3NS	−4.7	−4.8NS	48.3	56.1NS
	ROLECON	−9.2	−8.6NS	−5.1	4.1**	43.5	−42.4*
		NS	*	NS	**	NS	**

* Difference significant, $p < 0.05$.
** Difference significant, $p < 0.01$.
NS, Difference nonsignificant.

these positions. If the policy makers made in-role responses which were anchored in their own positions, i.e., a more or less constant shift from SELF to ROLE, then one would expect an appreciable correlation between SELF and ROLE responses. If, on the other hand, they made their role responses independently of their own positions, then only low correlations between SELF and ROLE responses would be expected.

In order to test these hypotheses, two correlations were computed for each respondent: the correlation between SELF and ROLE belief-strength responses over the 20 attributes used to construct the four factor-summary indices; and the correlation between SELF and ROLE attribute evaluations over the same 20 items. These correlations (after conversion to z' scores) were examined using a 2 × 2 (ROLEPRO/ROLECON × ATTRIBUTE EVALUATION/BELIEF STRENGTH) ANOVA. The main effect of role group (ROLEPRO *vs.* ROLECON) on the correlation between personal and in-role responses was not statistically significant; the main effect of ATTRIBUTE EVALUATION *vs.* BELIEF STRENGTH was significant ($p \leqq 0.05$). The interaction between these two main effects was nonsignificant. The mean values of the correlation coefficients are shown in Table 5. Note first that, on average, the policy makers relied significantly on their own positions in playing the role of the public ($\bar{r} = 0.53$). It is interesting, however, that the policy makers were more likely to use their own positions as a basis for estimating the attribute evaluations of the public than for estimating the belief strengths of the public. This is demonstrated by the higher correlation for evaluation ($\bar{r} = 0.61$) than for belief strengths ($\bar{r} = 0.44$) between the SELF and ROLE responses.

For beliefs and evaluations considered together, the role-play shift was quite similar for the ROLEPRO ($\bar{r} = 0.56$) and the ROLECON ($\bar{r} = 0.50$) groups. The correlations between SELF and ROLE in both conditions were also approximately the same for attribute evaluations ($\bar{r} = 0.60$ and 0.62, for ROLEPRO and ROLECON, respectively). However, in estimating public beliefs there was a tendency for those in the ROLECON group to rely less on their own positions ($\bar{r} = 0.36$) than did those in the ROLEPRO group ($\bar{r} = 0.51$).

TABLE 5
MEAN VALUES OF CORRELATION COEFFICIENTS FOR SELF WITH ROLE RESPONSES.

	Attribute evaluation	Belief strength	Overall SELF/ROLE
ROLEPRO ($N = 17$)	0.60	0.51	0.56
ROLECON ($N = 18$)	0.62	0.36	0.50
Total ($N = 35$)	0.61	0.44	0.53

* All correlations statistically significant at $p < 0.05$.

To summarize, when playing the role of public subgroups, the policy makers essentially used their own positions as anchors for estimating the positions of the public. They did so to a greater extent for attribute evaluations (perhaps reflecting a perceived commonality of values within society) than for beliefs. It was shown earlier that in the ROLECON condition the policy makers changed their beliefs to a greater extent than in the ROLEPRO condition. It can now be seen that, although not statistically significant, those assigned to the ROLECON group also tended to make more qualititative changes in their beliefs (as opposed to anchored shifts) than did those assigned to the ROLEPRO group. In other words, the policy makers tended to see their own views and feelings with respect to using nuclear energy as being more similar to those of members of the public who are in favor of nuclear energy rather than of those who are opposed to its use.

POLICY MAKERS' REPRODUCTION OF PUBLIC PRO AND CON ATTITUDES

The public subgroups whose beliefs and attitudes the policy makers were asked to reproduce were defined by the following instructions (translated from the German-language questionnaire):

> Your answers should reproduce the opinions of a hypothetical person . . . please imagine that you are an average Austrian citizen who does not have any specific knowledge about energy matters. Your only sources of information are the mass media such as newspapers and television, and discussions with friends. Moreover, you are a definite proponent (opponent) of nuclear energy.

While the role-playing of militant extremists was discouraged by these instructions, it is clear that the ROLEPRO and ROLECON responses made by the policy makers refer to loosely defined public groups. Nevertheless, because a detailed examination had already been made of the beliefs and attitudes of the fifty or so members of the public with the most favorable (most unfavorable) attitudes toward the use of nuclear energy, these two subgroups, PUBPRO and PUBCON, were used as a baseline by which to judge the policy makers' in-role responses. Since there is a sense in which the initial definition of the PUBPRO and PUBCON subgroups is arbitrary, additional comparisons were made between the two role-play conditions and increasingly "moderate" subgroups in the public sample, using the overall attitudes, belief strengths, and attribute evaluations. These additional subgroups are described in Fig. 1. However, the main analyses reported here are based on comparisons with the original PUBPRO and PUBCON subgroups of the public sample; but comparisons with the additional subgroups are also reported as illustrative of trends, as opposed to absolute accuracy, in the policy makers' perceptions.

The first comparison between the policy makers' in-role responses and those of the public was made, using analysis of variance, on the belief-based (overall) attitude toward the use of nuclear energy. Only the PRO/CON main effect was statistically significant ($p \leqq 0.01$).

Table 6 shows that the mean values of these belief-based attitudes were remarkably similar in the PUBCON and ROLECON groups, but that there was rather less correspondence between the PUBPRO and ROLEPRO groups. The implication of this is that the policy makers' role-play responses

TABLE 6

MEAN VALUES* OF BELIEF-BASED ATTITUDES OF PUBLIC SUBGROUPS AND POLICY MAKERS IN-ROLE.

	Public subgroups ($N = 95$)	Policy makers in-role ($N = 35$)
PRO ($N = 65$)	52.3	163.9**
CON ($N = 65$)	−275.5	−259.4NS
	†	†

* Range of values = ±900.

** Difference significant, $p < 0.05$.

† Difference significant, $p < 0.01$.

NS, Difference nonsignificant.

more closely matched those of the public subgroup opposed to, rather than in favor of, nuclear energy. These findings were essentially unchanged when the role-play responses were compared with those of less extreme subgroups. The first and second shifts (see Fig. 1) in the CON group of the public sample resulted in mean values for the belief-based attitude of −218.7 and −179.4, respectively, neither of which were significantly different from the policy makers' ROLECON responses. But, in the case of those in favor of nuclear energy, comparisons with less extreme PRO subgroups further widened the gap between the policy makers' perceptions and the reality of the public's overall attitudes (32.7 and −1.1, respectively, for the first- and second-shift subgroups). This tendency is interesting since it indicates that, despite the fact that the policy makers in the ROLEPRO condition shifted their own responses less than those in the ROLECON condition, these relatively small shifts led to overestimation of the PUBPRO attitudes. In contrast, the large shifts that the policy makers made from their own positions when the in ROLECON condition resulted in accurate estimates of PUBCON attitudes.

Our main concern, however, was not so much the overall attitudes attributed by the policy makers to the public, particularly since this was an indirect (belief-based) measure, but rather the profile of beliefs and attribute evaluations which the policy makers perceived as contributing to the public's attitudes. The major analysis was therefore a comparison between the public and the policy makers in-role, using the three factor-summary indices, i.e., belief strength, attribute evaluation, and the product of these factors (i.e., the contribution to attitude) for each of the four belief dimensions. A 2 × 2 × 4 ANOVA (PRO/CON × PUBLIC/POLICY MAKERS × 4 BELIEF DIMENSIONS) showed that all possible main effects were significant, with the single exception of the comparison between the public and the policy makers in-role for the belief-strength × attribute-evaluation product, i.e., the overall attitude. More relevant to this discussion is the finding that there were neither significant PRO/CON × PUBLIC/POLICY MAKERS interactions nor significant three-way interactions for any of the three factor-summary indices. These findings indicate that the policy makers in the two role-play conditions (ROLEPRO and ROLECON) were equally accurate in their perceptions of the public's positions. Once again, however, there was a slight, but nonsignificant, tendency for those in the ROLEPRO group to see the public as being somewhat more positive toward nuclear energy than in fact they were.

As can be seen in Table 7, it was only with respect to the contribution of the psychological-risk dimension to overall attitude that the policy makers were inaccurate to a significant degree. In the ROLEPRO condition they rightly attributed a negative evaluation of psychological risks to the PUBPRO subgroup, but they then assumed a disbelief that the use of nuclear energy would actually lead to these risks. The product of these attribute evaluations and belief strengths thus resulted in a positive contribution to overall attitude, indicating that the policy makers in the ROLEPRO condition felt that the Austrian public, being in favor of the use of nuclear energy, would not associate this form of energy generation with psychological risks, while, in fact, the public PRO subgroup was quite aware of these risks. Comparisons between the policy makers' ROLEPRO group and the less extreme public subgroups (see Fig. 1) emphasized this mistaken perception: as the public subgroups became less extreme, the discrepancies in these beliefs and their contribution to attitude increased, since the public in these less extreme subgroups believed even more strongly that the use of nuclear energy is associated with psychological risks. In playing the PRO role, the policy makers underestimated the relevance of these risks to such an extent that they attributed a profile which was more positive in its implications than that actually held by *any* systematic subgroup of the sample of the Austrian public.

Inspection of the difference in the policy makers' perception of the public CON groups revealed the following pattern: the former again underestimated the original PUBCON subgroup's negative evaluation of psychological risks and also its belief strength about the association of these risks with the use of nuclear energy. As a consequence, the contribution of psychological risks to overall attitude was underestimated. But when less extreme CON subgroups of the public were used as a baseline for comparisons these differences diminished. This finding indicates that the policy makers in the ROLECON condition demonstrated an understanding of belief strengths and attribute evaluations about the psychological risks associated with the use of nuclear energy which was appropriate to a less extreme antinuclear subgroup than the original CON group.

TABLE 7
MEAN VALUES OF ATTRIBUTE EVALUATIONS AND BELIEF STRENGTHS: PUBLIC SUBGROUPS AND POLICY MAKERS IN-ROLE.

Belief dimension		Mean attribute evaluation (range = ±15)		Mean belief strength (range = ±15)		Mean contribution to attitude (range = ± 225)	
		Public sub-groups	Policy makers in-role	Public sub-groups	Policy makers in-role	Public subgroups	Policy makers in-role
Psychological risk	PRO	−10.3	−7.4*	3.7	−1.7**	−38.1	32.1**
	CON	−11.9	−10.1*	13.5	11.5**	−162.9	−130.8**
		**	**	**	**	**	**
Economic/technical benefits	PRO	9.0	9.7NS	9.1	6.2*	80.9	83.4NS
	CON	5.8	2.6NS	0.4	−1.8*	1.7	−5.6NS
		**	**	**	**	**	**
Sociopolitical risk	PRO	−3.6	−2.0NS	9.2	8.6NS	−34.8	−7.7NS
	CON	−6.1	−6.7	12.5	11.9	−79.9	−80.6NS
		**	**	**	NS	**	**
Environmental/physical risk	PRO	−8.5	−6.2**	−4.8	−4.8NS	44.3	56.1NS
	CON	−11.1	−8.6**	3.0	4.1NS	−34.5	−42.4NS
		**	**	**	**	**	**

* Difference significant, $p < 0.05$.
** Difference significant, $p < 0.01$.
NS, Difference nonsignificant.

Table 7 also shows some divergent perceptions of the policy makers in-role with regard to two other belief dimensions. Regardless of whether they were in the ROLEPRO or ROLECON conditions, they tended to underestimate the PUBPRO and PUBCON subgroups' negative evaluations of environmental/physical risks and the public's belief strength that the use of nuclear energy would lead to economic/technical benefits. Although both these latter differences were statistically significant, they did not result in significant differences in terms of the contributions of these two dimensions to overall attitude.

When comparisons were made between the policy makers in-role and less extreme public subgroups, the policy makers' underestimation of the public's negative attribute evaluation of environmental/physical risks increased for the PRO subgroups (becoming even less accurate) and decreased for the CON subgroups (becoming more accurate). With regard to belief strength about economic/technical benefits, the policy makers' misperception of the public subgroups was more fundamental. There was very little difference, for any of the three public PRO subgroups examined, in the belief strength that the use of nuclear energy leads to economic benefits, and in all cases this belief was stronger than expected by the policy makers. As less extreme CON subgroups were selected, their belief strength about the economic benefits of nuclear energy actually increased, thus remaining substantially stronger than appreciated by the policy makers.

SUMMARY AND CONCLUSIONS

The main objective of this study was to test the accuracy of policy makers' perceptions of the beliefs and attitudes of public groups with respect to the use of nuclear energy. This was done by asking a group of Austrian senior civil servants specializing in energy matters to fill in a questionnaire in the *role* of an average (not extreme) member of the public who was in favor of or opposed to the use of nuclear energy. The same questionnaire had been used earlier to obtain data on the beliefs and attitudes of similar subgroups of the Austrian public, thus allowing direct comparisons to be made. In addition, the policy makers completed the same questionnaire from their own personal points of view, which permitted comparisons between the policy makers' own positions and those of the public. Perhaps not surprisingly, the policy makers tended to have more favorable overall attitudes toward the use of nuclear energy than did the Austrian public in general.

Four major independent dimensions had been found to underlie public attitudes toward the use of nuclear energy: psychological risks, economic/technical benefits, sociopolitical risks, and environmental/physical risks. Analysis in terms of these dimensions indicated that the difference in overall attitudes between policy makers and the public was primarily due to the fact that, for the public, psychological risks were strongly associated with the use of nuclear energy, while environmental issues only made a minimal positive contribution toward their attitude. A similar analysis of the policy makers' own personal responses showed that here psychological risks were associated only to a small extent with the use of nuclear energy, whereas environmental issues were perceived as a substantially positive aspect.

When the policy makers responded to the questionnaire in-role, they were successful in shifting their original responses in the directions indicated by their role-play assignments (ROLEPRO or ROLECON); and they were able to reproduce fairly accurately the general attitudes toward the use of nuclear energy held by the appropriate subgroups of the public. There was, however, a tendency to overestimate the positive attitudes of the subgroup in favor of the use of nuclear energy.

In terms of the four belief dimensions, the policy makers were also able to satisfactorily reproduce the general attitudes of public subgroups in favor of or against the use of nuclear energy. This was particularly true with respect to the attitudinal contributions made by economic/technical benefits, sociopolitical risks, and environmental/physical risks. The accuracy of the policy makers' perceptions was somewhat diminished, however, by their failure to recognize the extent to which issues of psychological significance contributed negatively to the public's attitudes, irrespective of whether they were in favor of or against the use of nuclear energy. The policy makers underestimated the public's negative evaluation of psychological risks and they also underestimated the public's belief that the use of nuclear energy would lead to such risks.

Although the policy makers had relatively accurate perceptions of the belief and value systems underlying public attitudes for or against the use of nuclear energy, it would be interesting to know the degree to which this understanding is actually reflected in policy recommendations. Furthermore, the degree to which policy makers view public opinion as a legitimate input into the decision-making process remains to be investigated.

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USE OF NONDIFFERENTIABLE OPTIMIZATION IN A HEALTH CARE PROBLEM[1]

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Those who study health care systems (HCS) seek to model the features of health care systems of societies that are common to different countries, so as to assist those who plan health services. The mathematicians interested in nondifferentiable optimization (NDO) seek to extend the classical optimization techniques to functions that have "non-smooth" regions where no unique gradient can be defined.

This article reports how a health resource allocation model was solved by minimizing a function with points of nondifferentiability. It describes how an example of the model arose in the joint strategic planning of health and personal social services in a county in England with a population of about one million. It also formulates the model as a problem of NDO. Ways to obtain numerical solutions are reviewed, and the solution of the example by NDO is compared to another method based on linear approximation.

KEY WORDS: society, producer subsystem, health care system, nondifferentiable optimization.

RESOURCE ALLOCATION MODELING IN DEVON

DEVON IS a county in the southwest of England in which health services (e.g., hospitals, clinics) are managed by the Area Health Authority (AHA), and personal social services (e.g., residential homes, social workers) are managed by the Local Authority (LA). Many individuals receive both sorts of services, which often overlap. After surgery, for example, some hospital patients may be discharged earlier if suitable nursing support is available for them at home. Elderly individuals may receive equivalent care in residential homes or in geriatric hospitals. The problem for Devon is to provide a balanced mix of health and personal social services within constraints of total resources.

McDonald, Cuddeford, and Beale (1974) describe a model to help in this task. It models the balance chosen by the many agents in the health care systems (HCS)—doctors, nurses, social workers, etc.—between the use of health services and personal social services for different categories of patients. The model's underlying hypothesis is that the aggregate behavior of these agents can be represented as the maximization of a utility (or inferred worth) function, whose parameters can be estimated from the results of previous choices. If these parameters do not change with time, the model can be used to simulate how future resource levels will be allocated in the HCS. Furthermore, because the underlying hypothesis is an optimistic one, the model may suggest reallocations. The full model is quite sophisticated, with several special features. Only a simple version is reported here, both to clarify the presentation and because the example is one that actually arose in using the model to assist health care planning in Devon.

Table 1 categorizes elderly patients (65 or older) under 17 headings according to their housing, social isolation, physical disability, mobility, and mental state. This categorization is part of a more detailed classification designed in conjunction with case workers who meet the patients. Table 2 lists six resources used in the domiciliary care of these patients. The first two resources (psychiatric and geriatric day hospitals) are provided by the AHA; the others by the LA. Other institutional resources (such as inpatient hospitals and residential homes) are also used by elderly patients in

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TABLE 1
SEVENTEEN CATEGORIES OF ELDERLY PATIENTS.

Patient category	Housing condition (1)	Social isolation (2)	Physical disability (3)	Mobility (4)	Degree of dementia in mental state
1	poor/good	mild	very severe	severe/mild	severe
2	poor/good	mild	severe	mild	severe
3	poor/good	mild	very severe	severe/mild	mild
4	poor/good	severe	severe	mild/good	mild
5	poor/good	mild	severe	mild/good	mild
6	poor/good	severe	mild	mild/good	mild
7	poor/good	mild	mild	mild/good	mild
8	poor	mild	very severe	severe/mild	none
9	good	mild	very severe	severe/mild	none
10	poor	severe	severe	mild/good	none
11	good	severe	severe	mild/good	none
12	poor	mild	severe	mild/good	none
13	good	mild	severe	mild/good	none
14	poor	severe	mild	mild/good	none
15	good	severe	mild	mild/good	none
16	poor	mild	mild	mild/good	none
17	good	mild	mild	mild/good	none

(1) Good housing means easy access to inside toilet and hot water; poor housing means neither.

(2) Mild social isolation means not living alone; severe social isolation means living alone.

(3) Mild = unable to carry out household care; severe = unable to carry out household and personal care; very severe = incontinent and/or unable to feed himself.

(4) Mild = can get around house, or can get out of house with aids or personal assistance; severe = chairfast or bedfast.

Devon, but for this study their use was assumed to be fixed.

Patients in each of the 17 categories could receive many different combinations of the six resources. Table 3, however, defines up to four alternative modes of care for each category. These alternatives, which derive from discussions with consultants, senior nurses, and other professionals, indicate how much of each resource might be used to provide equivalent levels of care for each patient. In a sense, the resource levels in these alternative "packages" represent ideal standards which doctors would like to attain. Unfortunately, these standards lie well above what can currently be afforded. The Devon AHA and Devon LA want together to provide a mix of health and personal social services which they can afford and with which the HCS can approach the ideal standards for a large number of patients. The model was used to assist this debate by simulating who gets what.

TABLE 2
SIX RESOURCES FOR DOMICILIARY CARE.

Name of resource	Unit of resource
Psychiatric day hospital	day place
Geriatric day hospital	day place
Home nurse	WTE*
Day center	place
Home help	WTE*
Meals	service

* WTE = whole time equivalent (many nurses work only part time).

We use the indices

$i = 1, 2 \cdots$ 17 patient categories
$k = 1, 2 \cdots$ 6 resource types
$l = 1, 2 \cdots$ 4 care modes,

and label the numbers in Table 3 as

U_{ikl} = the ideal levels of resource type k in care mode l for patient category i.

Because of resource constraints, rather lower resource levels u_{ikl} are actually achieved, and it is these that the model seeks to predict. It also predicts

x_{il} = the number of patients in category i who receive care in mode l

so as to satisfy constraints on the total number d_i of patients in each category receiving care, and the total resources A_k of each type available for care,

(1) $$\textstyle\sum_l x_{il} = d_i \quad \forall\, i,$$

(2) $$\textstyle\sum_{i,l} x_{il} u_{ikl} = A_k \quad \forall\, k.$$

Both d_i and A_k are assumed to be known, and Tables 4 and 5 give the numbers of elderly patients, and the levels of health service and personal social service re-

TABLE 3

RESOURCES NEEDED BY ELDERLY PATIENTS IN ALTERNATIVE MODES OF CARE.

Patient category*	Mode of care	Amount of resource needed per patient per year**					
		Psychiatric day hospitals	Geriatric day hospitals	Home nurse	Day center	Home help	Meals
1	1			1125	85	235	120
	2		100	1125		220	105
	3	100		1125		220	105
2	1	200		330		65	
	2			540	105	110	
	3			770		155	100
3	1		150	520		175	65
	2			690	85	235	120
	3			910		310	205
4	1		125	165		530	25
	2	250		75		235	
	3			165	125	530	25
	4			255		825	150
5	1		100	105		100	
	2			105	105	100	
	3			150		145	100
6	1	250				80	
	2				50	245	50
	3					285	100
7	1	50				40	10
	2		50			40	10
	3				40	40	10
	4					45	50
8	1		150	490		200	55
	2			860		330	205
9	1		150	490		150	55
	2			860		270	205
10	1		125	100		560	25
	2			100	125	560	25
	3			155		870	150
11	1		100	110		555	50
	2			100	125	500	25
	3			155		810	150
12	1		75	75		145	25
	2			65	105	130	
	3			90		185	100
13	1		50	80		85	50
	2			65	105	70	
	3			90		125	100
14	1		50			275	50
	2				50	275	50
	3					320	100
15	1		50			215	50
	2				50	215	50
	3					260	100
16	1		50			70	
	2					80	50
17	1		50			70	
	2				40	70	10
	3					20	50

* As defined in Table 1.

** The units in this table are, for each resource, respectively: daily attendances (1 psychiatric day place = 500 daily attendances); daily attendances (1 geriatric day place = 1000 daily attendances); visits (1 home nurse WTE = 3820 visits); daily attendances (1 day center place = 125 daily attendances); hours (1 home help/WTE = 1550 hours); meals (1 meal service = 1000 meals).

sources, used in the Devon example. The former arise from assuming that an approximately constant proportion of the elderly need care; the latter from certain assumptions about growth in the United Kingdom health service.

It remains to specify the form of the utility function maximized by the model. It is

(3) $$Z(\mathbf{x}, \mathbf{u}) = \textstyle\sum_{i,k,l} x_{il} h_{ikl}(u_{ikl}),$$

where

(4) $$h_{ikl}(u) = (C_k U_{ikl})/\beta_k \, [(u/U_{ikl})^{\beta_k} - 1],$$

TABLE 4
NUMBER OF ELDERLY IN DEVON.

Patient category i	Number of elderly patients d_i	Patient category i	Number of elderly patients d_i
1	43	10	51
2	38	11	198
3	326	12	132
4	90	13	777
5	200	14	918
6	891	15	3410
7	703	16	339
8	184	17	2667
9	818		

(5) $\beta_k = 1 - 1/F_k,$

and where $\mathbf{x}$, $\mathbf{u}$ denote $\{x_{il}\ i = 1, 2, \cdots, 17, l = 1, 2, \cdots, 4\}$, $\{u_{ikl} i = 1, 2, \cdots, 17, k = 1, 2, \cdots, 6, l = 1, 2, \cdots, 4\}$, respectively. The function $Z(\mathbf{x}, \mathbf{u})$ is:

1) Additive across i, k, l. This implies no correlation between the objectives of increasing each and every $x_{il}h_{ikl}(u_{ikl})$.
2) Linearly increasing in x_{il}. The extra benefit from taking care of one more patient in a particular care mode is independent of the number already cared for in that mode.
3) Zero when u_{ikl} equals U_{ikl} for all i, k, l. At this point, marginal increases in Z resulting from increasing resource levels equal the marginal resource costs C_k. Normally, $u_{ikl} < U_{ikl}$ for some i, k, l, and Z is then negative.
4) Monotonically increasing and concave downwards in u_{ikl} for $\beta_k \leqq 0$. This implies diminishing returns as the ideal resource standards are approached. The speed with which the returns diminish is measured by the power parameters β_k, or the corresponding elasticities F_k.
5) Not unlike a similar function defined in the model DRAM (Hughes & Wierzbicki, 1980). DRAM, however, does not incorporate the constraint (1) and does not require NDO.

TABLE 5
MODEL PARAMETERS FOR EXAMPLE.

Resource type k	Resources available in Devon* A_k	Resource costs** C_k	Elasticities† F_k
1	10	5830	0.595
2	30	9190	0.800
3	125	5665	0.800
4	79.6	374	0.202
5	773.5	1778	0.325
6	275.4	230	0.325

* Units as in Table 2.
** £ running per year.
† As defined in Eq. (5).

Whether the results of maximizing the function $Z(\mathbf{x}, \mathbf{u})$, subject to the constraints of Eqs. (1) and (2), are good predictions of future HCS behavior depends partly upon the two parameters C_k and F_k. The first of these (the marginal resource costs) can be estimated by various accounting analyses. But the second set of parameters (the elasticities) are much harder to choose. In Devon several runs were carried out to check the accuracy of models with different parameters in reproducing known historical allocations. Table 5 gives the values used in our example.

The assistance provided to Devon was not limited to a couple of model runs like this one. Canvin, Hamson, Lyons, and Russell (1978) describe in more detail how the project team worked with the local planners. In this paper, however, we concentrate on the model, and in particular on how to solve it. It is perhaps surprising that the maximization of Eq. (3) subject to Eqs. (1) and (2) is not straightforward. The next section explains why.

SOLUTION OF THE MODEL

In purely mathematical terms the problem is to find x_{il} and u_{ikl} for all i, k, l, satisfying

(1) $\sum_l x_{il} = d_i \quad \forall\ i,$

(2) $\sum_{i,l} x_{il}u_{ikl} = A_k \quad \forall\ k,$

that maximize

(3) $Z(\mathbf{x}, \mathbf{u}) = \sum_{i,k,l} x_{il}h_{ikl}(u_{ikl}),$

where

(4) $h_{ikl}^{(u)} = (C_k U_{ikl}/\beta_k)\ [(u/U_{ikl})^{\beta_k} - 1].$

There are various possible approaches, of which the most elementary would be direct numerical search. We can, however, make more use of the forms of Eqs. (1)–(4). We note, for example, that Eqs. (1)–(3) are linear in x_{il}, and that if u_{ikl} were known for all i, k, l, the problem would be a simple linear program (LP). Unfortunately, the coefficient terms in Eqs. (2) and (3) are functions of the unknown variables u_{ikl}. But in both equations we can make a piecewise linear approximation such as

$$(5) \qquad \tilde{Z}(\mathbf{x}, \mathbf{u}) = \sum_{i,k,l} \left\{ \begin{array}{l} {}_1x_{il}h_{ikl}(0.1) + {}_2x_{il}h_{ikl}(0.2) \\ \quad + \cdots + {}_{10}x_{il}h_{ikl}(1.0) \end{array} \right\},$$

by introducing programming variables ${}_jx_{ikl}$, $j = 1, \cdots, 10$, that satisfy

$${}_jx_{il} = \begin{cases} x_{il} : j = \bar{j}, & \forall\, i, l \\ 0 \ \ : j \neq \bar{j}, & \forall\, i, l \end{cases}.$$

In theory, LP techniques can then be used. In practice, the approach requires a computer program or LP package with special features.

This analysis might suggest that difficulties arise because of nonlinearity in Eqs. (2) and (3). In fact, these nonlinearities can be handled using Lagrange multipliers. Doing this, we shall reveal a problem of NDO.

We formulate the dual problem

$$\min_{\lambda} \Phi(\boldsymbol{\lambda}),$$

where $\Phi(\boldsymbol{\lambda})$ is the solution to an internal problem

$$\Phi(\boldsymbol{\lambda}) = \max_{\substack{\mathbf{x} \geq 0 \\ \Sigma\mathbf{x}=\mathbf{d}}} \max_{\mathbf{u} \geq 0} L(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda})$$
$$= L(\mathbf{x}^*, \mathbf{u}^*, \boldsymbol{\lambda}),$$

in which * denotes the optimal value or function, and

$$(6) \quad L(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}) = \textstyle\sum_{i,k,l} x_{il}h_{ikl}(u_{ikl}) + \sum_k \lambda_k (A_k - \sum_{i,l} x_{il}u_{ikl}),$$

is the result of adjoining the constraint of Eq. (2) to the function of Eq. (3) with Lagrange multipliers λ_k, $k = 1, 2, \cdots, 6$. We now have three embedded problems which we can take in turn, and under certain conditions the solution to this dual problem also solves the original problem.

The first, innermost problem is easy to solve. Find $\mathbf{u}(\mathbf{x}, \boldsymbol{\lambda})$ so as to

$$\max_{\mathbf{u} \geq 0} L(\mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}).$$

Setting $\dfrac{\partial L}{\partial \mathbf{u}}$ equal to zero gives

$$(7) \qquad u^*_{ikl}(\mathbf{x}, \boldsymbol{\lambda}) = r_k U_{ikl},$$

provided that $x_{il} \neq 0$, where

$$(8) \qquad r_k = (\lambda_k / C_k)^{-F_k}$$

are "reduction factors" which, when applied to the ideal resource levels U_{ikl}, give the actual resource levels. In the model, the r_k do not vary across patient categories or modes of care, and the balance between the reduction factors for different resource types is controlled largely by the elasticities F_k. The result defined by Eq. (7) is always positive and therefore satisfies the constraint on $\mathbf{u}$. The result of the maximization is

$$(9) \qquad L(\mathbf{x}, \mathbf{u}^*, \boldsymbol{\lambda}) = b + \textstyle\sum_{i,l} c_{il}x_{il},$$

where

$$b = \textstyle\sum_k \lambda_k A_k$$
$$c_{il} = \textstyle\sum_k (C_k U_{ikl}/\beta_k)[F_{k^{-1}}(\lambda_k/C_k)^{1-F_k} - 1],$$

Strictly, c_{il} is determined only when $x_{il} \neq 0$. However, when $x_{il} = 0$, the corresponding terms in Eq. (9) are zero anyway.

The second problem is also easy to solve. Find $\mathbf{x}(\boldsymbol{\lambda})$ so as to

$$\max_{\substack{\mathbf{x} \geq 0 \\ \Sigma\mathbf{x}=\mathbf{d}}} L(\mathbf{x}, \mathbf{u}^*, \boldsymbol{\lambda}).$$

This is a very simple LP, for which the solution can be found by inspecting c_{il}.

$$(10) \qquad x^*_{il} = \begin{cases} d_i : l = \bar{l} \\ 0 : l \neq \bar{l} \end{cases}$$

where

$$c_{i\bar{l}} = \max_l \{c_{il}\}.$$

Strictly, this unique solution for $\mathbf{x}^*$ exists only when there is a single mode in each category with maximum c_{il}. Typically, however, categories have more than one such mode, and in such circumstances a unique solution for $\mathbf{x}^*$ cannot be found until $\boldsymbol{\lambda}^*$ is determined. Nevertheless, the result of the maximization is unaffected, being equal to

$$(11) \qquad \Phi(\boldsymbol{\lambda}) = L(\mathbf{x}^*, \mathbf{u}^*, \boldsymbol{\lambda})$$
$$= \textstyle\sum_k A_k\lambda_k + \sum_i c_{i\bar{l}}d_i.$$

There remains the third problem of choosing $\boldsymbol{\lambda}$ so as to

$$(12) \qquad \min_{\lambda \geq 0} \Phi(\boldsymbol{\lambda}).$$

The difficulty here is that small continuous changes in λ, while causing small continuous changes in $\mathbf{c}$, can cause large and discontinuous changes in the LP solution for $\mathbf{x}^*$. Because of this, $\Phi(\lambda)$ is a nonsmooth function of λ. Loosely speaking, it has "corners" like the graph in Fig. 1. Solution methods which ignore this fact may fail, especially when the solution lies on a corner. What is the meaning of a solution for λ on a "corner" of $\Phi(\lambda)$? It means that more than one mode in each category has maximum c_{il}, and patients in these categories are divided between two or more modes of care. It is these mixed-mode solutions, in which there is no unique solution for $\mathbf{x}^*$ until λ^* is found, that complicate the analysis. However, once the optimal λ^* is found, the values of $\mathbf{u}^*$ are also fixed and the determination of which modes are active in each category is a straightforward LP problem.

The results derived above show that the problem formulated at the beginning of this section can be solved by the procedure depicted in Fig. 2. The two innermost problems are solved by using Eqs. (7), (10), and (12) to determine $\Phi(\lambda)$ for a particular choice of λ. The way in which an NDO algorithm can be used to find the value of λ that minimizes $\Phi(\lambda)$ is described in the next section.

SOLUTION OF THE EXAMPLE

In the previous section we showed how a solution to the example given in the section on resource allocation modeling in Devon can be easily found once we have a procedure for finding the λ which solves the NDO problem of

$$\min_{\lambda \geq 0} \Phi(\lambda).$$

Such procedures are extensions of the procedures used for differentiable optimization. Where the latter use a gradient, NDO procedures use a subgradient defined as

$$g_\lambda = \partial\Phi(\lambda)/\partial\lambda.$$

Unlike the gradient, the subgradient is not unique. There is a set of supporting hyperplanes at any point of nondifferentiability, and this is one of the additional features that NDO procedures must handle.

Another obstacle to be overcome is that the subgradient does not generally tend to zero as the solution is approached. This makes it difficult to identify the neighborhood of the optimum. Furthermore, the direction of $-g_\lambda$ is not generally one in which $\Phi(\lambda)$ decreases, and a single member of a subgradient set provides very scant information about descent directions.

Methods to solve NDO problems began to appear in the mid-1960s, and Balinski and Wolfe (1975) can be recommended as a source of references and basic ideas. Devon's problem was solved using the method described in Nurminski and Zhelikhovski (1974) to regulate the step size in a generalized classical descent procedure. Although the original problem has $(17 \times 4) + (17 \times 4 \times 6) = 476$ variables, the dual problem has only six variables, and hence has negligible storage requirements. The second author wrote a computer program with about 50 Fortran statements, which makes repeated calls of a subroutine written by the first author to calculate Φ and its subgradient. The results tabulated below were found by the International Institute for Applied Systems Analysis PDP 11/70 minicomputer with a UNIX time-sharing operating system. This system makes convergence times difficult to assess. Subsequently, however, the computations were confirmed with the commercially available NDO solution routines developed by Lemarechal (1978). It took 0.5 CPU seconds to get a solution with machine precision on an IBM 370/168.

The same example was also solved by the third author using the piecewise linear ap-

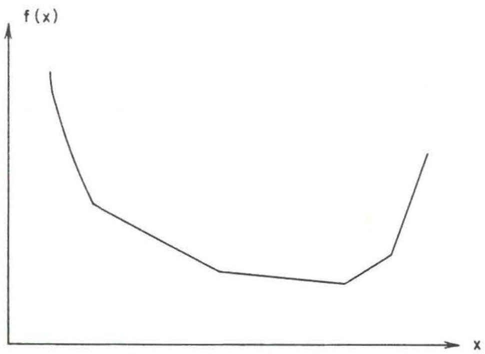

FIG. 1. Example of a nonsmooth function.

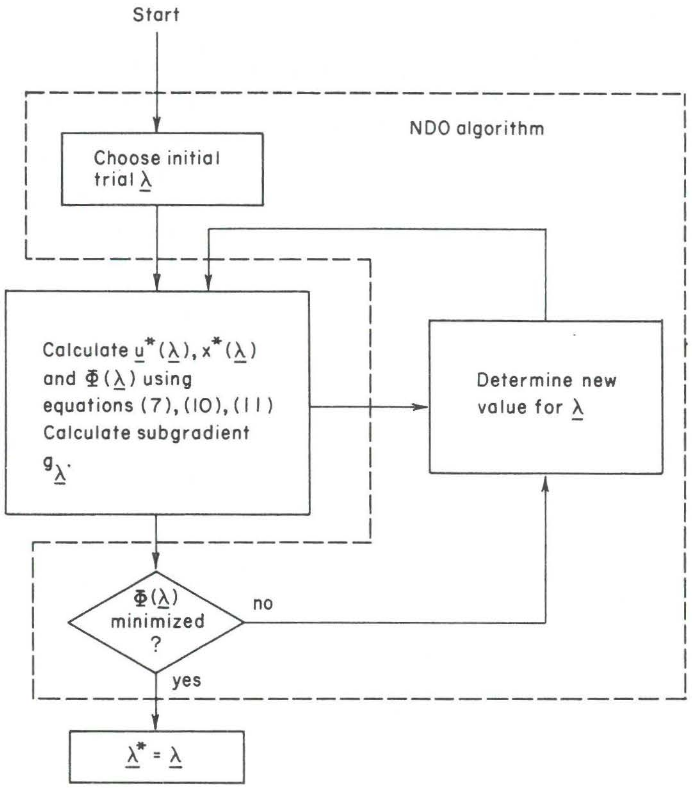

FIG. 2. Solution procedure.

proximation described at the beginning of the section on resource allocation modeling in Devon. The computer package which was used (called SCICONIC) had the necessary separable programming facility with associated matrix generation and report writing. Starting from the solution to a similar problem, the central part of the SCICONIC solution (the solution of the linearized problem as a large LP) took 64 iterations and 1.7 CPU seconds—slightly longer than the NDO solution. A solution from "scratch" might have taken up to twice as long.

Table 6 gives the results obtained both by NDO and by piecewise linear approximation. Although the second method neither uses nor calculates the Lagrange multipliers $\boldsymbol{\lambda}$ used by the first method, the reduction factors $\mathbf{r}$ of Eq. (8) are calculated by both methods and provide an equivalent comparison. We see that they are practically identical, the small differences (<1%) probably being due to rounding. We conclude that both methods reached the same solution. The allocations of patients to modes of care are identical in 12 modes and different in the remaining 5. These differences arise not from the different solution methods but from the discontinuous nature of the solution for $\mathbf{x}^*$ as a function of $\boldsymbol{\lambda}$. Because this particular example was part of a hypothetical scenario, a direct validation of these predictions for Devon is impossible. However, similar runs have shown that the reduction factors can be quite accurately predicted (Coverdale & Negrine, 1978), although the actual use of different modes of care is usually more homogeneous than predicted by the model. Canvin, Hamson, Lyons, and Russell (1978) give additional results for Devon. The extreme modal allocations can be regarded as optimistic predictions of reallocations within the HCS,

TABLE 6
SOLUTIONS TO DEVON EXAMPLE BY NDO AND LINEAR APPROXIMATION.

Resource types (k)	Reduction Factors (r_k): Solution via NDO	Reduction Factors (r_k): Solutions via linear approximation
1	0.741	0.745
2	0.451	0.453
3	0.373	0.374
4	0.652	0.653
5	0.536	0.536
6	0.257	0.257

Patient categories (i)	Allocation of patients to modes (x_{il}): Solution via NDO, Modes (l)				Solution via linear approximation, Modes (l)			
	1	2	3	4	1	2	3	4
1	43				43			
2			38				38	
3	277		49		233	93		
4		7	83		63	27		
5			200				200	
6	20		871				891	
7				703				703
8		184				184		
9		818				818		
10	43	8			51			
11	196	2			169	29		
12			132				132	
13			777				777	
14			918				918	
15			3410				3410	
16		339				339		
17			2667				2667	

giving reduction factors that are slightly higher than would be obtained in practice. When historical factors seem likely to prevent this, appropriate constraints can be easily applied in the model and incorporated in either method of solution.

CONCLUSION

The example analyzed here is interesting because it tests alternative ways to solve a practical example. Although the NDO solution was faster, it had none of the diagnostic or presentational print-outs available from the SCICONIC solution, being written primarily to see how a different method would solve the example. On the other hand, the programming of a full-scale solution program to use NDO would appear to be straightforward. Because the main burden of computing falls on the subroutine that solves the internal problem (and *not* on the NDO routines), there is more room to extend the scope of the model wherever this might be necessary. Provided that modifications to the model do not damage the duality results exploited in the solution, the small NDO routines can remain unchanged.

From the point of view of resource allocation modeling, the new analysis of this example makes plain what solving the model actually means, and helps discussions about whether the right model is being solved. Within the framework of strategic planning in Devon, the results of Table 5 indicate how current levels of care are likely to change, and suggests what pattern of modal allocation will follow if the many agents in the HCS act (or can be encouraged to act) so as to maximize levels of care.

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MOBILITY OF RESOURCES, ACCESSIBILITY OF KNOWLEDGE, AND ECONOMIC GROWTH[1]

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This paper presents an analysis of the role of public phenomena like knowledge and research and development in the economic growth process of a spatially extended economy. It deals with the organizational level of living systems (regions) and the societal level, and with monetary information flows, chiefly in the decider and channel and net subsystems. Accessibility to knowledge pools is used as a way of connecting regions with each other. It is shown with analytical methods as well as with simulation that improving information networks will generally lead to a higher rate of growth in all regions if the economies behave according to the neoclassical paradigm. Superimposing an accessibility function with spatial frictions in the information flows on a technology with economies of scale leads to uneven but realistic dynamics. In this case there is an increasing inequality of income per capita between regions with different centrality up to a point of maximum inequality with a subsequent convergence thereafter. The analysis demonstrates that increasing research and development activities can, under certain probable technologies, lead to increasing inequalities between rich and poor regions.

KEY WORDS: organization, region, monetary information flows, decision making, economic policy.

THE CONCEPT OF MOBILITY

THE REGIONAL development problem brings into focus the concepts of space and time. Time is brought in because regional patterns of population distribution and economic phenomena are regulated by dynamic inertia; space, because regions can never be seen as independent points. Regions have to be analyzed as nodes interacting with each other through one or many communication–transportation networks.

These basic observations indicate that *mobility* as a time–space concept can be seen as an essential aspect of regional and national economic theory and policy. Mobility is by no means a simple concept. Although it is used frequently in economics, its basic meanings are not usually clarified. Marshall (1890) used it in his *Principles of Economics*, but his analysis of mobility is limited because he focused on the time dimension only. The subdivision into three basic time periods of economic analysis—short, medium, and long time perspectives—was, however, instructive. He wished to show that the slopes of the excess demand functions (or rather the supply functions) are influenced systematically by the time perspective as a consequence of shifts in general mobility of resources. He observed that the longer the time period is the more elastic is the supply function with respect to price. One consequence of this analysis is that substantial reallocations in the economic system can only be achieved over a very long time period. Mobility of resources is then generally high; thus the effect of a persistent change in the price vector can influence the substitution processes of the whole economic system.

It is one of our basic hypotheses that economic policies in Europe have been oriented towards *reducing* mobility in this dynamic Marshallian sense. Lower mobility of certain resources must, therefore, to an increasing extent be compensated for by higher mobility of other resources in order to maintain economic efficiency.

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It is also necessary to define mobility as a spatial concept. Although this is often related to the concepts of transportation and communication costs, it is more appropriate to relate mobility to spatial *frictions*. No trade can occur unless communication has taken place. Business contracts have to be drawn up before actual trade and transportation can even begin. The amount of such uncertainty-reducing preliminaries differs very much among different types of commodities. Highly standardized commodities, such as oil and grain, do not need any extensive personal communication before a contract of trade is set up. Because of bulkiness some of these commodities, such as low-grade mining products, exhibit large spatial *frictions*, in spite of standardization. This is shown in Table 1. The distance sensitivities show considerable variation among sectors. It can be assumed that this variation is dependent on three factors: bulkiness, storability of the commodity, and personal communication requirements per unit of sales.

The relative interregional mobility of intermediate commodities is considerable in comparison with labor mobility. Using Swedish data for the 1970s, approximately 50% of the total value of intermediary commodities in each region was exported to some other region. At the same time, using the same subdivision of the country, the yearly out-migration of young members of the labor force was less than 5% of the total population of the same age (20–24 years of age). There is thus a relative difference of spatial mobility of the order of magnitude of ten to one between nondurable, intermediary goods and labor.

TABLE 1
DISTANCE SENSITIVITIES FOR SALES OF INTERMEDIATE COMMODITIES BETWEEN LARGE SWEDISH FIRMS (MORE THAN 50 EMPLOYEES).*

Sector	Distance Sensitivity** ($\times 10^{-3}$)
Agriculture and forestry	−5.7
Food manufacturing	−3.4
Printing and publishing	−2.2
Wood and paper products	−2.2
Wholesale and retail trade	−1.6
Machinery and equipment	−1.5
Construction	−1.2
Private services	−1.1
Chemical industry	−1.0
Textile and clothing	−0.7
Non-metallic minerals	−0.6
Petroleum and coal	−0.6
Basic metals	−0.5

Other distance sensitivities not significantly different from zero (mining, rubber products, shipbuilding, electricity, transport, etc.)

* Adapted from Snickars, 1978.
** γ_i in exp γ_i (distance from seller to buyer)

There are also marked differences in spatial mobility of labor between different social groups and age cohorts. Young members of the labor force, such as those referred to above, have a mobility rate that is three times as large as the group between 35 and 39 years of age. It is, therefore, necessary to take into account these differences in mobility in the formation of economic policies and especially labor market policies.

In general, commodities, including durable capital commodities, exhibit small spatial frictions over the long term. Urban infrastructure is, however, a clear exception to this rule. Reallocation of urban infrastructure capital is not usually based on measurements of relative productivity differences. Decisions about investments in urban infrastructure are more often based on local income and local considerations of need. An outmoded spatial structure can thus be kept unchanged for very long periods. Every country of Europe has examples of such regions with obsolete infrastructures.

It must be stressed at this point that a low investment-capital ratio in a sector can give the same kind of spatial stability as the existence of large spatial frictions. An example is housing, for which, in Europe, the average economic durability is more than sixty years and for which the net investments normally amount to little more than one percent of the capital stock. The transportation network changes at an even lower rate in most advanced economies. Railway networks are mostly maintained with a fairly given structure over decades and the rate of investment in new roads is in most developed countries smaller than one percent per year. This stability of the environment in terms of housing, urban infrastructure, transportation networks, and natural resources makes the planning of firms much easier than if such mainly public resources could be instantaneously and without spatial frictions changed in accordance with some planning objectives.

In this context we assume that fundamental institutional arrangements, such as constitutions, are unchangeable over the long term and have very large spatial frictions in the sense that they cannot be transferred from one geographical unit to another. Furthermore, we assume that the generation and diffusion of new knowledge is a factor of general importance for regional and thus national development.

Table 2 gives a tentative classification of different inputs in terms of spatial and temporal mobility. Inputs differ in mobility both spatially and temporally. It should be an ambition of economic theorists to take these differences of input mobility into consideration. The problem of spatial and/or temporal immobility of inputs has consequences for regional economic policies over both the long and the short run.

This paper will be subdivided into two sections. The first section deals with the problem of optimal policies in a short-time perspective. In this case it is only possible to create a regional policy in which intermediate nondurable commodities and certain groups of the labor force can be moved between regions. Other groups of the labor force, capital commodities, knowledge, public goods, and natural resources serve only as the environment for decision making. The second section of this paper is devoted to the problem of public goods policies within a framework of long-term regional development.

THE SHORT-TERM REGIONAL POLICY PROBLEM IN A NATIONAL CONTEXT

The short-term policy problem, often illustrated by the Phillips curve, was already a politically discussed problem in Sweden at the end of the 1940s. At that time a group of economists—Bent Hansen, Erik Lundberg, and Gosta Rehn—became involved in a discussion of the conflict between national policies and goals to avoid regional and sectoral structural unemployment. It was already then realized that a low level of registered unemployment at the national level, coupled with an implied high rate of inflation, was normally accompanied by extensive unemployment in certain industrial sectors, occupations, age groups, and regions. As early as 1952, two economists working within the Swedish Association of Trade Unions—Gosta Rehn and Rudolf Meidner—developed a theory of modern labor market policy. Their scheme can be described in the following way.

A centralized wage policy aimed at equalizing wages throughout the whole economy is proposed by the labor union, subject to constraints determined by the maximallly accepted increase in prices and the minimal rate of growth of the national product. The general increase in wages could then be rather large and, if implemented, would imply a sharply declining demand for labor in those regions and sectors having a bad economic environment, and/or low income elasticity of demand for their products. It was then recommended by Rehn and Meidner that the government should act in two ways. It should subsidize some firms to prevent shutdowns and/or it should increase the sectorial and regional mobility of those people in danger of becoming unemployed.

Policies implemented during the period 1955–1965 show that interregional and intersectorial mobility measures were favored politically; the Meidner–Rehn recipe was, however, never followed in both of its as-

TABLE 2
DIFFERENCES IN THE MOBILITY OF PRODUCTIVE RESOURCES (Examples).

Temporal mobility/Spatial mobility	Small spatial frictions	Medium spatial frictions	Large spatial frictions
Changeable in the short term	Low weight intermediate non-durable commodities	Information on existing knowledge Younger members of labor force	Older members of labor force
Changeable in the medium term	Semi-durable capital commodities	Innovations	—
Changeable in the long term	Transportation networks Housing	Urban infrastructure Inventions	Natural resources Institutions

pects. Increased mobility of labor was used as a means of decreasing unemployment in some regions and decreasing excess demand for labor in other regions, thus checking inflation and regional inequality at the same time. The reallocation of labor would also be a means of increasing the rate of economic growth in the economy as a whole. After 10 years of successful implementation there was a political reaction against this scheme in Sweden and also in other countries that had implemented similar policies. Such reactions should have been expected. Following the initial stage of modern labor market policies, when only the younger and more mobile groups are participating in the increased mobility, inevitably there comes a stage when also older and less mobile groups are assumed to move. At this point it becomes unprofitable for society to move such groups because of excessive mobility costs. Also, it is obviously unprofitable for society as a whole (and surely for the unemployed) to be unemployed in their region of residence.

It has become a political requirement that policies accommodating full employment at the regional and other disaggregate levels at a regionally equalized wage rate should be devised. In order to discuss this problem we contrast the results of a simple static social optimization model with the optimization procedures of a firm. The regional policy problem is analyzed within the framework of an environment that is given and unchangeable within the time horizon of the policy objectives. It is thus assumed that private capital (K_i^r) as well as the public goods environment (a^r) are given and enter the production functions of the firms (i) in the regions (r) in a parametric form. The only factor of production that can be changed at the firms' discretion is the level of employment of labor located in any one of the regions (L_{ji}^{sr}). Furthermore, it is assumed that the employment of labor is politically constrained for each region to be at a certain "full employment" level. The assumption that similar employment goals exist at the occupational level, as determined by national labor unions or politicians, is also made. Finally, it is assumed that the institutional framework, consumption infrastructure, and so on, puts constraints on mobility between regions.

Optimal mobility of labor for society

(1) Maximize$Q$
$$= \sum_{ri} p_i^r Q_i^r (L_{1i}^{ir}, \dots, L_{1i}^{kr}, \dots, L_{mi}^{kr}; \bar{K}_i^r, \bar{a}^r);$$

subject to

(2) $\sum_{jsi} L_{ji}^{sr} = L^r;$

Employment goal for region $r = 1, \dots, k$

(3) $\sum_{ji} L_{ji}^{sr} \leq L^{sr};$

Mobility constraint for link sr

(4) $\sum_{srl} L_{ji}^{sr} = L_j;$

Employment goal for occupational category $j = 1, \dots, m$

$$L_{ji}^{sr} \geqq 0$$

where

p_i^r = net price of commodity (firm) i produced in region r;

Q_i^r = production of commodity i in region r;

L_{ji}^{sr} = move of labor of category j located in regions s to work with commodity i in region r

$\bar{K}_i^r$ = predetermined amount of capital in firm i in region r;

$\bar{a}^r$ = accessibility to public goods from region r.

Social optimality conditions

(5) $$\frac{\partial \Lambda}{\partial L_{ji}^{sr}} = p_i^r \frac{\partial Q_i^r}{\partial L_{ji}} - \omega^r - \omega_j - \beta^{sr} \leqq 0;$$

$(s, r = 1, \dots, k),$
$(j = 1, \dots, m)$
$(i = 1, \dots, n)$

(6) $$\frac{\partial \Lambda}{\partial \omega^r} = \sum_{s,j,i} L_{ji}^{sr} - L^r = 0;$$

$(r = 1, \cdots, k),$

(7) $$\frac{\partial \Lambda}{\partial \omega_j} = \sum_{s,r,i} L_{ji}^{sr} - L_j = 0;$$

$(j = 1, \cdots, m),$

(8) $$\frac{\partial \Lambda}{\partial \beta^{sr}} = \sum_{j,i} L_{ji}^{sr} - C^{sr} \leqq 0$$

$(s, r = 1, \cdots, k),$

(9) $$L_{ji}^{sr} \geqq 0$$

As a contrast, firms are assumed to allocate their labor use so as to maximize the profits.

Optimal mobility of labor for firms

(10) $$\underset{\{L\}}{\text{Maximize}}\ \pi_i^r = P_i^r Q_i^r (L_{1i}^{1r}, \cdots, L_{1i}^{kr}, \cdots, L_{mi}^{kr}, \bar{K}^r, \bar{a}^r) - {}_j\sum_s (\bar{w}_j + c_{ji}^{sr}) L_{ji}^{sr}.$$

Firm optimality conditions

(11) $$\frac{\partial \pi_i^r}{\partial L_{ji}^{sr}} = p_i^r \frac{\partial Q_i^r}{\partial L_{ji}} - (\bar{w}_j + c_{ji}^{sr}) = 0; \quad (s, r = 1, \ldots, k) \quad (j = 1, \ldots, m)$$

Coincidence of firm and social optimality conditions if:

(12) $$\underbrace{\omega^r + \omega_j + \beta^{sr}}_{\text{socially optimal information}} = \underbrace{\bar{w}_j + C_{ji}^{sr}}_{\text{firm information}}.$$

The social optimality conditions are straightforward. Employment should be adjusted to each region in such a way that the marginal value product can compensate for the shadow price of occupational full employment plus the shadow price of regional full employment plus a possible shadow cost of mobility between the regions of a certain occupational category.

The optimization of the firms is assumed to be a question of maximizing short-term profits in a situation where the wage rate is *uniform* for all regions within a given occupation. This description corresponds fairly well to the institutional situation in Scandinavia. To this wage rate should be added the cost of moving people (in commuting or migration) from the region of origin to the region of use.

Private and social optimality conditions can only coincide in a situation such as the one described. The demand for labor can easily be larger or smaller than the socially optimal use of it. It is then necessary for the private price information to be modified by a regionally differentiated subsidy on employment (or tax if negative). Such a scheme has been successfully implemented in Sweden during the last decade.

REGIONAL PRODUCTIVITY AND ACCESSIBILITY DIFFERENCES

The concept of accessibility

In the production functions used above a mysterious parameter a^r is introduced. We have called this parameter "accessibility." It is closely connected to the concept of public goods. A study by J. Weibull (1976) has narrowed down the meaning of this concept in the following way. It is assumed that each point or region can be described by d, the distance from a point of reference and g, the attractiveness of the point or zone. An ordered (d, g) is called an opportunity $d \in R_+$, $g \in R_+$ A configuration $\bar{c}$ is defined as a n-tuple of opportunities.

(13) $$\bar{c} = \langle (d_1, g_1); (d_2, g_2); \ldots; (d_n, g_n) \rangle = \langle (d_i, g_1) \rangle_{i=1}^{n},$$

where n is a finite and positive integer, $n \in N = \{1, 2, \ldots.\}$. Let C denote the sum of such configurations.

Axiom 1. For any configuration

$$\bar{c} = \langle (d_i, g_i) \rangle_{i=1}^{n} \text{ and } i, j \in N_n = \{1, 2, \ldots, n\}:$$

$$f[\langle (d_1, g_1); \ldots; (d_i, g_i); \ldots; (d_j, g_j); \ldots; (d_n, g_n) \rangle] = f[\langle (d_1, g_1); \ldots; (d_j, g_j); \ldots; (d_i, g_i); \ldots; (d_n, g_n) \rangle].$$

Axiom 2.

(a) $$d_i \leqq d_i', \forall i \in N_n \Rightarrow f[\langle (d_i, g_i) \rangle_{i=1}^{n}] \geqq f[\langle (d_i', g_i) \rangle_{i=1}^{n}],$$

for any attractions $g_1, \ldots, g_n$ and $n \in N$.

(b) $$g_i \leqq g_i', \forall i \in N_n \Rightarrow f[\langle (d_i, g_i) \rangle_{i=1}^{n}] \leqq f[\langle (d_i, g_i') \rangle_{i=1}^{n}],$$

for any distances $d_1, \ldots, d_n$ and $n \in N$.

Axiom 3. (a) f_0 is continuous, (b) f_0 is increasing.

Axiom 4.

$$f[\langle (d_1, g_1); (d_2, g_2) \rangle] < \lim_{g \to +\infty} f[\langle (0, g) \rangle],$$

for every pair of opportunities (d_1, g_1) and (d_2, g_2).

Axiom 5.

(a) $$f[\langle (d, 0)\rangle \cup \bar{c}] = f[\bar{c}],$$

for any distance d and configuration $\bar{c}$;

(b) $$f[\langle (d, 0)\rangle] = 0,$$

for any distance d.

Axiom 6.

$$f[\bar{c}'] = f[\bar{c}''] \Rightarrow f[\bar{c}' \cup \bar{c}] = f[\bar{c}'' \cup \bar{c}],$$

for every configuration $\bar{c}$.

An *AM* satisfying all of the six axioms in this section will be called a standard *AM* relative to the chosen distance and attraction characteristics.

One structural equation consistent with these axioms is the following spatial discounting index:

$$a^r = \textstyle\sum_s f(d_{rs})G_s, \tag{14}$$

where

a_r = accessibility to the public good (assumed to be of one kind only) in region r,

$f(d_{rs})$ = a monotonously nonincreasing function of distance (somehow measured from region r to region s),

G_s = amount of the public good in region s.

$f(d_{rs})$ is often given the specification $\exp\beta d_{rs}$ where $\beta < 0$. With $\beta = 0$ the public good is pure in the sense that no one is excluded from using it, however distantly located the user may be. $\beta < 0$ means that only the subjects located at zero distance will receive the full effect of it.

Empirical measurements of accessibility to public goods

The economic importance of accessibility or other spatial measures of the availability of public goods has been empirically assessed in a number of studies. The simplest approach is to assume that only local availability of public goods is of importance (which corresponds to a large negative value of β). One can further assume that the supply of public goods is positively related to the total population of the region.

Kawashima (1975) has tested such an assumption on American manufacturing statistics (two- and three-digit SIC breakdown). He assumed that value added per employee (V/L) is linearly related to capital per employee (K/L) and nonlinearly related to the total population of the SMSA (B):

$$V/L = ar(K/L) + b_1B + b_2B^2 + b_0. \tag{15}$$

He generally found that $b_1 > 0$, $b_2 < 0$ and that the manufacturing sectors could be ranked according to their productivity maximizing population size:

1. Stone, clay, and glass,
2. Food and kindred,
3. Apparel and related products,
4. Lumber and wood products,
5. Furniture and fixtures,
6. Electrical machinery,
7. Leather and leather products,
8. Machinery,
9. Fabricated metal products,
10. Paper and allied products,
11. Primary metal products,
12. Chemicals and allied products,
13. Rubber and plastic products.

With a similar approach and more disaggregated data (Åberg, 1973) obtained the following results for the Swedish economy using the following equation:

$$V/L = (rK/L)^{\alpha}\,(\text{Plantsize})^{\gamma}\,(\text{Regionsize})^{\phi}. \tag{16}$$

Also in this case a very simple measure of accessibility to public goods has been used. However, in the Åberg study the influence of the scale of individual plants is included, so that there is little risk of confusing internal scale economies with public good effects. The statistical results turn out to be extremely stable over time; this indicates that the external factors do not change in the short run (see Table 3).

It is obvious that the measurements of Kawashima and Åberg are valuable but of limited interest from the explanatory point of view. Both use a highly indirect and restrictive measure of public good accessibility, like many others who have studied the problem of regional productivity differences.

A more ambitious approach has been tried by Wigren (1978), who used disaggregated manufacturing data to establish the impact of public good accessibility on the productivity of plants in Swedish regions. The study showed that three public factors are of great importance for the productivity of manufacturing plants. These are:

1. an index of accessibility to Swedish market regions, export markets, consultants, and white collar employees;

2. an index of total size of local labor market and size of expenditure on city planning and local transportation equipment;

3. an index of industrialization of the region.

The impact of these features on productivity varies from industry to industry and seems to be stable over the same time spans as those that have been observed in other studies.

All of these studies show that public goods phenomena are of great importance for the productivity of private industry. Public goods supply and their effects are to a large extent determined by long-term public sector spending, taxation, and communication/transportation policies. As a consequence the next section is devoted to an analysis of taxation, public expenditure, and communication network policies in the context of regional growth.

A MODEL OF PUBLIC GOODS AND REGIONAL ECONOMIC GROWTH

We have shown that accessibility to public goods has a measureable relation to the productive efficiency of the manufacturing industry. The influence of accessibility to public goods differs from industry to industry but is almost never statistically negligible. The accessibility of most public goods influences industrial productivity through the accumulated stocks available. This is especially true of research and other forms of knowledge accumulation.

The growth of productivity is thus related to the growth of the stock of public goods. This section is devoted to an analysis of the interactions between the public goods sector and the private goods sector of a regional economic system. Each region is assumed to have one private sector of production, producing a malleable commodity, according to a neoclassical production function.

Four factors of production are assumed to be used in production, capital (the malleable private commodity), labor, human capital, and the public good, measured by accessibility to the stocks available in all regions.

$$Q_i = Q_i(K_i, L_i, H_i, a_i), \tag{17}$$

where

Q_i = the rate of production of the malleable commodity in region i;

TABLE 3

THE ELASTICITY OF PRODUCTIVITY WITH REGARD TO CAPITAL INTENSITY, SIZE OF ENTERPRISE, AND SIZE OF REGION OVER THE PERIOD 1965–1968 IN SELECTED MANUFACTURING INDUSTRIES IN SWEDEN.

Group of industry	Number of observations	α (S_α)	γ (S_γ)	ϕ (S_ϕ)	R^2
Engineering industry	826	0.328 (0.006)	0.036 (0.005)	0.020 (0.003)	0.832
Wood, pulp, and paper industry	784	0.354 (0.006)	0.055 (0.005)	0.018 (0.004)	0.856
Foodstuffs and drinks industry	748	0.473 (0.007)	0.017 (0.007)	0.009 (0.005)	0.876
Textile, leather, and rubber goods industry	644	0.352 (0.008)	0.016 (0.008)	0.039 (0.006)	0.766
Repair workshops	771	0.247 (0.006)	0.033 (0.007)	0.014 (0.004)	0.733

α = elasticity with regard to capital intensity;
γ = elasticity with regard to size of enterprise;
ϕ = elasticity with regard to population density;
S = standard deviation for the appropriate elasticity;
R = multiple correlation coefficient.

K_i = the stock of capital available for private production in region i;

L_i = the amount of labor available for private production in region i;

H_i = the amount of human capital available for private production in region i;

a_i = level of accessibility in region i and is defined as:

$$a_i = \sum_j e^{\beta d_{ij}} G_j,$$

where

G_j = stock of public goods available in region j;

d_{ij} = distance from region i to region j;

β is a parameter of distance friction assumed to be less than zero.

There is no interregional trade. All economic interaction is through the public good accessibility. Private capital accumulation is determined by a standard Keynesian equation:

$$\dot{K}_i = s_i(1 - t_i)Q_i(K_i, L_i, H_i, a_i), \tag{18}$$

where

s_i = propensity to save in region i,

t_i = rate of taxation in region i.

Expansion of the labor supply can be assumed to depend on consumption per capita (Schultz, 1976) and the total size of the labor force:

$$\dot{L}_i = F_i[(1 - s_i)(1 - t_i)\, Q_i/L_i, L_i]; \tag{19}$$

Assumptions: $\partial F_i/\partial(Q_i/L_i) > 0$;

$$\partial F_i/\partial L_i > 0.$$

In other studies, investment in human capital has been shown to depend on income per capita and the amount of human capital per capita (see Michael, 1972; and Anderson, 1977):

$$\dot{H}_i = H_i[(1 - s_i) \cdot (1 - t_i)\, Q_i/L_i, H_i/L_i]; \tag{20}$$

Assumptions: $\partial H_i/\partial(Q_i/L_i) > 0$;

$$\partial H_i/\partial(H_i/L_i) > 0.$$

The expansion of public goods can be determined by a more or less realistic public sector production function. To keep matters simple it is assumed that the public sector has a fixed labor force, which transforms the taxed amount of private goods, t_i, Q_i, into additions to the stock of public goods with efficiency g_i:

$$\dot{G}_i = g_i t_i Q_i(k_i, L_i, H_i, a_i). \tag{21}$$

The Eqs. (17) to (21) together give a regional growth system with public goods.

$$\left.\begin{cases} \dot{K}_i = s_i(1 - t_i)\, Q_i(K_i, L_i, H_i, \sum_j e^{\beta d_{ij}} G_j) \\ \dot{L}_i = F_i[(1 - s_i)(1 - t_i)Q_i(K_i, L_i, H_i, \sum_j e^{\beta d_{ij}} G_j)/L_i, L_i] \\ \dot{H}_i = H_i[(1 - s_i)(1 - t_i)Q_i(K_i, L_i, H_i, \sum_j e^{\beta d_{ij}} G_j)/L_i, H_i/L_i] \\ \dot{G}_i = g_i t_i Q_i(K_i, L_i, H_i, \sum_j e^{\beta d_{ij}} G_j) \end{cases}\right\} \quad (i = 1, \cdots, n) \tag{22}$$

More compactly, this is a dynamic system that can be written in matrix notation as $\dot{x} = M(x)$, where

$$\dot{x} = (\dot{K}_1, \dot{L}_1, \dot{H}_1, \dot{G}_1, \cdots, \dot{K}_i, \dot{L}_i, \dot{H}_i, \dot{G}_i, \cdots, \dot{K}_n, \dot{L}_n, \dot{H}_n, \dot{G}_n),$$

$$x = (K_1, L_1, H_1, G_1, \cdots, K_i, L_i, H_i, G_i, \cdots, K_n, L_n, H_n, G_n),$$

$M(x)$ is a semipositive mapping from x to $\dot{x}$.

For such a system a theorem by Nikaido can be applied.

Theorem (see Nikaido, 1968): Assume the following conditions to hold:

(a) $M(x) = (M_i(x))$ is defined for all non-negative x in R^n_+, with its values being also non-negative vectors in R^n_+, $M(x) \geq 0$.

(b) $M(x)$ is continuous as a mapping M: $R^n_+ \to R^n_+$, except possibly at $x = 0$.

(c) $M(x)$ is positively homogenous of order m, $1 \geq m \geq 0$ in the sense that $M(\alpha x)$ for $\alpha \geq 0$, $x \geq 0$.

Let $\Lambda = \{\lambda M(x) = \lambda x \text{ for some } x \in P_n\}$, where

$$P_n = \{x \mid x \geq 0, \ \textstyle\sum_{i=1}^n x_i = 1\} \text{ is the standard simplex.}$$

Then Λ contains a maximum which is denoted $\lambda(M)$. Furthermore, if $m = 1$, $\lambda(M)$

is the greatest among all the eigenvalues of M. It is consequently clear that there exists an economically meaningful equilibrium growth maximizing solution to this problem. It is also clear that we can analyze the qualitative properties of this system by linearizing it in the vicinity of its equilibrium solution. This gives us the system:

$$\lambda z = M(x^*)z, \tag{23}$$

in which $M(x^*)$ is a matrix of parameters and λ is a local growth rate, the eigenvalue. M is a sparse, quadratic, non-negative, in-decomposable matrix which admits the application of the Frobenius–Perron theorem.

Theorem (F–P): Let M be a non-negative square in-decomposable matrix. Then:

(1) M has one characteristic value $\lambda^* > 0$;

(2) if x is a characteristic vector corresponding to λ^*, we have $x^* > 0$;

(3) for any other characteristic value λ of M we have $\lambda^* \geq |\lambda|$;

(4) the value of λ increases with the increase of any element of M.

F–P shows that an increase in at least one of the parameters of M will increase the growth rate of the economy. Such an increase can be achieved in many ways, for instance:

(a) An increase in a productivity parameter, i.e., g_i,

(b) A decrease in any one of the communication distances (d_{ij}),

(c) A decrease in the distance friction (increase in β).

It should be observed that such changes will *in the long run* influence the growth rates of all regions to the same extent. Nothing in general can be said about the effect of changing the rates of taxation and saving, because these parameters enter the different equations with different signs. It has also been shown (Andersson, 1979) that a linear system z is stable in the relative sense, provided that all coefficients are positive. Relative stability is a stability of a rather peculiar kind. It means that each component of a simulated corresponding system y will converge to a fixed *ratio* to the corresponding eigenvector component of z. Each such ratio will be positive. This observation indicates that there is some hope that the nonlinear model can be simulated with results of interest also in the long time perspective, relevant for analysis of accessibility to public goods (such as knowledge, public infrastructure, etc.). Because of the nonlinearity of the original system it is more revealing to analyze the original system with numerical methods.

SIMULATION EXPERIMENTS WITH A COMPUTATIONAL MODEL

In order to simulate the model discussed above, which is represented by Eqs. (17) and (21), it has been made explicit as follows. The CES production function was specified as

$$Q_i = A(\alpha_1 K_i^{-\rho} + \alpha_2 L_{1i}^{-\rho} + \alpha_3 H_i^{-\rho} + \alpha_4 G_i^{-\rho})^{-1/\rho}, \quad i = 1, \cdots, 3, \tag{24}$$

where

$$a_i = \textstyle\sum_j e^{-\beta d_{ij}} G_j, \tag{25}$$

and the time derivatives of its input variables as

$$\dot{K}_i = s_i(1 - t_i)Q_i, \quad i = 1, \cdots, 3, \tag{26}$$

$$\dot{L}_i = c_1[(1 - s_i)(1 - t_i)Q_i/L_i]\lambda\, L_i^{\gamma_i}, \quad i = 1, \cdots, 3, \tag{27}$$

$$\dot{H}_i = c_2[(1 - s_i)(1 - t_i)Q_i/L_i]^{\delta}[H_i/L_i]^{\epsilon} \tag{28}$$

$$\dot{G}_i = tgQ_i, \quad i = 1, \cdots, 3, \tag{29}$$

The notation used for Eqs. (24) to (29) can be applied here:

$$h_1 L_i = L_{1i}, \qquad (1 - h_1)L_i = L_{2i}, \quad i = 1, \cdots, 3, \tag{30}$$

$$h_2 H_i = H_{1i}, \qquad (1 - h_2)H_i = H_{2i}, \quad i = 1, \cdots, 3, \tag{31}$$

The index i refers to region. No sectorial division is used at this stage with the exception of the division of labor force and human capital into two parts. They may be called productive and nonproductive parts in the material sense of production. The

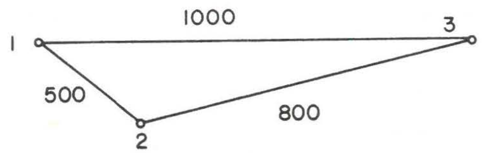

FIG. 1. Basic transportation network (the lines joining points in regions 1, 2, and 3 represent distance).

first part is included in the production function and the second is excluded from it. As a starting point we used the following regional structure of distance and initial endowments (see Fig. 1 and Table 4).

Several parameters of the systems were assumed to be the same for all regions. Their values are given in Table 5.

The computational model defined by Eqs. (24) to (31) was programmed in FORTRAN IV and run on the IIASA computer. The program was made interactive to facilitate simulation experiments and it soon proved to be the only reasonable way of operating the model. Time was not included as an explicit index variable, neither was any numerical integration used to obtain a precise evaluation of the derivatives. The reason for this was that the model was designed to be solved iteratively in order to find out steady state values of the variables. The theorems presented above made it probable that, if the program were correctly written, the system would converge to a vicinity of a stable solution. In general, this proved to be the case after 50 iterations.

Results of the simulation experiments

Four kinds of experiments were made with the model. First, the value of ρ was varied; second, the distance matrix was changed to reduce the central–periphery contrast; third, economies of scale were included in the production function; and, finally, the value of β was changed to zero.

TABLE 5
VALUES OF PARAMETERS THAT ARE ASSUMED TO BE UNIFORM FOR ALL REGIONS.

Parameter	Symbol	Value
Savings rate	s	0.30
Labor distribution parameter	h_1	0.70
Human capital distribution parameter	h_2	0.70
Coefficient of labor equation	c_1	50.0
Coefficient of human capital equation	c_2	10.0
Exponent of labor	γ	0.20
Exponent of the bracket terms in the labor equation	λ	0.20
	ϵ	1.00

The results are presented in Table 6. The tax rate has been used as a national control variable that affects the regional production efficiency. This effect works two ways, it reduces the accumulation capacity of the firms, and, at the same time, it increases the availability of public goods. The tax rate was varied with an appropriate step length to approximate the response surface of the system involved. This step length was one percent and the maximum was thus precisely located in all the results reported in the table.

Some conclusions can be drawn from the search for an optimal tax rate:

1. The optimal tax rate varies with the region. There is a general tendency to larger gains from taxation for the periphery region.

2. The optimal tax rate is lower when consumption per capita is used as an objective instead of production per capita.

3. The optimal rate of taxation increases with the elasticity of substitution in production.

Other conclusions are in accordance with theoretical a priori expectations. Thus, the average rate of growth depends strongly on the value of ρ or its counterpart, elasticity of substitution (defined as $\sigma = 1/1 + \rho$). Great substitution possibilities should imply a high growth rate and vice versa and this is shown in Fig. 2.

TABLE 4
INITIAL VALUES OF VARIABLES.

Description	Region Number			
	1	2	3	Σ
Type of region	Intermediate	Central	Periphery	
Initial labor force (L)	200	100	100	400
Initial capital stock (K)	1000	300	300	1600
Initial human capital (H)	50	50	50	150
Initial amount of public good (G)	100	100	100	300

TABLE 6

SIMULATION RESULTS AFTER 50 ITERATIONS IN THE SEARCH FOR AN "OPTIMAL" TAX RATE (OPTIMAL MEANS OF PRODUCTION MAXIMIZATION AT TIME PERIOD 50).

Purpose	Parameter	Optimal tax rate	Allocation of production to regions		
			1	2	3
Study of high elasticity of substitution	$\rho = -0.5$	0.51	0.52	0.35	0.13
Study of slight complementarity (basic test)	$\rho = 0.5$	0.25	0.29	0.40	0.31
Study of large degree of complementarity	$\rho = 2.0$	0.13	0.24	0.39	0.37
Zero labor response from population	$\rho = 0.5$ $\gamma = 0$	0.19	0.24	0.45	0.31
Decreased distances for the periphery region	$\rho = 0.5$ $d_{13} =$ 100 instead of 1000 $d_{33} =$ 0 instead of 50	0.17	0.28	0.36	0.36

The case of $\rho = -1$ when the CES production function becomes a linear combination of inputs was not simulated. This was because the results for that and other cases seemed to be very similar to the earlier ones (Andersson, January 1979).

The regional distribution of production is most skewed towards the intermediate region in the case of high substitutability ($\rho = -0.5$), which also implies a high growth rate. In other experiments the distributions are skewed towards the central region and, in general, the modes of the distributons lie in the central region. The importance of this kind of spatial position is emphasized even more by the fact that in all cases the highest growth rate is realized in the intermediate region. In regional policy making

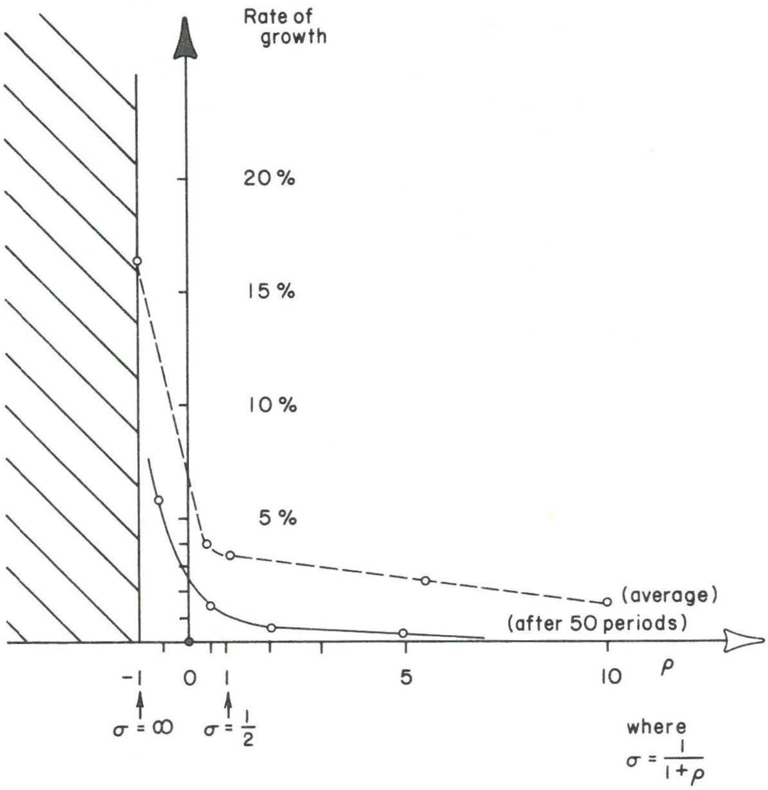

FIG. 2. Substitution possibilities. (The curve is taken from Andersson, 1979.)

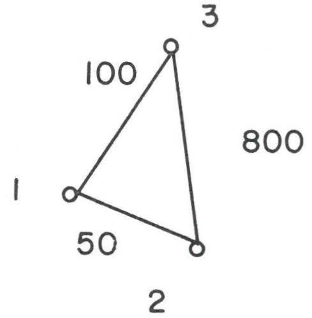

FIG. 3. New transportation network (the lines joining points in regions 1, 2, and 3 represent distance).

a choice has to be made about whether regional support should be assigned to the intermediate region or to the most remote and usually poorest region.

The distance matrix was changed to demonstrate the effect of reducing spatial friction by means of selective development of the transportation and communication networks. The new structure is given in Fig. 3.

The distance between the central and periphery region was decreased from 1000 to 100. At the same time, the internal radius dimension of the periphery region was reduced from 50 to 0. This led to an overall increase in production in regions 1 and 3. The periphery region increased its share, whereas the central region lost in both absolute and relative terms. The optimal tax rate dropped from 25% to 19%.

The stability properties of this model conjectured from the above theorems for linearized systems proved to be true. When constant returns to scale in production were assumed, the system steadily converged to a situation of constant proportions without fluctuations, except during the first three iterations.

ECONOMIES OF SCALE AND LONG-TERM ECONOMIC DEVELOPMENT

An assumption of economies of scale can easily be introduced in the CES production function by raising the exponent of the whole bracket to a power larger than 1. In one simulation experiment this was done by raising it by 1.5. This experiment is extremely interesting. It shows among other things that a regional system of the kind modeled by us is relatively stable, even with increasing returns to scale.

The optimal tax rate is increased to 0.51 with this assumption and the regional allocation greatly disfavored the periphery region. The growth rate is on the average much higher than in any other test, but after 50 simulation periods there is a clear tendency of convergence towards a common growth rate.

The dynamic pattern of growth is quite different from the cases with constant re-

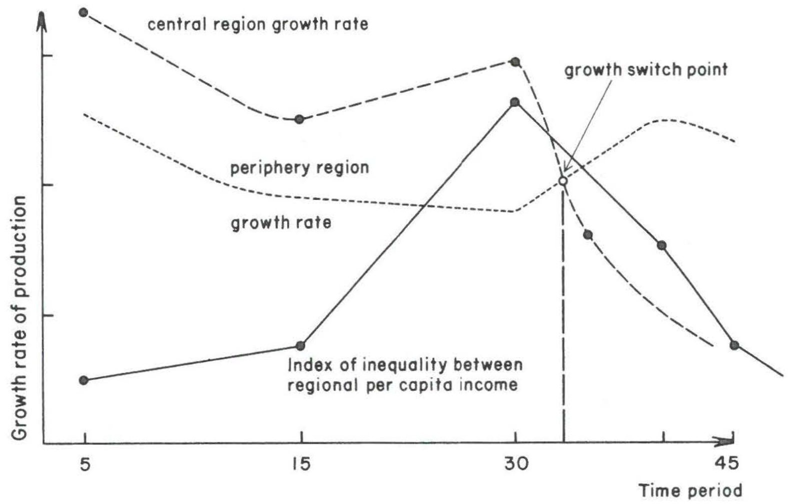

FIG. 4. Growth pattern of regions with economies of scale.

turns to scale in production. Fig. 4 gives the simulated growth rates at different points of time for the center and the periphery. It also shows that the spatial dimension gives rise to delays in the growth path, although no temporal lags are assumed in the model. These delays have important implications for equality between regions. The well-known Williamson-effect, according to which regional inequality increases in earlier stages of economic development and decreases at later stages (Williamson, 1965), is consistent with the results of the simulation.

CONCLUSIONS

The approach to regional economics used in this paper differs from the usual one, because we have been concentrating on information flows instead of material flows. However, some of the results may well hold for the more general case, including flows of intersectorial information, as well as interregional trade flows. The main conclusions to be drawn from our analysis and simulation experiments can be listed as follows:

1. In the short term one must consider the supply of public goods as essentially given and nonmobile. This means that public goods will enter the model as environmental accessibility factors in the production functions of private firms.

Empirical studies have shown that public goods, as measured by accessibility indices, have an important impact on productivity. Thus, there must by necessity be regional differences in the labor productivity of private firms. In the short run and in situations of equal pay for similar types of occupation in different regions, there is a need for regionally differentiated employment taxes or subsidies.

2. The optimum way of controlling national and regional economies depends greatly on the structure of the real system in terms of model parameter values.

3. Public goods are important prerequisites for increasing productivity and growth in the private sector and in the whole economy, both at the national and regional level.

4. It is possible to control the regional economies by using national public policies, such as taxation. Furthermore, there exists a positive nonconfiscatory tax rate that maximizes long-term regional production. Tax rate controls can probably always be made more effective by using different tax rates in different regions.

5. Accessibility is a means of introducing public goods into regional growth analysis. It has been shown that:

a. a reduction of communication distance between any two regions will increase the rate of equilibrium growth;

b. a reduction of communication distance leads to changes in the relative regional shares of total production.

6. There is a trade-off between communication/transportation network policies and taxation policies. If, for example, regional policy is directed to the reduction of communication distances, the national tax rate can possibly be lowered and vice versa. Thus, national and regional control strategies should be considered and decided together. In this way inconsistent and mutually conflicting combinations of control strategies can be avoided.

7. The simultaneous considerations of public goods phenomena and economies of scale in private production can easily lead to lagged responses in a spatial model. This, in turn, can give rise to a Williamson phenomenon, with regional inequalities following an inverted U-curve over time. Such regional inequality development has been observed in most development processes.

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FOOD AND ENERGY CHOICES FOR INDIA: A PROGRAMMING MODEL WITH PARTIAL ENDOGENOUS ENERGY REQUIREMENTS[1]

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This paper presents a mathematical model for all matter-energy processing subsystems at the level of the society, specifically India. It explores India's choices in the food and energy sectors over the coming decades. Alternative land intensive, irrigation energy intensive, and fertilizer intensive techniques of food production are identified using a nonlinear programming model. The land saved is devoted to growing firewood. The optimum combination of railway (steam, diesel, and electric traction) and road (automobiles, diesel trucks, and diesel and gasoline buses) transport is determined. For the oil sector, two alternative sources of supply of crude oil and petroleum products are included, namely, domestic production and imports.

The optimum choice is determined through a linear programming model. While the model is basically a static one, designed to determine the optimal choice for the target year of 2000-2001, certain intertemporal detail is incorporated for electricity generation. The model minimizes the costs of meeting the needs for food, transport in terms of passenger kilometers and goods per ton per kilometer, energy needs for domestic cooking and lighting, and the energy needs of the rest of the economy.

KEY WORDS: society, matter-energy processing, food, energy, choice, programming model, India.

THE ENERGY problems of a large, densely populated country with a low per capita income such as India are different from those of the rich countries. The latter have been analyzed both in theory and empirically by a number of researchers in the last few years. In this paper we take a look at the choices available to India over the next three decades in the energy and agricultural sectors.

India's energy consumption per capita is very low, being of the order of 700 kg of coal replacement, while that of the USA is over 11,000 kg. The per capita consumption in Western Europe is in the range of 3000 to 6000 kg. Nearly 50% of the energy consumed in India is obtained from noncommercial sources such as firewood, agricultural wastes, and animal dung, whereas in high income countries this proportion is negligible. The pattern of end use of energy in India is also quite different from that of advanced countries. Nearly 90% of the energy required for household cooking is supplied by noncommercial sources in India. Petroleum products account for a little over 70% of the energy needs of the transport sector in India, while in advanced countries this proportion exceeds 90%. Another feature of the Indian energy scene is the use in agriculture—mainly for irrigation and partly in terms of chemical fertilizers—of significant amounts of electricity and oil, amounting to nearly 10% of the total electricity use and 5% of oil. Altogether the transport, agriculture, and domestic sectors of the Indian economy account for more than 55% of commercial energy consumption and almost all of noncommercial energy consumption. In this paper we explore the alternatives available to these sectors only.

Briefly stated, the choices in agriculture arise from the following substitution and complementary possibilities: Given the sown area, output can be increased only by increasing yield per unit area. In increasing the yield per unit area, however, alternative

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combinations of irrigation and fertilizers can be applied. While some modes of lift irrigation such as tubewells are users of energy, other modes such as irrigation from major storage reservoirs often provide energy in the form of hydroelectric energy. Availability of irrigation, to the extent it makes it possible to grow more than one crop during a year, in effect, also increases the availability of land. In the production of fertilizers there are energy choices in terms of feedstock: coal, fuel oil, naphtha, or hydrogen obtained from water through electrolysis. Further, in a country as large as India, where the potential for producing agriculture products varies from region to region, there is a choice between the strategy of concentrating production in a few regions and transporting final products to others, and the strategy of regional self-sufficiency. While the latter strategy may save energy used in transportation, it is conceivable that it may require more total energy in terms of irrigation needs and fertilizer use (and its transportation, in case its production is concentrated because of considerations of economics of scale).

Though the agricultural sector covers all crops grown in India, over 75% of the cropped area is devoted to the cultivation of foodgrains, with rice and wheat accounting for more than 30%. The irrigated area, accounting for less than 30% of the total cropped area, is even more concentrated on foodgrains, with nearly 80% of the irrigated area devoted to foodgrains, and rice and wheat accounting for over 60%. For these reasons and for the more important reason that data on yield response to fertilizer use are more extensively documented for rice and wheat, in this paper we confine ourselves to choices in respect of these crops. We have also not explored the choice between extensive and intensive cultivation mentioned above.

In the production of nitrogenous fertilizers the following feedstocks are considered: naphtha, fuel oil, and coal. Also nitrogen available from dung processed through biogas plants is taken into account.

We have included two alternative sources of supply of crude oil and petroleum products, namely domestic production and imports. Process choices in the production of petroleum products are introduced by means of alternative refinery processing activities. These include a number of secondary processing activities such as vacuum distillation, visbreaking, hydrocracking, catalytic cracking, and coking. In deriving these we have extensively drawn on the work of Bhatia (1974).

In the transport sector the optimum combination of railway (steam, diesel, and electric traction) and road (automobiles, diesel trucks, and diesel and petrol buses) transport is to be determined with respect to goods transport as well as regional and urban passenger transport. In the case of goods transport, we distinguish between different density classes, density being defined as the number of net ton kilometers (ntkm) carried per km of route length per day. This distinction enables us to examine the relative economics of different tractions such as steam, diesel, and electric, and the number of tracks on a route.

In the generation of electricity the alternatives considered are conventional coal-based thermal plants, CANDU-type nuclear reactors, fast breeder reactors (FBRs), and high temperature reactors (HTRs).

The cooking energy needs of rural and urban households are considered separately, the alternatives available being firewood, softcoke, biogas, kerosene, and liquified petroleum gas (LPG). With respect to lighting energy, the choice is between kerosene and electricity.

The optimal choice is determined through a linear programming model. While the model is basically a static one, designed to determine the optimal choice for the target year 2000–2001, certain intertemporal detail is incorporated with respect to electricity generation.

In order to clarify the solution procedure and to indicate how the various sectoral models may be interconnected to maintain consistency, a schematic block diagram is given in Fig. 1. Rectangular boxes indicate models, and round blocks show the interfaces or information that is passed on from one box to another. However, we have not implemented all the steps shown in the figure. The static multisectoral input-output model was not implemented, and the final demands for the output of energy-

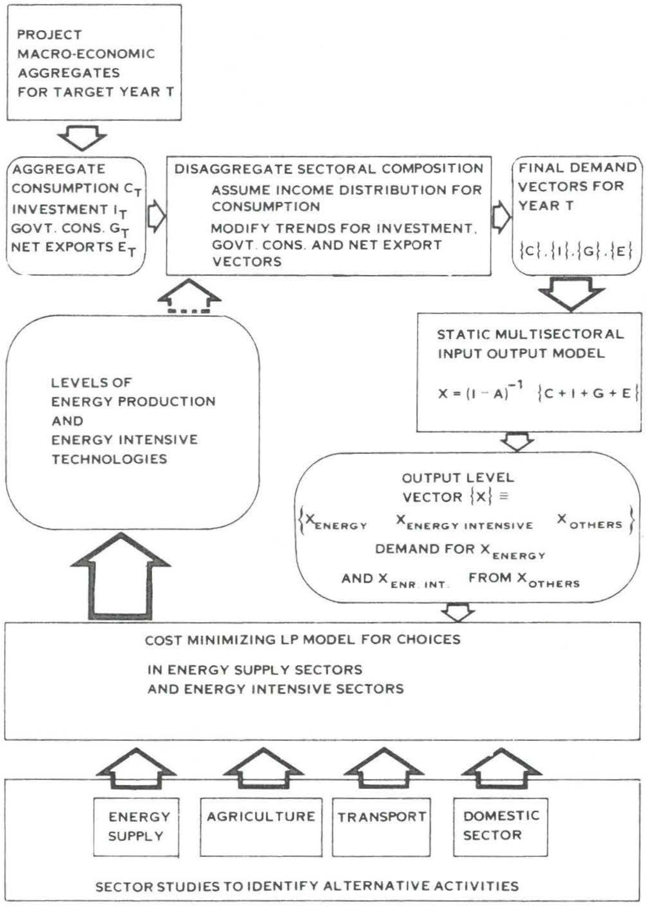

FIG. 1. Solution procedure.

intensive sectors and the demand for energy from sectors other than those studied in detail were projected from other studies.

THE MODEL

For the target year 2000–2001, the alternatives in food production, fertilizer production, modes of transport, domestic energy for cooking and lighting, refining techniques, and electricity generation are explored in an activity analysis model. The alternative activities for each of these sectors are described in greater detail in subsequent sections. Though these choices are posed for the target year, the choices for electricity supply techniques cannot be satisfactorily examined for only one period. The extent of availability of FBR or HTR technologies depends on the availability of plutonium, which has to be produced in first-generation nuclear power plants. In order to explore these choices, the problem of electricity supply has to be posed in an intertemporal model of plutonium accumulation. Such intertemporal considerations are introduced in the model only for the supply of electricity, confining other alternatives only for the target year.

The total demand for electricity for the target year consists of two parts—that which is oxogenously prescribed, and that which is endogenously determined. For the earlier periods the demand corresponding to the endogenous portion is assumed to grow exponentially over the planning period. To achieve this, we assume a value for the target year endogenous demand, prescribe the demand for an earlier year on that basis, and solve the problem. If the resulting solution value in the first iteration for the target year endogenous demand differs from its assumed value, then a new assumed value equal to the solution value of the first iteration is prescribed for the second iteration. This iterative process is continued until convergence is achieved.

The linear programming model is described below. The equations of the model are given in Appendix 1. Separate constraints are written for each time period only for the electricity sector. For all the other sectors constraints are written only for the temporal period T. Consequently, the costs of capital investment are annualized for all activities except for the electricity generation activities for which capital and operating costs are kept distinct. A credit is taken for the stock of power plants surviving at the end of the planning period. This is done on the basis of the discounted value of the operating cost advantage over the remaining life offered by that plant compared to the plant with the highest operating cost (coal-based plants).

The objective function is to

(1) Minimize the discounted:

(a) costs of the capacity and energy of CANDU, FBR, HTR, and coal-based power plants installed in periods $1, 2, \ldots, T$;

less (b) the credit for terminal capital stocks and the post-terminal operating cost advantage of CANDU, FBR, and HTR plants over the coal plants;

less (c) the credit for surplus plutonium;

plus (d) the cost in period T of agriculture excluding the cost of irrigation energy and nitrogenous fertilizers;

plus (e) nonfuel costs in period T of passenger transport by electric, diesel and steam trains, and buses run on diesel and motor gasoline (mogas);

plus (f) nonfuel costs in period T of goods transport by electric, diesel and steam trains, and diesel trucks;

plus (g) cost in period T of coal;

plus (h) costs in period T of the domestic and imported crude oil, of imported kerosene, diesel, light diesel oil (LDO), mogas, naphtha, fuel oil and other oil products, and of refining processes;

Subject to the following constraints:

(2) Demand for electricity, for domestic lighting, for urban and regional passenger transport, and for goods transport, for irrigation and exogenous demand $\leq$ supply from coal, FBR, HTR, and CANDU plants for the period T;

(3) Exogenous demand for electricity $\leq$ supply for periods $1, 2, \ldots, T-1$;

(4) Electricity generated in period $\leq$ capacity in period for periods $1, 2, \ldots, T$;

(5) Demand for uranium over the lifetime of all CANDU plants installed $\leq$ supply from known reserves;

(6) Demand for plutonium in the period for FBR and HTR $\leq$ supply from domestic accumulation until the period from past CANDU and FBR operations.

(7) Demand for plutonium for the post terminal life of installed HTR $\leq$ supply;

(8) Demand for coal for fertilizer feedstock, for rural and urban cooking, for trains for regional passenger and goods transport, and for electricity generation $\leq$ supply of coal for period T;

(9) Nitrogenous fertilizer required by food activities $\leq$ fertilizer produced using coal, naphtha, fuel oil, and biogas in period T;

(10) Demand for food $\leq$ supply of food in period T;

(11) Domestic lighting energy requirement $\leq$ lighting energy from kerosene and electricity in period T;

(12) Rural domestic cooking energy requirements $\leq$ cooking energy from coal, kerosene, biogas, and firewood in period T;

(13) Urban domestic cooking energy requirement $\leq$ cooking energy from LPG, kerosene, coal, and firewood in period T;

(14) Demand for firewood $\leq$ exogenous availability plus availability from land saved from agriculture by increasing fertilizer and/or irrigation intensity in period T;

(15) Demand for biogas $\leq$ supply from families with adequate animal dung to install their own plants in period T;

(16) Demand for urban passenger transport $\leq$ supply by diesel and mogas buses, electric trains, private automobiles, and scooters in period T;

(17) Urban passenger transport by electric trains $\leq$ demand in large metropolises;

(18) Demand for regional passenger

transport ≤ supply by diesel buses, and electric, diesel and coal trains in period *T*;

(19) Demand for goods transport in each of six traffic density class ≤ supply by diesel trucks and electric, diesel and coal trains in period *T*;

(20) Goods transport required as feeder traffic ≤ goods transport by diesel trucks in period *T*;

(21) Demand of each petroleum product ≤ supply from domestic refining and imported products in period *T*;

(22) Demand for crude ≤ domestic availability and imports in period *T*.

DEMAND PROJECTIONS

Our model assumes that the demands in the target year for rice, wheat, and transport as well as those for energy for cooking and lighting are exogenously determined. We now describe the basis of our exogenous projections of demand.

Demand for rice and wheat

We first project the likely population in India in the target year 2000–2001, using 1971 government census data and on the basis of age-specific fertility and mortality rates computed by the Census Commission of the Government of India. The assumed time pattern of gross reproduction and fertility rates is given in Table 1.

The projected population in India in 2000–2001 is then 960 million, of which 30% are assumed to live in urban areas. The corresponding 1971 census figures are 547 million and 20%.

We next project the average aggregate consumption expenditure at 1970–1971 prices in the target year by assuming a 5% per annum growth for the period 1975–1991, and a 6% per annum growth thereafter. The ratio of urban per capita consumption expenditure to that in rural areas in the target year was set at 1.25. Given this ratio, the projected urban and rural population, and the aggregate consumption expenditure, we calculated that the urban per capita consumption expenditure would be Rs 1378 (1970–71 exchange rate, 7.5 Rs to US $1.) and the corresponding value in rural areas would be Rs 1098.

The pattern of distribution of rural and urban households among 13 per capita expenditure classes was derived by assuming this distribution to belong to the two-parameter log-normal family in each case. The projected average per capita consumption expenditure (rural and urban), together with an assumed Lorenz ratio of 0.3, determine completely the distribution. By using data from the 1970–1971 round of the National Sample Survey on the per capita consumption (in physical units) of rice and wheat by rural and urban households in each of the 13 expenditure classes, in conjunction with the distribution of the households among these classes in the target year, the total private consumption of these two foodgrains was obtained. By adding a customary 12.5% margin for feed, seed, and wastage, and assuming net foreign trade as well as stock changes in the target year to be negligible, the output target for foodgrains and, in particular, for rice and wheat were determined.

TABLE 1
GROSS REPRODUCTION RATE AND FERTILITY RATE FOR INDIA.

	1971–1976	1976–1981	1981–1986	1986–1991	1991–1996	1996–2001
Gross reproduction rate	2.409	2.168	1.952	1.759	1.662	1.590
Gross fertility rate Births per 1000 females (15–44 years of age)	168.0	150.1	135.6	124.0	118.0	112.1

Source: Census Commission, Government of India.

Demand for passenger transport

Two different kinds of passenger transport were distinguished. The first, urban passenger transport, consisted essentially of traffic within cities and towns. The demand in terms of passenger kilometers (pkm) of this kind of transport was assumed to grow in proportion to the growth of urban population. The second regional passenger transport consisted of all other passenger transport. This category included all long-end medium distance passenger traffic, for which demand was assumed to grow in proportion to the growth in total population. This procedure resulted in the following projections for 2000–2001 (in 10^9 pkm): 960 for urban, and 2020 for regional.

Demand for goods transport

We first estimated on the basis of past data the following regression relation between tkm of goods carried by the railways (Y) and real gross national product (GNP) originating outside agriculture (X_1), the stock of trucks (X_2), and a time trend (X_3). We have

$$Y = 3387 + \underset{(2.12)}{13.401X_1} - \underset{(2.155)}{0.331678X_2} + \underset{(3.717)}{3940X_3}$$

$\bar{R}^2 = 0.9839$ DW (Durbin Watson) = 1.784.

By assuming both a stock of a million trucks in 2000–2001 and projected values of GNP outside agriculture, a forecast of Y for 2000–2001 was made, amounting to 660×10^9 tkm. To this was added 400×10^9 tkm that would be carried by the million trucks, and 1070×10^9 tkm representing the projected demand for goods transport in 2000–2001 given this projection, in the model we did not in any way constrain the division of the total between railways and trucks. In many ways this procedure is rather unsatisfactory, since it implies that a projection based on a past relationship and the projection of the numbers of trucks in 2000–2001 are used to determine the total demand, which is then subsequently optimally divided between railways and trucks. But the number of trucks implied by the optimum amount of truck traffic need not equal the number used in the projection. We have not attempted to iterate in this respect, preferring to assume consistency to emerge through changes in the efficiency of trucking.

Energy demand for cooking and lighting

These projections were derived on a normative basis. A target of energy consumption for cooking and lighting of 0.38 kg of coal replacement per person per year was set for rural areas. The corresponding target for urban areas was set at 0.40 kg. The lighting component of these targets was set at 5 kg of kerosene or 40 kWh per person per year for both rural and urban areas.

PRODUCTION CHOICES

Choices in foodgrain production

The production of only rice and wheat is treated in the model. The choices available were summarized in terms of 10 activities included in the programming model. In deriving these activities we adopted a quadratic programming model that we developed earlier. In the earlier model, India is divided into 57 agro-climatic zones, based on soil characteristics and rainfall. For each zone for which sufficient data from experiments on farmers' fields were available, a quadratic response function relating yield of a particular variety of a crop to applications of fertilizers was estimated. The varieties included a number of high yielding ones (usually dwarf varieties developed and propagated by agricultural scientists) and local varieties. The responses were separately estimated for irrigated, rainfed, and dry (less than 90 cm average rainfall in a year) areas of a zone. The interested reader is referred to Parikh and Srinivasan et al. (1974) for more details about this model.

The programming model works as follows: Given the area (irrigated, rainfed and dry portions separately) in each zone and the exogenously specified demand for the output of each crop for the country as a whole, the model determines the varieties to be grown and the cost minimizing amount of chemical fertilizers (nitrogen, phosphorus, and potassium) to be applied in each zone in respect of each crop that will result in production at least as large as demand. In executing the model, we had to face the problem that experimental response data were not available in some zones in respect of some crops. In our earlier study referred to above, we circumvented this problem by substituting the *minimum* observed response of a crop over all zones for which data were available for the non-available response (keeping, of course, the irrigated, rainfed and dry area district). In the present paper the substitute response function is the *weighted average* of observed responses in the zones with data, the weights being the area under the crop in each zone. Thus the basic data specified are the areas devoted to each crop in each zone (separately for irrigated, rainfed, and dry) and the demand for output.

The procedure by which we obtained the Indian demand for rice and wheat has already been described. While keeping the demands the same, our 10 activities were obtained by varying the gross area and the irrigated portion of it. In "gross sown area," hectare of land is treated as 2 hectares gross if it grows 2 crops a year, whereas in "net sown area," each hectare of land is included only once, regardless of the number of crops grown on it in a year. Thus the net sown area can be increased only by bringing more land under cultivation, while gross sown area can be increased both by increasing net sown area and by cultivating more crops in a year on the same piece of land; that is, by increasing the cropping intensity. In a country such as India, where agriculture has been practiced for millennia and where population growth has been substantial, very little area is available to be brought under cultivation for the first time. Hence, the scope for increasing gross sown area lies mostly in increasing cropping intensity. While the availability of irrigation is essential for such multiple cropping, provision of irrigation to a previously unirrigated piece of land need not, and often does not, lead to more than one crop since the irrigation provided may not be sufficient to grow more than one crop. Thus the availability of irrigation may mean simply shifting from growing a single unirrigated crop to a different, perhaps more profitable crop with irrigation. While we allow some increase in gross sown area to result from an extension of irrigated areas, we permit cropping intensity to change for other reasons as well. In fact, we assume three alternative values for additions to gross sown area by 2000–2001: 0, 10, and 20 million hectares for the country as a whole.

The Irrigation Commission in its report (1972) has provided statewide estimates of ultimate irrigation potential. We adjusted these figures for certain obvious biases of underestimation in their procedure and assumed six alternatives in the 65 to 85% for the proportion of the ultimate potential to be realized by the year 2000–2001. The assumed alternative values for additions to gross sown area for the country as a whole were then allocated between states in proportion to the addition to irrigated area arising from the assumed proportion of the ultimate irrigation potential to be realized. The statewide projections thus obtained for gross sown area and irrigated area were then allocated to the 57 agro-climatic zones and crops within a zone using a procedure adopted in the earlier study.

TABLE 2

	Activity									
	1	2	3	4	5	6	7	8	9	10
Addition to gross sown areas (10^6 ha)	20	20	20	10	0	0	0	0	0	0
Realized irrigation potential (%)	85	75	65	75	85	80	75	72	68	65

Table 2 lists the 10 combinations considered used in the model. For each combination the food sector submodel was run to obtain the minimum amount of nitrogen (together with phosphorus and potassium, assumed used in fixed proportion to nitrogen) needed to produce the specified amount of rice and wheat. For example, activity 10 represents a fertilizer-intensive strategy of food production, since with no additions to gross sown area and the irrigated area fixed at its minimum permissible value, the required output of food can be produced only by increasing the use of fertilizers. By contrast, activity 1 is a fertilizer-saving strategy, while activities 1 and 5 are irrigation-intensive ones. Activities 4 to 10 require less net land compared to activities 1 to 3, which are land intensive. The land saved could be devoted to growing firewood. Credit for firewood available from this land is taken for activities 4 to 10. The resulting 10 activities in Fig. 2 thus represent the spectrum of choices with respect to energy in food production. The activity coefficients are given in Appendix 2.

Choices in modes of transport

The alternatives considered in transporting goods are electric, diesel, and steam traction on the railways and diesel and gasoline trucks. The alternatives for passenger transport were, in addition to the three modes of traction on the railways, diesel, and gasoline buses. The technological details are given in Tables 3 and 4.

Choices in cooking and lighting energy

The alternatives are: LPG, coal gas, firewood, kerosene, and biogas for cooking and electricity, and kerosene for lighting. The details are shown in Tables 5 and 6.

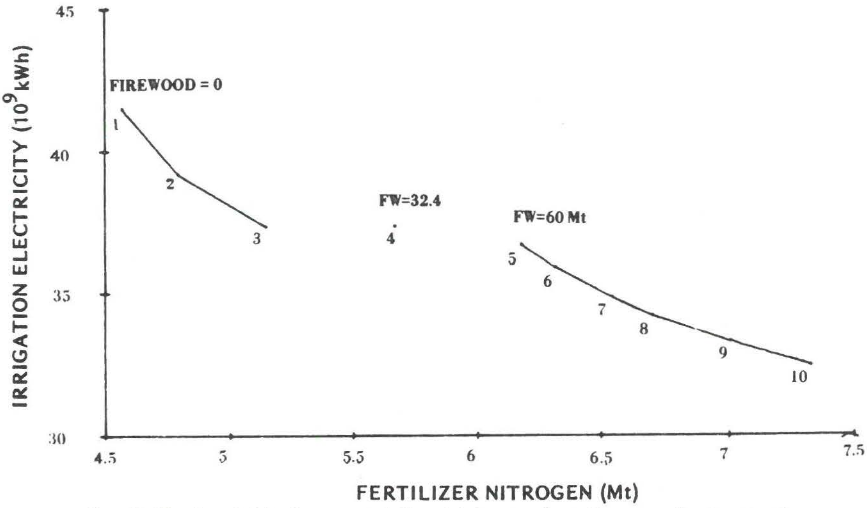

FIG. 2. Food activities isoquants (all activities pro-duce the same food output).

Choices in refinery processes

Nine types of crude oil are considered—two from domestic fields, and seven imported crudes. The secondary processes include vacuum cracking, visbreaking, hydrocracking, and catalytic cracking. The choices considered are shown in Fig. 3; details of activities are given in Appendix 3.

Choices in electricity generation

India is well endowed with coal, but the coal is of inferior quality and the reserves are geographically concentrated. The known reserves of oil and uranium are meager, but a vast amount of thorium is available. Thus a long-term development strategy has to be geared to the use of thorium either in HTRs or in FBRs. However, both these reactors require plutonium, which has to be produced as a joint product with electricity in a first-generation nuclear power plant. For a country with small reserves of uranium (about 30,000 t), a neutron efficient path of CANDU reactors using natural uranium is attractive. In order to explore the choices in electricity generation which involve plutonium accumulation, a multiperiod treatment is required. We have therefore treated electricity generation choices in a multiperiod framework. The choices available are shown in Table 7.

Hydel development is assumed to be fixed exogenously. While a large number of good sites still remain to be developed, the pace of development is constrained primarily by construction capability. However, it is assumed that hydel plants in the future will be used mainly for peaking and would have a load factor of 0.3 compared to the present hydel load factor of 0.6.

Similarly the power available from the

TABLE 3

CHOICES IN PASSENGER TRANSPORT.

	Urban passenger transport					Regional passenger transport			
	Trains (Electric)	Buses (diesel)	Buses (gasoline)	Private automobiles	Private scooters	Buses (diesel)	Trains (diesel)	Trains (electric)	Trains (coal)
Costs* 10^6 Rs/10^9 pkm	11.05	32.5	32.5	240	40	78.125	27.62	27.62	27.62
Energy: Electricity 10^9 kWh/10^9 pkm	.017	—	—	—	—	—	—	.016	—
Diesel 10^6 t/10^9 pkm	—	.008225	—	—	—	.006854	.004308	—	—
Petrol 10^6 t/10^9 pkm	—	—	.015	.0473	.025	—	—	—	—
Coal 10^6 t/10^9 pkm	—	—	—	—	—	—	—	—	.057

* Includes capital charges but excludes energy costs.

TABLE 4
CHOICES IN GOODS TRANSPORT.

Activity				Cost excluding energy 10^6 Rs/10^9 tkm	Fuel required		
No.	Traction	Single/double tracks	Density class*		Electrical energy 10^9 kWh/10^9 tkm	Diesel 10^6 t/10^9 tkm	Coal 10^6 t/10^9 tkm
1	S	s	1	122.93	—	—	.109
2	S	s	2	60.73	—	—	.109
3	S	d	3	58.85	—	—	.109
4	S	d	4	56.59	—	—	.109
5	S	d	5	56.59	—	—	.109
6	S	d	6	56.59	—	—	.109
7	D	s	1	187.00	—	.004308	—
8	D	s	2	72.66	—	.004308	—
9	D	s	3	59.60	—	.004308	—
10	D	s	4	53.37	—	.004308	—
11	D	s	5	49.80	—	.004308	—
12	D	d	6	47.35	—	.004308	—
13	E	s	1	231.10	.031	—	—
14	E	s	2	82.47	.031	—	—
15	E	s	3	65.48	.031	—	—
16	E	s	4	57.37	.031	—	—
17	E	s	5	52.74	.031	—	—
18	E	d	6	49.56	.031	—	—
19	Truck			112.30	—	.04112	—

* Density class defines the traffic density in terms of ntkm/day per km of route. The following density classes have been considered: Class 1, 0–10000; Class 2, 10001–20000; Class 3, 20001–30000; Class 4, 30001–45000; Class 5, 45001–60000; Class 6, 60001 and above.

The proportion of total route km belonging to each density class and the goods traffic to be carried in the class are assumed as follows:

		Fraction of total route km	10^9 ntkm/year carried
Density Class	1:	.10	20
	2:	.15	110
	3:	.30	270
	4:	.30	270
	5:	.20	190
	6:	.10	140
All Classes		1.00	1000

Trucking for local distribution is constrained to be at least 70×10^9 ntkm. Further trucking if found desirable is assumed to be distributed evenly on all routes.

For each density class, the number of tracks are determined for each traction to minimize costs.

The costs include costs of track including electrifications and rolling stock, but not the fuel costs.

Traction code: S (Steam), D (Diesel) and E (Electric); Track code: s (single), d (double).

LWR reactor at Tarapore is taken as given, as the fuel for it comes from the USA under a special agreement. The assumed availabilities of power from these sources are shown in Table 8.

Choices in fertilizer production

The main chemical fertilizers used in India are nitrogenous, phosphastic, and potassic fertilizers and their mixtures. Indian farmers tend to use relatively more nitrogenous fertilizers than would be optimal if they were to base their decisions on the experimental yield response functions. We have assumed that the potassic and phosphatic fertilizers are used in fixed ratios to the amount of nitrogenous fertilizers, these ratios being based on past behavior.

There are alternative ways of producing nitrogenous fertilizers, while there is not much of a technological choice in the others. Further, animal dung is also a source of nitrogen. We assume that the amount of dung that was being composted before 1975

TABLE 5
ENERGY CHOICES FOR COOKING.

Fuel units	LPG* (10^6 t)	Coal gas** ($10^9 m^3$)	Firewood (10^6 t)	Kerosene (10^6 t)	Coal (10^6 t)	Biogas** ($10^9 m^3$)
Cost 10^6 Rs/10^6 t or $10^9 m^3$	†	240	10‡	†	95	196.7
Coal replacement factors	8.3	2 (t/1000 m^3)	0.95	8.3	1.0	2.60 (t/1000 m^3)
Nitrogen produced 10^6 t/$10^9 m^3$	—	—	—	—	—	.032

* LPG and coal gas are considered options only for urban areas, and biogas is confined to rural areas.

** Biogas coefficients refer to small family-sized units. The nitrogen produced is additional to what would be obtained by composting animal dung instead of feeding it in the plant.

† Costs determined by the model from prescribed crude and refining costs.

‡ Nonland costs.

TABLE 6
CHOICES IN ENERGY FOR LIGHTING.*

	Kerosene	Electricity	Biogas
Requirement per person per year	5 kg	40 kWh	220 m^3

* Progress of rural electrification is exogenously speciied. Other substitutes are not strictly comparable to electricity.

will in the future be put through biogas plants, and the extra nitrogen obtained by processing the dung through a biogas plant as compared to composting is a net addition to the supply of nitrogen. The technolgical choices in the production of nitrogen (other than from dung) are described in Table 9.

In Table 10 we list the choices with respect to total energy, agriculture, transport, and domestic sectors. Case 1 is the base case to which all comparisons of other cases refer.

In the base case solution, food activity 10, which is a land-saving and fertilizer-intensive technology, is selected, and coal is preferred as feedstock for fertilizer manufacture. For urban passenger transport electric trains are selected up to the prescribed maximum and then diesel buses are selected. For goods transport trains with all three tractions, steam, diesel and electric, are selected depending upon the density of traffic on the route. Trucks are not selected beyond the prescribed minimum feeder traffic. For the domestic sector a mix of kerosene, LPG, coal, biogas, and firewood is selected.

Case 2 differs from case 1 in that the crude oil and product prices are doubled compared to the base case. This results in substantial reduction in the import of crude oil in case 2. The reduction of about 10 Mt in oil consumption is accomplished by increasing the consumption of coal by more than 54 Mt. Though the food activity 10 is still selected, naphtha is no longer used as a fertilizer feedstock. The saving in naphtha leads to increased availability of mogas, and

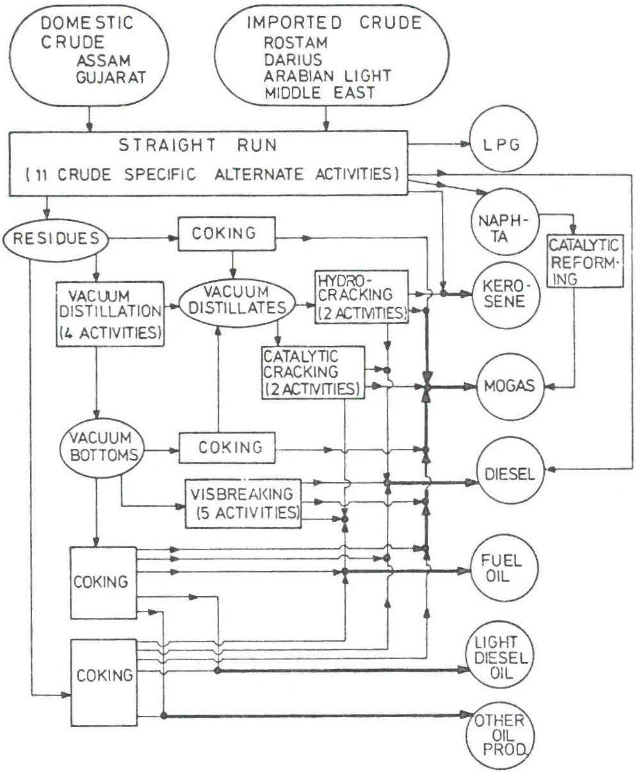

FIG. 3. Choices in refining and secondary processing.

TABLE 7
CHOICES IN ELECTRICITY GENERATION.

	Coal-based thermal plant	CANDU natural uranium based nuclear plant	Fast breeder reactor (FBR)	High temperature reactor (HTR)
Capital cost (10^6 Rs/GW(e))	2050	3650	3100	3100
Operating cost* (10^6 Rs/10^9 kWh)	32	12.3	10	10
Load factor	0.8	0.85	0.85	0.85
Fuel input uranium (natural)	—	—	—	—
(t/10^9 kWh)	—	19.7	—	—
Coal (450 kcal/kg)	—	—	—	—
10^6 t/10^9 kWh)	0.55	—	—	—
Plutonium (t/10^9 kWh)	—	—	0.208	0.068
Fuel inventory:				
Uranium (t/10^6 kw(e))	—	260	—	—
Fissile plutonium (t/10^6 kW(e))	—	—	3.5	—
Fuel recovery:				
Fissile plutonium (t/10^9 kWh)	—	.0565	.276	—

* Excluding plutonium credit.

mogas buses are used marginally for urban passenger transport. For goods transport in the density class 4, electric traction replaces diesel traction. In the domestic sector, as oil becomes more expensive in case 2, about 4.5 Mt of petroleum products are replaced by coal. As can be seen from Table 11, the increased requirement of electricity in case 2 comes from coal, and for nuclear plants the pattern of electricity generation in cases 1 and 2 are the same.

In case 3, the price of coal is decreased by 20% as compared to the base case. Naturally this results in an increase, over the base case, in the consumption of coal by nearly 34 Mt. Crude oil imports are reduced even more substantially than in case 2, but about 9 Mt of fuel oil are imported. The electricity generation remains unaltered. There is also no change in choices in the food activity and the transport sector. The bulk of the fertilizer manufacture is now coal based. In the domestic sector, coal replaces kerosene in rural cooking to a large extent. Since less of kerosene and diesel are consumed in cases 2 and 3, refinery processes get changed to accommodate this (see Table 12).

TABLE 8
AVAILABILITY OF ELECTRICITY FROM HYDEL PLANTS AND LIGHT WATER REACTORS (LWRS).

Midyear	Hydel (10^9 kWh)	LWR (10^9 kWh)
1975–1976	46	2
1980–1981	66	2
1985–1986	88	2
1990–1991	109	2
1995–1996	135	2
2000–2001	158	2

In case 4, the exogenous availability of firewood was set at zero instead of at 60 Mt. This reduction in the availability of an energy source for the domestic sector is made up entirely of coal, and no other change takes place in any of the sectors.

In case 5, availability of domestic crude was raised by 75%. As is to be expected, this eliminates the need for importing crude. Fertilizers are mainly produced with naphtha as feedstock, but some coal is still used as feedstock. Regional passenger transport demand is now met partly by diesel trains. However, the choices in goods transport remain unaltered. In the domestic sector the relative proportions of coal, LPG, and kerosene change. The pattern of electricity generation is altered as slightly less electricity is required in this case compared to the base case.

In case 6, when the capital costs of FBR and HTR are increased by 20% over the base case, the solution is the same as in the base case and these results are not therefore tabulated separately.

As seen in Table 11, CANDU and FBR

TABLE 9
CHOICES IN FERTILIZER FEEDSTOCK.*

	Fertilizer plants based on feedstock		
	Naphtha	Fuel oil	Coal
Cost** 10^6 Rs per 10^6 t of nitrogen	848	935	1143.8
Feedstock required (including fuel) 10^6 t/t of N)			
Naptha	1.0724	—	—
Fuel oil	0.3980	1.404	—
Coal	—	—	3.974

* Biogas fertilizers produced as joint product. For details see Table 5 on energy choices for cooking.

** Excluding cost of feedstocks.

TABLE 10
SUMMARY OF FUEL CHOICES.

			Base case	Oil prices doubled	Coal costs reduced 20%	Exogenous availability firewood set at zero	Domestic crude availability increased 75%
Case Number			(1)	(2)	(3)	(4)	(5)
Total consumption							
Coal** (10^6 t)			593.322	647.781	627.029	650.322	574.765
Electricity† (10^6 kWh)			467.907	476.277	*	*	459.060
Agriculture sector							
Food activity number			10.	*	*	*	*
Fertilizer nitrogen (10^6 t)			7.328	*	*	*	*
From coal			4.018	6.848	6.203	*	1.763
From biogas			0.480	*	*	*	*
From naphtha			2.830	0	0.645	*	5.085
Transport sector							
Urban passenger (10^9 pkm)							
Electric trains			320.0	*	*	*	*
Diesel buses			640.0	608.182	*	*	*
Mogas buses			0	31.818	*	*	*
Regional passenger (10^6 pkm)							
Diesel trains			0	*	*	*	552.911
Electric trains			2020.0	*	*	*	1467.089
Goods transport (10^9 tkm‡)							
Trains							
Traction	Tracks	Density class					
Steam	single (s)	1	20.0	*	*	*	*
Steam	double (s)	2	110.0	*	*	*	*
Diesel	s	3	270.0	*	*	*	*
Diesel	s	4	270.0	0	*	*	*
Electric	d	4	0	270.0	*	*	*
Electric	d	5	190.0	*	*	*	*
Electric	d	6	140.0	*	*	*	*
Trucks diesel		1	70.0	*	*		*
Domestic sector							
Cooking							
Biogas (10^9 m^3)			15.000	*	*	*	*
Firewood (10^6 t)			120.000	*	*	60.000	*
Coal (10^6 t)			27.034	65.028	52.058	84.034	22.381
Kerosene (10^6 t)			13.253	8.889	10.540	*	13.285
LPG (10^6 t)			1.949	1.734	1.646	*	2.477
Lighting							
Kerosene (10^6 t)			0.670	*	*	*	*
Electricity (10^9 kWh)			38.400	*	*	*	*

* Indicates that the value is the same as in the base case.
** Includes coal for electricity generation.
† Excludes energy from hydel and LWR.
‡ For details regarding density classes, see Table 4.

plants are installed in all cases, and the shadow price on uranium and plutonium constraints are positive. This is the case even when capital costs of FBRs are increased by 20%. However, the HTR is not selected in any of these cases.

The refinery processes vary from case to case as does the source of imported crude, depending upon the product mix that emerges. In all cases the product mix is such as to make economical secondary processing activities such as hydrocracking.

Family-sized biogas plants are found to be economical and in all cases are selected up to the prescribed limit of availability of animal dung.

In conclusion, we feel that the insensitivity observed, particularly in the agricultural sector, in food and fertilizer, production, in urban passenger, and in goods transport in the six cases treated indicates that the technological choices in these have to be modeled in greater detail. In particular, economies of scale in passenger transport should also be taken into account. Additional choices in the agricultural sector, such as those arising out of regional self-sufficiency, should be introduced. Increas-

TABLE 11

ELECTRICITY GENERATION.

	Base case	Oil prices doubled	Coal costs reduced 20%	Exogenous firewood availability set at zero	Domestic crude availability increased 75%
Case Number	(1)	(2)	(3)	(4)	(5)
Energy generated (in 10^9 kWh/year)					
CANDU *(in period)*					
1	2.234	*	*	*	*
2	5.957	*	*	*	*
3	6.739	*	*	*	*
4	85.122	*	*	*	79.190
5	85.122	*	*	*	87.642
6	85.122	*	*	*	87.642
FBR *(in period)*					
5	60.131	*	*	*	56.566
6	60.131	*	*	*	56.566
Thermal (in period)					
1	27.054	28.183	*	*	24.058
2	62.023	64.009	*	*	56.757
3	125.121	128.364	*	*	116.527
4	140.234	145.164	*	*	133.152
5	197.249	201.968	*	*	179.727
6	338.454	347.945	*	*	329.467
New capacity created (in GW(e))					
CANDU *(in period)*					
4	10.292	*	*	*	9.495
5	0	*	*	*	1.135
6	0	*	*	*	*
FBR *(in period)*					
5	8.076	*	*	*	7.597
6	0	*	*	*	
Coal (in period)					
4	1.012	1.714	*	*	0
5	8.134	8.106	*	*	6.646
6	20.149	20.830	*	*	21.367

* Indicates that the value is the same as in the base solution.

TABLE 12

OIL IMPORTS AND REFINERY PROCESSES (10^6 T).

	Base case	Oil prices doubled	Coal costs reduced 20%	Exogenous firewood availability set at zero	Domestic crude availability increased 75%
Case Number	(1)	(2)	(3)	(4)	(5)
Domestic crude	40.000	*	*	*	70.0
Imported crude	23.813	14.284	8.390	*	0
Imported petroleum products					
Fuel oil	0	*	9.240	*	*
Others	13.320	*	13.306	*	*
Product availability					
LPG	1.949	1.734	1.646	*	2.477
Kerosene	13.923	9.559	11.210	*	13.955
Diesel	15.469	14.044	*	*	17.851
Naphtha	6.035	3.0	3.692	*	8.453
Fuel oil	14.026	12.9	13.157	*	14.924
Mogas	4.4	4.877	*	*	*
LDO	4.4	*	*	*	*
Others	15.0	*	*	*	*
Refinery processes					
Straight runs of crude					
Assam 2	10.000	*	*	*	20.000
Gujarat 1	0	*	*	*	25.524
Gujarat 2	30.000	*	*	*	24.476
Middle East 1	0	14.284	8.390	*	*
Middle East 4	23.813	0	*	*	*
Cat. Refor. of Naphtha	1.736	3.030	1.637	*	2.380
Hydrocrack. of Vac. Dist. 1	0	2.512	9.761	*	*
Hydrocrack. of Vac. Dist. 2	5.280	0	0	*	1.472
Vac. Dist. of Residues 3	8.756	9.961	0	*	13.083
Vac. Dist. of Residues 4	7.197	2.326	16.323	*	0
Visbreaking of Vac. Bott. 1	10.664	0	0	*	11.611
Visbreaking of Vac. Bott. 2	0	9.775	*	*	*
Coking of Residues 1	14.004	*	7.442	*	*
Coking of Vac. Bottoms 1	0	0	6.562	*	*

* Indicates that the value is the same as in the base solution.

ing costs in the production of coal is another improvement that can be made. Also our demand projections have not reflected the changes in costs arising from alternative production choices. This price inelasticity assumption should perhaps be revised, particularly with respect to transport choices. Finally, a truly dynamic version of the model has to be built.

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APPENDIX 1. THE MATHEMATICAL MODEL

List of symbols

r	: Rate of annual discount
t	: Period from 1,2,..,T. (Each period consists of 5 years, $T = 6$).
T	: Terminal period, midyear 2000-2001.

Electricity generation

k_i	: Investment cost in 10^6 Rs/GW(e) of capacity for plant type i, i = CANDU, FBR, HTR, coal.
K_{it}	: Capacity created at the beginning of t of plant type i in GW(e).
v_i	: Operating cost in 10^6 Rs/10^9 kWh of plant type i.
E_{it}	: Electricity generated in midyear of period t from ith type plant in 10^9 kWh.
g_i	: Energy that can be generated in one year from GW(e) of the i^{th} type plant in 10^9 kWh/year.
p_{plut}	: Price of plutonium in 10^6 Rs/t in midyear of period 1.
$plut_i$	: Plutonium produced or required per 10^9 kWh of generation from ith type of nuclear plant in t.
Pu_{inv}	: Plutonium inventory required in t/GW(e) of installed capacity of FBR.
u_{inv}	: Uranium inventory required in t/GW(e) of installed capacity of CANDU.
u_{CANDU}	: Uranium required in t/10^9 kWh of generation from CANDU.
$elec_i$	: 10^9 kWh of electricity required for ith need per year in period T.
$\overline{ELED}_t$	: Exogenously specified demand for electricity for midyear of period t in 10^9 kWh.
ELE_t	: Demand for electricity in 10^9 kWh determined in the model.
$\overline{ELE}_o$	: Base year demand for electricity in 10^9 kWh for agricultural use and for urban and rural lighting, urban and regional passenger transport by electric trains, and transport of goods by electric trains.

Food production

i_j	: Firewood produced per unit level food activity j.
a_j	: Cost in Rs 10^6 for a unit level of food production activity j.
e_j	: 10^9 kWh of energy required for pumping water for unit level of food activity $FOOD_j$.
$fert_j$	: 10^6 t on N required for activity $FOOD_j$.
$FOOD_j$	: Alternative activities to produce food. Unit level of any activity produces all the required food.

Fertilizer production

f_i	: Cost of ith type fertilizers, excluding the cost of fuel and feedstock, in 10^6 Rs/10 t of N from fertilizers FERT_i.
n	: Naphtha required as feedstock per unit of nitrogenous fertilizers production.
FERT_i	: Fertilizer produced by process using feedstock, i, i = naphtha (N) coal (C), biogas (BG), and fuel oil (FO).
β	: Fuel oil required as feedstock per unit of nitrogenous fertilizer production.

Fuels

c_i	: Cost of fuel type i in 10^6 Rs/10^6 t or 10^9 m^3.
coal_i	: 10^6 t of coal required for ith need per year in period T.
FUEL_i	: Fuel type i used, i = coal, electricity, kerosene, etc.
$\overline{\text{COALD}}$	: Exogenous demand for coal in 10^6 t for midyear of period T.
COAL	: Total coal used other than for electricity production.
$\bar{\text{U}}$	: Uranium availability.
RCBG	: Animal dung used for biogas production for rural cooking.
$\overline{\text{RCBGB}}$	: Availability of animal dung for biogas production.

Energy

s_i^L, s_i^C	: Fuel to energy conversion ratios in 10^9 kWh/10^6 t or 10^9 m^3; for example s^L_{KER} converts kerosene to lighting energy.
R, U	: Prefixes stand for rural, and urban, respectively.
L, C	: Stand for lighting, and cooking, respectively.
E, KER, BG, FW, C	: Stand for electricity, kerosene, biogas, firewood, and coal, respectively.
Example	: Rural lighting kerosene (in 10^6 t): RLKER.
$\overline{\text{RLED}}$	: Demand for energy for rural lighting.
$\overline{\text{ULED}}$	: Demand for energy for urban lighting.
$\overline{\text{RLEE}}$	: Exogenous supply of electrical energy for rural lighting
$\overline{\text{ULEE}}$	: Exogenous supply of electrical energy for urban lighting.
$\overline{\text{RCED}}$	: Demand for energy for rural cooking.
$\overline{\text{UCED}}$	: Demand for energy for urban cooking.
$\overline{\text{RCAW}}$	: Exogenous supply of energy from agricultural wastes used in rural cooking.

Passenger transport

$\left.\begin{array}{l}(\text{up})_i\\(\text{rp})_i\end{array}\right\}$	: Cost of urban passenger and regional passenger transport by mode i, excluding the cost of fuel, in 10^6 Rs/10^9 pkm.
$\left.\begin{array}{l}\text{UPK}_i\\\text{RPK}_i\end{array}\right\}$	: Urban and regional passenger transport in 10^9 pkm carried by mode i, i = petrol buses, diesel buses, automobiles, scooters, electric, diesel, and steam trains.
$\left.\begin{array}{l}\overline{\text{UPKD}}\\\overline{\text{RPKD}}\end{array}\right\}$	: Urban and regional passenger transport in 10^9 pkm.

Goods transport

$(\text{gt})_{ij}$	: Cost of goods transport by mode i for density class j in 10^6 Rs/10^9 tkm.
α_j	: Fraction of rail route kilometer with traffic density of class j.
GTK_{ij}	: Goods carried by trains of traction i in density class j, in 10^9 tkm, i = diesel (D), electric (E), steam (S).

TRUK_c	: Goods tkm (10^9) carried by diesel trucks, competing with goods transported by rail, in 10^9 tkm.
TRUK_f	: Volume of feeder traffic to be carried by diesel truck.
$\overline{\mathrm{TRUKD}}$	: Exogenously specified volume of feeder traffic.
GTKD_j	: Goods carried in density class j in 10^9 tkm.

Petroleum and oil products

p_j	: Price of crude oil in 10^6 Rs/10^6 t.
m_q	: Price of imported oil product q in 10^6 Rs/10^6 t.
r_h	: Cost of refinery process h in 10^6 Rs/10^6 t of processing per year.
$(\mathrm{rp})_h$	: Coefficients of refinery process activity h.
REFIN_h	: Level of refining activity hm 10^6 t of input.
d_{rb}, d_{ub}, d_{rt} d_{gm}, d_{gt}	: Diesel required for regional and urban passenger transport by buses, for regional passenger transport by trains, and for goods transport by trucks and trains per unit per year.
pet_a, pet_b pet_s	: Petrol required by automobiles, buses, and scooter per unit per year for passenger transport.
OILPR_q	: Oil product q imported, q = mogas, naphtha, kerosene diesel, fuel oil, light diesel oil, and other products.
CRUD_j	: Crude used, j = domestic (D), imported (M).
$\overline{\mathrm{CRUDD}}$	: Exogenously specified domestic crude availability.
$\overline{\mathrm{KEROD}}$	: Exogenously specified portion of kerosene demand.
NAPHTHA	: Naphtha.
$\overline{\mathrm{NAPTHAD}}$	: Exogenously specified portion of naphtha demand.
FOIL	: Fuel oil.
$\overline{\mathrm{FOILD}}$	: Exogenously specified portion of fuel oil demand.
LDO	: Light diesel oil.
$\overline{\mathrm{LDOD}}$	: Exogenously specified portion of light diesel oil demand.
OOPS	: Other oil products in 10^6 t.
$\overline{\mathrm{OOPSD}}$	: Exogenously specified portion of other oil products demand.

(1) Objective function: Minimize

$Z = \sum_{t=1}^{T} (1+r)^{-(5t-5)} \sum_i (K_{it} + 5v_iE_{it})$	Costs of capacity K_{it} and energy E_{it} of plant type i installed at t, i = CANDU, FBR, HTR, and coal.
$- \sum_{t=1}^{T} \sum_{j=1}^{30-5(T-t+1)} (1+r)^{-(5T-5+j)} \sum_i (v_i - v_{\mathrm{coal}})g_iK_{it}$	Credit for post terminal cost advantage; i = CANDU, FBR, HTR, and coal.
$- p_{\mathrm{plut}} \sum_{t=1}^{T} \sum_{j=5t}^{30+5t-1} (1+r)^{-(j-5)} \{\sum_i \mathrm{plut}_iE_{it} - \mathrm{plut}_{htr}E_{htr,t} - Pu_{\mathrm{inv}}K_{\mathrm{fbr},t}\}$	Credit for plutonium surplus; i= CANDU, FBR.
$- 5(1+r)^{-(5T-5)} [\sum_{j=1}^{10} a_j\mathrm{FOOD}_j + \sum_i f_i\, \mathrm{FERT}_i$	Nonfuel and fertilizer feedstock cost in agriculture; i = naphtha, coal and fuel oil.
$+ \sum_i (\mathrm{up})_i\, \mathrm{UPK}_i + (rp)_i\, \mathrm{RPK}_i$	Nonfuel cost of passenger transport; i = electric trains, diesel trains, steam trains, petrol, and diesel buses.
$+ \sum_{j=1}^{6} \sum_i (\mathrm{gt})_{ij}\, \mathrm{GTK}_{ij} + (\mathrm{gt})_{\mathrm{truck}} (\mathrm{TRUK}_f + \mathrm{TRUK}_c)$	Nonfuel costs of goods transport; i = electric, diesel, and steam trains.

$+ \sum c_i\,\mathrm{FUEL}_i + \sum_j p_j\,\mathrm{CRUD}_j + \sum_q m_q + \sum_{h=1}^{30} r_h\,\mathrm{REFIN}_h]$

Fuel, crude, oil products and refining costs; i = coal, kerosene, diesel, mogas, LPG, fuel oil, biogas, and firewood; j = domestic, imported; q = imported kerosene, HSDO, LDO, mogas, naphtha, fuel, oil, and OOPS.

Subject to:

(2) $\overline{\mathrm{ELED}}_t + \mathrm{ELE}_t \leqq \sum_i E_{it}$

Demand $\leqq$ supply constraint for electricity $t = 1, \ldots, T$; i = CANDU, FBR, HTR, coal.

(2a) $\mathrm{ELE}_T = \sum_{j=1}^{10} e_j\,\mathrm{FOOD}_j + \sum_i \mathrm{elec}_i$

i = urban lighting, rural lighting, electricity for transport of urban passenger, regional passenger, and goods.

(2b) $\mathrm{ELE}_t = \overline{\mathrm{ELE}}_0 \dfrac{(\mathrm{ELE}_T - \overline{\mathrm{ELE}}_0)^{t/T}}{\overline{\mathrm{ELE}}_0}$

(3) $\overline{\mathrm{COALD}} + \sum_i \mathrm{coal}_i \leq \mathrm{COAL}$

Demand $\leq$ supply constraint for coal; i = fertilizer, urban cooking, rural cooking, goods per tkm regional pkm carried by steam traction.

(4) $\sum_{j=1}^{10} \mathrm{fert}_j\,\mathrm{FOOD}_j \leq \sum_i \mathrm{FERT}_i$

Demand $\leq$ supply constraint for fertilizers; i = naphtha, fuel oil, coal, biogas.

(5) $\sum_{j=1}^{10} \mathrm{FOOD}_j \geq 1.0$

Supply of food $\geqq$ requirement.

(6) (a) $\sum_i s_i^L\,\mathrm{RL}_i\ \overline{\mathrm{RLED}} - \overline{\mathrm{RLEE}}$

(b) $s_{\mathrm{Elec}}^L\,\mathrm{ULE} \geqq \overline{\mathrm{ULED}} - \overline{\mathrm{ULEE}}$

Domestic energy for lighting $\geqq$ demand:

(a) *Rural*: i = electricity, kerosene, and biogas;

(b) *Urban*: i = electricity.

(7) (a) $\sum_i s_i^C\,\mathrm{RC}_i \geqq \overline{\mathrm{RCED}} - \overline{\mathrm{RCAW}}$

(b) $\sum_i s_i^C\,\mathrm{UC}_i \geq \overline{\mathrm{UCED}}$

Energy available for cooking $\geqq$ demand:

(a) Rural cooking: i = firewood, biogas, coal, kerosene

(b) Urban cooking: i = firewood, coal, kerosene, LPG.

(8) $\mathrm{RCFW} + \mathrm{UCFW} \leqq \sum_{j=1}^{10} 1_j\,\mathrm{FOOD}_j$

Availability of firewood $\geqq$ demand.

(9) $\mathrm{RCBG} \leqq \overline{\mathrm{RCBGB}}$

Availability of animal dung for biogas $\geqq$ dung used for biogas production.

(10)

Passenger transport carried by all modes $\geqq$ demand.

(a) $\sum_i \mathrm{UPK}_i \geqq \overline{\mathrm{UPKD}}$, $\mathrm{UPKTE} = 0.3\ \overline{\mathrm{UPKD}}$

Urban: i = buses (diesel and petrol), electric trains, automobiles, and scooters.

(b) $\sum_i \mathrm{RPK}_i \geqq \overline{\mathrm{RPKD}}$

Regional: i = diesel buses and trains, electric and steam trains.

(11) $\alpha_j\ \mathrm{TRUK}_c + \sum_i \mathrm{GTK}_{ij} \geqq \overline{\mathrm{GTKD}_J}$ $j = 1, \ldots, 6$ density classes $\mathrm{TRUK}_f \geqq \overline{\mathrm{TRUKD}}$	Goods transport carried by all modes $\geqq$ demand; i = trains (electric, diesel, and steam); j = density class.
(12)	Supply for oil products $\geqq$ demand.
(a) $\mathrm{MOGAS} \geqq \mathrm{PET}_b\ \mathrm{UPKBP} + \mathrm{pet}_a\ \mathrm{UPKA} + \mathrm{pet}_s\ \mathrm{UPKS}$	Motor gasoline (mogas).
(b) $\mathrm{DIESEL} \geqq \mathrm{d}_{ub}\ \mathrm{UPKBD} + \mathrm{d}_{rb}\ \mathrm{RPKBD} + \mathrm{d}_{rt}\ \mathrm{RPKTD} + \mathrm{d}_{gt} \sum_{j=1}^{6} \mathrm{GTKD}_j + \mathrm{d}_{gm}\ \{\mathrm{TRUK}_f + \mathrm{TRUK}_c\}$	Diesel.
(c) $\mathrm{KERO} \geqq \mathrm{RCKER} + \mathrm{UCKER} + \mathrm{RLKER} + \overline{\mathrm{KEROD}}$	Kerosene.
(d) $\mathrm{NAPHTHA} \geqq n.\ \mathrm{FERTFO} + \overline{\mathrm{FOILD}}$	Naphtha.
(e) $\mathrm{FOIL} \geqq \beta\ \mathrm{FERTFO} + \overline{\mathrm{FOILD}}$	Fuel oil.
(f) $\mathrm{LDO} \geqq \overline{\mathrm{LDOD}}$	Light diesel oil.
(g) $\mathrm{OOPS} \geqq \overline{\mathrm{OOPSD}}$	Other oil products.
(13) $\mathrm{CRUDE} \geqq \mathrm{CRUDD} + \mathrm{CRUDM}$ $\mathrm{CRUDD} \leqq \overline{\mathrm{CRUDD}}$	Refinery balances.

$$\left\{\begin{matrix} \mathrm{CRUDE} \\ \mathrm{LPG} \\ \mathrm{NAPHTHA} \\ \mathrm{KERO} \\ \mathrm{DIESEL} \\ \mathrm{LDO} \\ \mathrm{RESIDUE} \\ \mathrm{FOIL} \\ \mathrm{MOGAS} \\ \mathrm{OOPS} \end{matrix}\right\} \leqq \left[\ rp\ \right] \left\{\begin{matrix} \mathrm{REFIN}_1 \\ \\ \\ \\ \\ \\ \\ \\ \\ \mathrm{REFIN}_{30} \end{matrix}\right\} + \left\{\begin{matrix} \mathrm{OILPR}_1 \\ \cdot \\ \\ \cdot \\ \\ \mathrm{OILPR}_q \\ \cdot \\ \\ \cdot \end{matrix}\right\}$$

The refining processes $(rp)_1, \ldots, (rp)_{30}$ are described in Appendix 3.

(14) $E_{it} \leqq g_{it}\ K_{it}$	Output $\leqq$ capacity electricity generation; i = CANDU, FBR, HTR, coal; $t = 1, \ldots, T$.
(15) $\sum_{t=1}^{T} u_{\mathrm{inv}}\ K_{\mathrm{candu},}\ t + \sum_{t=1}^{T} 5u_{\mathrm{candu}}\ E_{\mathrm{candu},}\ t \leqq \bar{\mathrm{U}}$	Uranium $\leqq$ availability.
(16) $\sum_{t=1}^{T} [Pu_{\mathrm{inv}}\ K_{\mathrm{fbr},}\ t + 5plut_{\mathrm{htr,t}}\ E_{\mathrm{htr},t} - 5\mathrm{plut}_{\mathrm{fbr}}\ E_{\mathrm{fbr},t-1} - 5\ \mathrm{plut}_{\mathrm{candu},t-1}\ E_{\mathrm{candu},t-1}] \leqq 0$ $\sum_{t=2}^{T} \sum_{j=t+1}^{t+5} + 5\ [\mathrm{plut}_{\mathrm{htr}}\ g_{\mathrm{htr}}\ K_{\mathrm{htr},t} - \sum_{i=\mathrm{candu,fbr}} \mathrm{plut}_i\ \mathrm{g}_i\ \mathrm{K}_{it}] \leqq 0$	Plutonium availability $\geqq$ plutonium used.

APPENDIX 2. ALTERNATIVE ACTIVITIES TO PRODUCE REQUIRED OUTPUT OF FOOD.

Item	Food Activities									
Irrigation potential realized (%)	85	75	65	75	85	80	75	72	68	65
Additional Area (10^6 *ha*)	20	20	20	10	0	0	0	0	0	0
Activity	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Wheat output: (78 Mt)										
Nitrogen (10^6t)	1.222	1.417	1.635	1.562	1.413	1.513	1.630	1.706	1.846	1.965
Land (10^6 ha)	26.617	26.617	26.617	26.066	25.606	25.606	25.606	25.606	25.606	25.606
Irrigated area (10^6 ha)	23.364	19.619	17.966	19.443	20.623	19.417	18.211	17.487	16.522	15.798
Paddy output: (180 Mt)										
Nitrogen (10^6 t)	2.435	2.418	2.483	2.975	3.352	3.543	3.606	3.657	3.758	3.897
Land (10^6 ha)	50.268	50.268	50.268	47.700	45.566	45.566	45.566	45.566	45.566	45.566
Irrigated area (10^6 ha)	33.318	31.137	28.051	29.059	29.555	28.313	26.991	26.178	25.075	24.141
All Food Crops										
Nitrogen (10^6 t)	4.571	4.794	5.148	5.671	6.181	6.320	6.545	6.704	7.005	7.328
Irrigated area (10^6 ha)	70.850	63.445	57.521	60.628	62.723	59.663	56.503	54.581	51.996	49.924
Electric energy for Irrigation (10^9 kWh)	41.5	39.2	37.35	37.4	36.7	35.9	34.85	34.2	33.3	32.45
Firewood (10^6 t)	0	0	0	32.4	60.0	60.0	60.0	60.0	60.0	60.0
Annual cost (10^6 Rs)										
Discounted	3166	2896	2693	2871	2987	2890	2791	2725	2652	2607
Undiscounted	34303	31377	29178	31107	32363	31312	30240	29525	29734	28246

Area and nitrogen requirements for wheat and paddy assumed to be 80% of the total.

Cropping intensity taken to be 1.67 for irrigated land.

Lift irrigation assumed to decrease at the rate of 2.5% for every increase of 10% in the irrigation potential, from a value of 50% for 65% irrigation potential.

Energy required per hectare of lift irrigation is 1300 kWh/year.

A hectare of land gives 12.35 *t* of firewood per year.

APPENDIX 3. REFINING AND SECONDARY PROCESSING ACTIVITIES (rp_h).

Activities / Products:	Crude	Gas	Naphtha	Kerosene	HSDO	LDO	Residue	Vacuum distillates	Vacuum bottom	Fuel oil	Motor gas	Other oil products
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Assam crude (AS)												
1	−1.0	.0160	.1440	.1900	.2760	.0	.3740	—	—	—	—	—
2	−1.0	.0290	.0970	.1690	.2750	.0	.4300	—	—	—	—	—
Gujarat crude (GU)												
1	−1.0	.0350	.2410	.2470	.2600	.0	.2170	—	—	—	—	—
2	−1.0	.0410	.1120	.1480	.1700	.0	.5290	—	—	—	—	—
Middle East crude (ME)												
1	−1.0	.0150	.1190	.1750	.2625	.0	.4285	—	—	—	—	—
2	−1.0	.0150	.1400	.1900	.2300	.0	.4250	—	—	—	—	—
3	−1.0	.0220	.1590	.1530	.1790	.0	.4870	—	—	—	—	—
4	−1.0	.0180	.1445	.2295	.1970	.0	.4110					
Aga Jari (AJ)	−1.0	.0345	.1605	.1400	.2020	.0	.4630	—	—	—	—	—
Rostam (ROST)	−1.0	.0150	.1520	.1970	.2350	.0	.4010	—	—	—	—	—
Arabian light (ARL)	−1.0	.0330	.1300	.1900	.1860	.0	.4610	—	—	—	—	—
Darius (DAR)	−1.0	.0170	.1780	.1780	.1960	.0	.4310	—	—	—	—	—
Vacuum distillation of residue (VACRD)												
1	0	0	0	0	0	0	−1.0	.5702	.4293	—	—	—
2	0	0	0	0	0	0	−1.0	.5037	.4959	—	—	—
3	0	0	0	0	0	0	−1.0	.1125	.8875	—	—	—
4	0	0	0	0	0	0	−1.0	.5980	.4020	—	—	—
Visbreaking of vacuum bottom (VBVB)												
1	0	0	0	0	0	0	0	0	−1.0	.9480	.0520	—
2	0	0	0	0	.0297	0	0	0	−1.0	.9190	.0396	—
3	0	0	0	0	.0323	0	0	0	−1.0	.9226	.0297	—
4	0	0	0	0	0	0	0	0	−1.0	.8791	.0906	—
5	0	0	0	0	0	0	0	0	−1.0	.9479	.0520	—
Catalytic reforming of naphtha (CATRF)	0	0	−1.0	0	0	0	0	0	0	0	.8410	—
Hydrocracking of vacuum distillate (HCVD)												
1	0	0	0	.3700	.4500	0	0	−1.0	0	0	.1492	—
2	0	0	0	.4400	.3600	0	0	−1.0	0	0	.1547	—
Catalytic cracking of vacuum distillates (CATVD)												
1	0	0	0	0	.1931	0	0	−1.0	0	.5238	.1401	—
2	0	0	0	0	.1931	0	0	−1.0	0	.5238	.1402	—
Coking of vacuum bottom (CVB)												
1	0	0	0	0	.0731	.3142	0	0	−1.0	.2797	.1119	.1200
2	0	0	0	0	0	0	0	.80	−1.0	0	.0300	0
Coking of residues (CR)												
1	0	0	0	0	.0731	.3142	−1.0	0	0	.2797	.1119	.1200
2	0	0	0	0	0	0	−1.0	.80	0	0	.0300	0

AN INTEGRATED APPROACH FOR IMPROVING DECISION-MAKING PROCESSES[1]

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This article deals with decision making at the organization level, but it is perhaps applicable to all other levels. Decision-making processes generally have multiple purposes and are made with uncertainty. The objectives are usually noncommensurate and in conflict with one another. The processes involve two phases: analytical and judgmental. For the analytical phase, mathematical optimization methods such as mathematical programming are efficiently applied. The nesting method of Lagrangian multipliers is one device intended to bridge the gap between both phases of decision-making processes. The System and Decision Science Area of the International Institute for Applied Systems Analysis has been very involved with multiobjective decision problems. This study is one of several works on methodological development for a multicriteria decision-making process.

KEY WORDS: organization, decision making, uncertainty, utility functions, mathematical programming.

DECISION-making processes are generally multiobjective, namely, the processes include some complexity, diversification, noncommensurability, conflict, and uncertainty. Due to the diversification of objectives involved in the decision-making processes, the decision maker is confronted with large-scale decision problems over various fields, such as social, economic, environmental, and aesthetic. Naturally, the criteria of the decision problems are noncommensurate and usually in conflict with each other. Besides, decisions are usually made with uncertainty. In many cases the decision maker cannot wait for obtaining empirical results from mass observation. Thus, he faces a complex decision problem which is called the *complex problematique.*

To solve this kind of decision problem one cannot rely on a conventional monodisciplinary approach. The monodisciplinary approach lacks comprehensiveness and coherence which are main characteristics of the complex problematique. Thus, a more comprehensive and integrated approach—the systems approach—is required. In this paper a brief description of a sophisticated device for improving decision-making processes is presented, with some examples for application of the methodology.

HIERARCHICAL MODELING OF MULTILEVEL SYSTEMS APPROACH

For modeling the large scale decision problems in order, a hierarchical modeling of multilevel decision systems can be formed. Corresponding to an overall decision problem, which is partitioned to multilevel systems (Mesarović, Macko, & Takahara, 1970), an objectives hierarchy is constructed at multiple levels. To solve these decomposed subproblems separately is more computationally efficient than conventional optimization procedures. In this device, the overall decision problems are not necessarily restricted by the size of the problems. The decomposition procedures of mathematical programming have been developed since the Dantzig-Wolfe decomposition algorithm (Dantzig & Wolfe 1960; 1961). Recently, the primal-dual method for nonlinear programming (Lasdon, 1968; 1970) has been applied to water quality management by Haimes, Foley, and Yu (1972). Moreover, as pointed out by Haimes (1975), the partitioned subsystem can be

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individually solved by particular methods in accordance with the nature of the modeling. Thus, the hierarchical systems approach can be used more efficiently for arranging specific characteristics in various aspects of an overall system.

On the other hand, mathematical programming is also considered in a hierarchical structure. Namely, an objective function of mathematical programming represents a lower-level objective peculiar to each subsystem. Constraint constants are considered as upper-level objectives which are sent from the upper-level decision maker. Decision variables are a normative instrument for achieving these objectives and considered as the lowest-level objectives. Thus, formulations of mathematical programming are considered in the framework of a hierarchical systems structure. In Fig. 1, the problem structure is depicted for three levels of planning—regional, local, and industrial. Here, mathematical programming is formulated as local-level planning. Mathematical programming is solved as a primal-dual problem, and a dual solution set $\boldsymbol{\lambda}^i$ as well as a primal solution set $\boldsymbol{x}^i$ are obtained for each subsystem i. The framework includes a feedback process. The upper-level decision maker compares the optimal value $\boldsymbol{\lambda}^i$ with actual performance $\boldsymbol{x}^{i\prime}$, and can modify his instruction d^i for local-level planning, which is implemented as a constraint constants set.

Integration of mathematical programming and decision analysis

The purpose of decision-making processes is to select a set of preferred solutions from among Pareto-optimal solutions with reasonable procedures. This procedure is known as a multiobjective optimization problem. To derive the Pareto-optimal solutions is an analytical aspect of the decision problem. To select the preferred solution from among the Pareto-optimal solutions is a judgmental aspect for the decision problem. Thus, from a methodological point of view, decision problems are composed of two main layers: analytical and

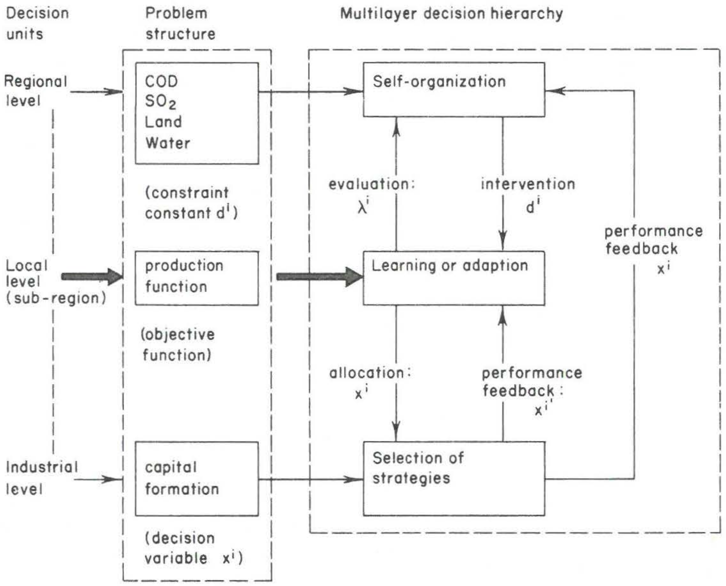

FIG. 1. Functional hierarchy of local-level planning. (Notations in this figure and in Figs. 2, 3, and 5 are: u^i = a set of multiattribute utility functions for a subproblem i; d^i = a vector of constraint constants for a subproblem i; λ^i = an optimal solution set of Lagrangian multipliers for a subproblem i; x^i = an optimal solution set of decision variables for a subproblem i; u = an overall multiattribute utility function; $f^i\ (x^i)$ = an objective function for a subsystem i; x^i = a feasible set for a subsystem i; $x^{i\prime}$ = a vector of actual performance for decision variables, X = a feasible set for all the system $\cup x^i$.)

judgmental. The analytical aspect of the decision problem has exclusively attached importance in conventional optimization processes. Mathematical programming as well as control theory is a representative technique for the optimization procedure.

Applications of mathematical programming to environmental management exclusively based on primal problems have shown many good performances (Sobel, 1965; Thomann, 1965; Revelle, Loucks, & Lynn 1968). Multiobjective programming techniques especially have been developed for environmental management and control, although many developments have been done only in the theoretical aspect (Cochrane & Zeleny 1973; Zeleny, 1974; 1975). Analytical techniques can be exclusively applied to a deterministic phase of the complex problematique. However, in mathematical modeling, many ambiguous aspects of actual processes still remain unspecified. Therefore, the discrepancy between model prediction and actual response often misleads the decision maker. Moreover, entire dependence on rigorous analytical solutions is dangerous because these solutions are generally in conflict with each other and any device for compromising them is not provided by the programming techniques themselves. Constituents may oppose "optimal" policies based on such an analytical solution in their own interest. This shows another discrepancy of mathematical expectation and social response. Thus, these discrepancies shall be filled by the subjective judgment of the decision maker or his council board as a coordinator. The judgmental gap composes an indeterministic phase of the complex problematique. A device for manipulating this phase is known as decision analysis; it has been developed by Pratt, Raiffa, & Schlaifer (1964), Raiffa (1968), and Schlaifer (1969). In these works, utility functions are set up for assessing the degree of satisfaction of performance for attributes quantitatively. In other words, the utility concept is utilized as a score or an index for measuring the worth given to a magnitude of the performance. A procedure for deriving multiattribute utility functions has been established by Keeney and Raiffa (1976). Many examples for application of their methods have been published (Keeney, 1975). Derivation of the multiattribute utility functions is based on the representation theorems under the utility independence as well as preferential independence assumptions (Keeney, 1974).

The nested Lagrangian multiplier method

A problem we face is how to treat the judgmental phase in combination with the analytical phase of decision problems for solving the complex problematique in totality. The surrogate worth trade-off (SWT) method by Haimes and Hall (1974; 1975) is one device for this approach. An alternative integration method has been presented by Seo (1977). Both methods depend on the utilization of the shadow prices as a base of the systems evaluation. The main objective of the new method is to explicitly combine mathematical programming at the first layer with decision analysis at the second layer. A proper procedure of this work has not been presented in the SWT method. In the new method dual optimal solutions of mathematical programming are directly utilized as inverse images of component utility functions, differing from the SWT method in which the shadow prices are used indirectly for worth assessment. In the SWT method, a derivation process of the surrogate worth functions is completely separated from estimation of the shadow prices, which are interpreted as the trade off rate function. Besides, assessment of the surrogate worth functions is done at once in an ordinal scale. The new method is intended to provide numerical assessment of the utility functions in a cardinal scale with sequential and interactive procedures in multilevel decision systems.

The outline of the new method is as follows:

First, a preference hierarchy is made according to systems decomposition and coordination. Many objectives which are included in an overall system are decomposed into subsystems, which are subsequently consolidated into a hierarchical system.

Second, mathematical modeling at the first layer is constructed. Each subsystem is independent and has its own mathematical formulation. Mathematical programming is solved separately as a single-objective optimization problem, which includes several constraints constants as the upper-level objectives.

Third, dual optimal solutions (i.e., Lagrangian multipliers) are utilized as shadow prices. The shadow prices are regarded as a numerical index which evaluates inversely the degree of performance of the upper-level objectives in terms of the lower-level objectives. Consider the following mathematical programming formulation:

maximize

$$(1) \qquad f^i(\boldsymbol{x}),$$

subject to

$$(2) \qquad h_j{}^i(\boldsymbol{x}^i) \leq d_j{}^i, j = 1, \ldots, p,$$

$$(3) \qquad g_s{}^i(\boldsymbol{x}^i) \leq b_s{}^i, s = p+1, \ldots, n,$$

where constraint (2) shows a target (soft) constraint imposed by the upper-level decision maker, and constraint (3) a technical (hard) constraint restricted by technological conditions. $\boldsymbol{x}^i$ is a vector of decision variables. Then the Lagrangian function is formulated:

$$(4) \qquad L^i(\boldsymbol{x}^i, \boldsymbol{\lambda}^i, | \boldsymbol{d}^i, \boldsymbol{b}^i) = f^i(\boldsymbol{x}^i) - \textstyle\sum_{j=1}^{p} \lambda_j{}^i(h_j{}^i(\boldsymbol{x})^i - d_j{}^i) - \textstyle\sum_{s=p+1}^{n} \lambda_s{}^i(g_s{}^i(\boldsymbol{x}^i) - b_s{}^i).$$

The inverse of the Lagrangian multiplier in optimal $1/\lambda_j{}^i$ is an opportunity cost of constraint constants $d_j{}^i$ traded-off to one additional unit of the objective function f^i because in optimal $1/\lambda_j{}^i = \partial d_j{}^i/\partial f^i$. Thus, the larger $\lambda_j{}^i$ is, then the smaller is the opportunity cost of $d_j{}^i$ in terms of one marginal unit of sacrifice of f^i. In other words, a large value of $\lambda_j{}^i$ (shadow price) shows that the degree of satisfaction for present performance level of $d_j{}^i$, the upper-level objective, is already high in terms of f^i, the lower-level objective. Similarly, the smaller $\lambda_j{}^i$ is, then the larger is the opportunity cost of $d_j{}^i$ in terms of an additional unit of sacrifice of the f^i. It shows that the degree of satisfaction for current performance level of $d_j{}^i$ is still low in terms of the f^i. Those numerical values for evaluation are normalized in terms of one marginal value of a common objective function. For example, consider the formulation (1) as a net profit function in subsystem i and the formulation (2) as resource constraints such as coal, steel, and electricity, etc. A constraint constant $d_j{}^i$ shows a resource availability. When a numerical value of the Langrangian multiplier combined with any one resource constraint (e.g., coal) is larger than the one for the other resource (e.g., steel), it means that a marginal quantity of coal to be traded off to a marginal unit of the local net profit is smaller than the same quantity of steel. Under an assumption that selection of the measuring units for all the resources is empirically reasonable and practically meaningful, this means that the degree of satisfaction for coal availability is already higher than the one for steel. The comparison can also be done for any one resource (e.g., coal) among subsystems. This interpretation of the shadow prices is almost the same as that of Luenberger (1973) and Intrilligator (1971), but is a new version based on the hierarchical structure of mathematical programming.

Fourth, the shadow prices are transformed into component utility functions. Based on our interpretation of the shadow prices, the shadow prices are utilized as an inverse image of the utility functions in the lower level. Because numerical values of the shadow prices correspond to a preference ordering of the decision maker, numerical valuation of utilities is determined by a linear transformation, according to the Von Neumann-Morgenstern theorem (1944) (see next section).

In practice, we choose $0 < \boldsymbol{\lambda}_j{}^i < \lambda_j{}^i$ min at $u_j{}^i$ $(\boldsymbol{\lambda}_j{}^i) = 0$ and $\bar{\lambda}_j{}^i > \lambda^i_{j\max} > 0$ at $u_j{}^i$ $(\bar{\lambda}_j{}^i) = 1$, where $\boldsymbol{\lambda}_j{}^i$ shows a lower bound of $\lambda_j{}^i$ and $\bar{\lambda}_j{}^i$ shows an upper bound of it. Thus, we calculate a linear equation passing through the two points $\bar{\lambda}_j{}^i$ and $\boldsymbol{\lambda}_j{}^i$ as follows:

$$\begin{aligned} u_j{}^i &= u_j{}^i(\lambda_j{}^i(x^i \mid d_j{}^i)), \\ &= -a_j{}^i + b_j{}^i\lambda_j{}^i(x^i|d_j{}^i). \end{aligned}$$

The $u_j{}^i$ $(\lambda_j{}^i$ $(x^i|d_j{}^i))$ is a component utility function which is related to a target constraint $d_j{}^i$ in a subproblem i.

Fifth, multiattribute utility functions are derived. Using the component utility functions, multiattribute utility functions (MUF) are constructed and nested one after another. The procedure for deriving the MUFs is almost similar to the method of multiattribute utility analysis (Keeney & Raiffa, 1976), except the evaluation of trade-offs between attributes is based on the normalized utility values. During this process, component utility functions are weighted by the decision maker and compromise each other. To include such a coordination procedure in the treatment of various attributes is a characteristic of this method.

Finally, an overall multiattribute utility function is derived for an overall evaluation of the hierarchical system. By this device, a comprehensive project evaluation among alternatives can be performed and compared for each region and/or each period. The evaluation can be done after as well as in advance. We call this procedure the nested Lagrangian multiplier (NLM) method. The main idea is depicted in Fig. 2. Using this procedure, the multicriteria decision problem is reduced to scalar optimization problems in the first step, and then they are coordinated into an overall decision problem in the second step, based on the duality of mathematical programming (Fig. 3).

Concept of the component utility functions

Now a concept of the basic component utility function $u_j^i\ (\lambda_j^i\ (x^i|d_j^i))$ should be

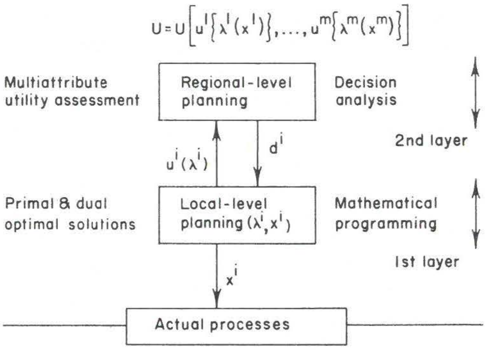

FIG. 2. Structure of two-layer planning. (See Fig. 1 for notation key.)

explained. First, the Lagrangian multipliers are defined as an inverse image of the utility functions. In the following, subscripts and notations are omitted because the definitions will be clear. Define a mapping Ψ such that $\Psi : \Lambda \to \Upsilon$. Let $\lambda \in \Lambda$, $u \in \Upsilon$. u is an image of λ by Ψ. A power set $\mathscr{P}(\Upsilon)$ is a set composed of a total of subsets of the set Υ. Let a subset of the set Υ be $\mathscr{U}$. In

$$\mathscr{U} \in \mathscr{P}(\Upsilon),$$

$$\Psi^{-1}(\mathscr{U}) = \{\lambda | \lambda \in \Lambda,\ \Psi(\lambda) \in \mathscr{U}\}$$

is an inverse image of $\mathscr{U}$, and $\Psi(\Lambda) = \{\Psi(\lambda) \geq 0 | \lambda > 0, \lambda \in \Lambda\}$.

Second, along the lines of Von Neumann and Morgenstern's theorem, it can be shown that positive linear transformation of λ to u is admissible. Define a system of relation $A = < \Omega, R >$ and call it the

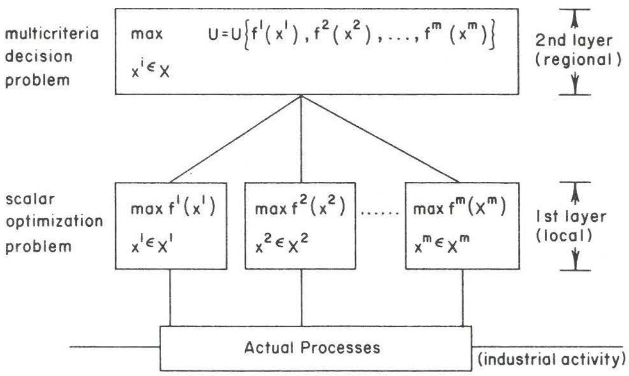

FIG. 3. Systems decomposition and coordination in two layers. (See Fig. 1 for notation key.)

preference relation A. Here Ω is a nonempty set and R is a binary relation defined on elements of Ω.

Definition 1 (*preference relation A*). If R is a binary relation on set Ω and if $\mathcal{X}, \mathcal{Y}, \mathcal{Z} \in \Omega$, then a preference relation A on individual choice satisfies the following axioms:

1. Transitivity: if $\mathcal{X}R\mathcal{Y}$, $\mathcal{Y}R\mathcal{Z}$, then $\mathcal{X}R\mathcal{Z}$;
2. Weak connectivity: $\mathcal{X}R\mathcal{Y}$, or $\mathcal{Y}R\mathcal{X}$;
3. Nonsatiety: if $\mathcal{X} > \mathcal{Y}$ then $\mathcal{X}p\mathcal{Y}$;
4. Continuity: if $\mathcal{X}R\mathcal{Y}$ and $\mathcal{Y}R\mathcal{Z}$, then there is a real number α such that $0 \leq \alpha \leq 1$ and $\{\alpha\mathcal{X} + (1-\alpha)\mathcal{Z}\}\, I\mathcal{Y}$.

Here R is "prefer to" (p) or "indifferent to" (I).

Definition 2 (*weak ordering*). R on a set Ω is weak ordering if and only if transitivity and connectivity are satisfied. According to the Von Neumann-Morgenstern theorem, the Theorem 1 on the preference relation A is derived (Luce & Suppes, 1965).

Theorem 1 (*Von Neumann-Morgenstern*). Under preference relation A, there exists a real-valued function S defined on Ω such that for every $\mathcal{Y}$ and $\mathcal{X}$ in Ω and a parameter α in [0, 1],

(i) $\mathcal{X}R\mathcal{Y}$ if and only if $S(\mathcal{X}) \geq S(\mathcal{Y})$

(ii) $S\{\alpha\mathcal{X} + (1-\alpha)\mathcal{Y}\} = \alpha S(\mathcal{X}) + (1-\alpha) S(\mathcal{Y})$

Moreover, if S' is any other function satisfying (i) and (ii), then S' is related to S by a positive linear transformation.

Theoretical background of the NLM method is based on the following proposition.

Proposition. According to the interpretation of Lagrangian multipliers as shadow prices, we replace the Lagrangian multiplier λ with S in Theorem 1.

The proposition shows that, because λ is an equivalence (namely, reflexive, symmetric, and transitive) set of S based on our interpretation of the Lagrangian multipliers, we can use λ in place of S in Theorem 1.

Now the equivalence concepts are defined.

Definition 3 (*equivalence*). A binary relation R on Ω is an equivalence when it is reflexive, symmetric, and transitive.

Definition 4.

1. A binary relation R on set Ω is reflexive if $\lambda R\lambda$ for every $\lambda \in \Omega$.
2. A binary relation R on a set Ω is symmetric if $\lambda RS \rightarrow SR\lambda$ for every $S, \lambda \in \Omega$.

Transitivity can always be assumed for λ.

Definition 5 (*equivalence classes*). Two elements λ and S of an original set Ω are in an equivalence class when they are equivalent.

Now, main theorems can be derived as follows:

Theorem 2. A set of Lagrangian multiplier $\Lambda = \{\lambda\}$ on a decision problem D $(\Lambda | \lambda \in \Omega)$ and a set of S defined on Ω in Theorem 1 are in an equivalence class defined on Ω.

Theorem 3. For every $\mathcal{X}$ and $\mathcal{Y}$ in the set Ω defined under the preference relation A, the following properties are preserved for the Lagrangian multiplier λ in optimal:

1. $\mathcal{X}R\mathcal{Y}$ if and only if $\lambda(\mathcal{X}) \geq \lambda(\mathcal{Y})$,
2. $\lambda\{\alpha\mathcal{X} + (1-\alpha)\mathcal{Y}\} = \alpha\lambda(\mathcal{X}) + (1-\alpha)\lambda(\mathcal{Y})$, where $\mathcal{X}$ and $\mathcal{Y}$ are some implicit evaluation factors.

Theorem 4 (*derivation of utility concept*). A Lagrangian multiplier λ can be positive-linearly transformed to a numerical utility u defined on a value between 0 and 1.

The basic idea for deriving the component utility concept is shown in Fig. 4. For the numerical utility, although differences between the utilities are numerically measurable, the position of origin and the unit of a numerical scale for the utilities can be arbitrarily decided. This type of scale is called an interval scale. Thus, the cardinal utility functions are derived.

APPLICATIONS

As a demonstration of this method, here are some examples of case studies. In Fig. 5, a hierarchical configuration of a regional

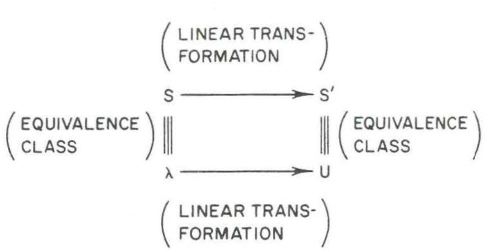

FIG. 4. Deviation of a component utility function U.

planning system in the Yodo River Basin is shown. The region is located in the industrialized greater Osaka area in the middle part of Japan. The people in the region have suffered increasingly from environmental pollution, resources shortage, and natural destruction during the high-speed period of industrial development since the 1960s. Thus the objective area forms a regional complex problematique. Our main concern is with improving the quality of life in the area, and for this purpose regional welfare functions showing the degree of satisfaction in lives should be evaluated.

The hierarchical structure is composed of two layers. In the first layer, functional decomposition has been done at two levels and mathematical programming has been applied to each subsystem for residential and industrial problems. The residential problem is to maximize the welfare of wage earners, which is expressed in a modified exponential type nonlinear satisfaction functions subject to equity constraints among industries and to minimum wage constraints for each industry. An industrial problem is to maximize the local industrial output which is described by Cobb–Douglas type production functions subject to environmental (COD, SO_2) as well as resource restriction (land, water). The problem also has upper and lower bound constraints of decision variables (capital and labor) for avoiding radical structural changes. In the second layer, regional decomposition has been done at three levels, and decision analysis has been applied for coordinating the analytical solutions which have been obtained from mathematical programming. In this stage, a trade-off experiment has been performed. The results for the residential problem have been presented by Seo (1977). Based on the NLM method, regional residential utility functions have been derived and assessed. For checking the results assessed with the utility concept, numerical values of standard deviations (σ^i) of average wages and salaries among industries are compared in each region (Table 1). It is known that the σ^i-values correspond well to the utility values for equity. Thus, this method seems to provide a good understanding for a welfare standard.

The results for minimum wage require-

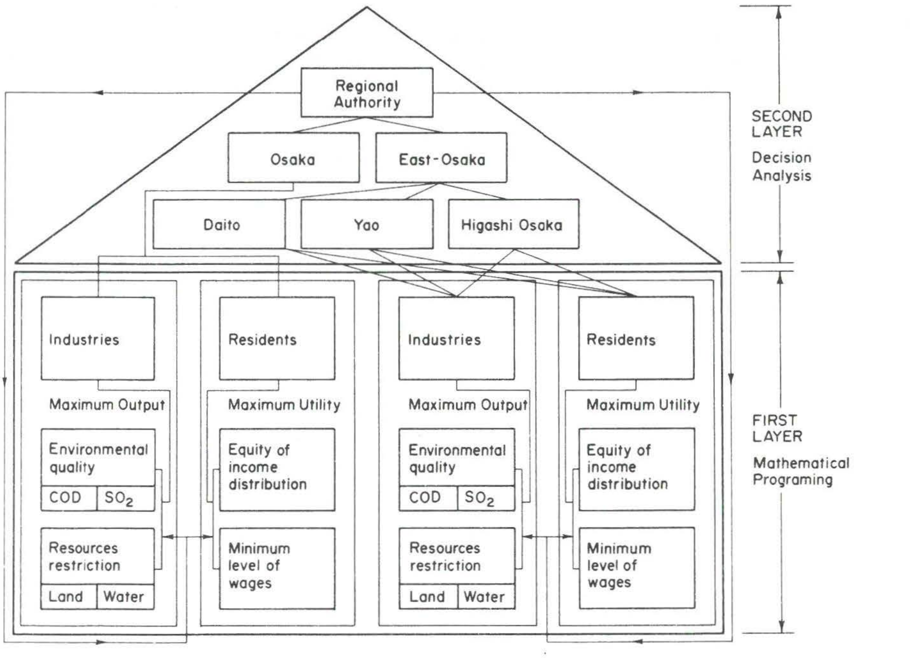

FIG. 5. A hierarchical system for regional complex problematique in the Yodo River Basin. (See Fig. 1 for notation key.)

TABLE 1

Assessment of Utility for Equity Requirement in Each Region u_e.

	Osaka	Yao	Daito	Higashi-Osaka
λ^i	1.6209×10^{-3}	1.6659×10^{-3}	1.6452×10^{-3}	1.6886×10^{-3}
u^i	0.2099	0.6593	0.4524	0.8864
σ^i	41.53	34.50	38.60	34.15

ment and equity consideration in the residential problem have been combined with ones for natural resources and environment management program in the industrial problem. Regional multiattribute utility functions have been derived and assessed (Seo & Sakawa, 1979a). The augmented Lagrangian algorithm is effectively used for solving nonlinear programming in the first layer.

The industrial problem has been revised for dynamic modeling, including technological changes. Hicks-neutral technological progress has been included in the Cobb-Douglas type production functions. Predicted changes of the unit load of environmental pollutants (COD, SO_2) have been also embedded (Seo & Sakawa 1979b). The dynamic problem includes 200 decision variables and 25 constraints, except upper and lower bound conditions for the decision variables. Planning horizon is over five periods. These problems have been formulated for each subregion with their particular parameters for each industry. For solving the nonlinear programming, generalized reduced gradient algorithm has been used effectively.

The NLM method has been also applied for evaluating alternative industrial land-use programs related to water quality management (Seo & Sakawa, 1980). The objective area is the Otsu River Basin in the Osaka prefecture. This area is composed of the coastal industrial complex which faces the Osaka Bay and the inland industrial area which is dispersed among residential areas. The inland area also includes agricultural areas. The systems configuration is shown in Fig. 6. In this research, a water quality simulation unit based on an ecological modeling for natural purification mechanism of water quality has been combined with a main programming unit in which mathematical programming for alternative industrial reallocation plans is solved. A dynamic loop via parameter input-solution output relationship between those units is constructed. Interventions by the upper level decision maker are executed

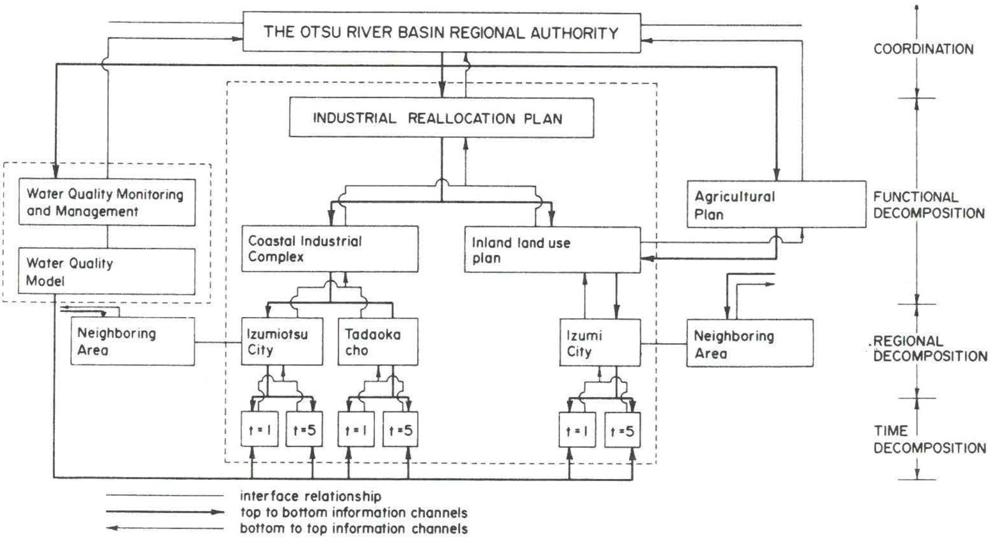

FIG. 6. Systems decomposition and hierarchical multilevel modeling for the Otsu River Basin.

sequentially via revised inputs of the control parameters (influent DO and BOD concentration) in the simulation processes of the river quality in each planning period. Thus a learning and adaptation process is embedded in the dynamic loop in the first layer. In the second layer, probability assessment for the component utility value is also performed and the multiattribute utility functions are derived and calculated in terms of expected value of the component utility functions.

INTERACTIVE COMPUTER UTILIZATION

For structuring the framework of this method with computer utilization, an interactive or conversational monitor system (CMS) is recommended. The outline is depicted in Fig. 7. Primal and dual solutions of nonlinear programming are separately saved, and then restored and utilized for calculating and assessing the multiattribute utility functions. In a feedback process for parameter setting, sensitivity analysis can be executed. Technical input factors can also be controlled by scientific policy of the decision maker in political processes.

For the MUF calculation and assessment procedure along with the sensitivity analysis, an integrated computer program is under development. The MUFCAP by Sicherman (1975) and MANECON by Schlaifer (1971) provide an excellent model. The MUFCAP especially is concerned with assessing and calculating the multiattribute utility functions. The MANECON has eminent characteristics for assessing single attribute utility functions and various types of probability distributions. A new computer program ICOPSS/I (Interactive computer program for subjective systems) has been presented based on both MAFCAP and MANECON (Sakawa & Seo, 1980). This program is also utilized in the computational structure of the nested Lagrangian multiplier method.

CONCLUSIONS

The nested Lagrangian multiplier method is one approach which aims to consolidate the analytical and the subjective phase of decision-making processes. The method also includes devices for evaluating noncommensurable attributes in a commensurate term and for compromising each evaluation which is often in conflict with each other. Because the numerical values of the shadow prices correspond to preference ordering of the decision maker, the values are used as inverse images of component utility functions. Multiattribute utility analysis depends on preferential as well as utility independence assumption. The system decomposition procedure in this new method will contribute to avoiding this difficulty because the value of the Lagrangian multiplier exclusively depends on each constraint of the independently constructed subproblem.

According to the duality of mathematical

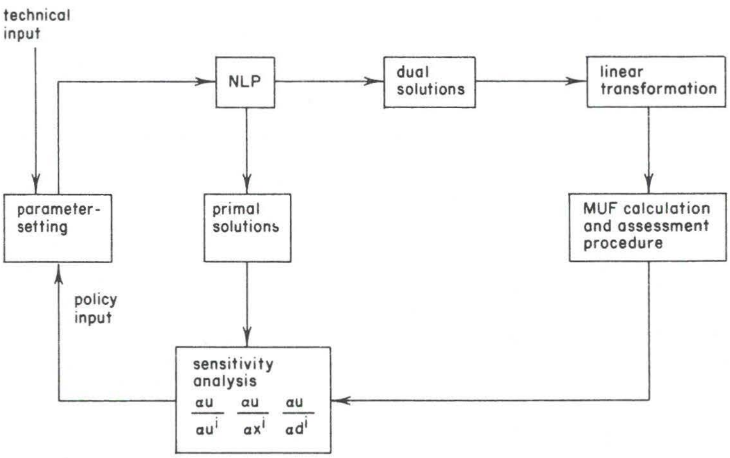

FIG. 7. Computational structure for the nested Lagrangian methods.

programming, optimal resource allocation problems can be solved simultaneously along with the systems evaluations. Thus, with this method, primal implications of alternative policy plans are compared with each other along with their evaluations on duality. This is a good characteristic of this method. However, we particularly intend to find trouble spots for carrying out any special policies which will be imposed by the "upper level" decision maker. The utility concept is used for measuring and comparing numerically the degree of satisfaction for alternative policy plans in a hierarchical configuration.

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