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SYSTEMS METHODS IN NATURAL RESOURCE ECONOMICS

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1. INTRODUCTION

Concern about the environment and the supplies of extractive resources available from it is not a recent phenomenon. Indeed, the study of natural resources has a rich tradition in the field of economics. Malthus (1798) and Ricardo (1817), for example, sketched a dismal picture in which population and economic growth would continue until population was checked by increasing misery, given fixed quantities of land suitable for the production of food. This early "limits to growth" concern was extended to mineral resources by Jevons (1865), who worried about the quantity of known coal deposits in England over one hundred years ago. Mill's (1865) emphasis on quality of life aspects derivable from the environment was a logical outgrowth of these early concerns about extractive uses of the environment.

Several decades ago, Ciriacy-Wantrup (1952) distinguished between renewable and non-renewable extractive resources on the basis of existence or economically significant rates of regeneration. The more recent literature has developed, in a more formalized context, theories for optimal exploitation of natural resources, emphasizing the difficult problems of intertemporal production and technology; measures of benefits, utility functionals and appropriate rates of time discount; and problems presented by common property and externalities of production and consumption. More modern models incorporate the uncertainty associated with use of renewable and non-renewable resources and provisions for learning about the technology of production and the benefits function on which the time allocation process is based (Rausser,
Willis and Frick [1972], Rausser and Howitt [1975]). Much of this work establishes the relationship between the natural resource problem and the problem of stochastic control (Tse [1975], Athans [1972], Joseph and Tou [1961]).

These formulations of natural resource problems in a control theory framework are of interest in at least two respects. First, they emphasize the complexity of the natural resource exploitation and allocation problems as presently perceived. At the core of this movement to more flexible models is an enlarged view of the concept of a natural resource. From emphasis on land, extractable minerals and timber, the subjects for natural resource studies have expanded to include air, the environment, wilderness, bodies of water, quality of life, and other resources. These diverse and changing topics of interest for study suggest extreme care in defining natural resource economics. Obviously it concerns problems of exploitation, allocation, production and distribution of natural resources. But perceptions of what constitutes a natural resource have changed or at least expanded.

In general, natural resources are often regarded as primary factors (Gaffney [1967], Krutilla [1967], Smith [1968]). Nevertheless, it seems clear that the concern for natural resources is very much a function of the point in time at which the related system is studied. Resources are not merely physical substances, but rather are products and manifestations of a continuing interaction between man and nature (Zimmermann [1951]). The systems describing both the behavior of man and relations existing in nature, and their interactions, clearly fall within purview of resource economics. Recognition of this fundamental aspect of resource economics serves to
establish its connection with systems concepts and the analytical constructs developed for their study.

The second feature of interest in examining modern models for studying natural resources relates to their technical or engineering aspects. All include as basic inputs detailed structures describing biological and physical processes. The appropriate framework for developing these structures traditionally has been that of a system (Clawson [1968], Herfindahl and Kneese [1974], Nordhaus [1973]). This is particularly evident in the applied work on resource problems. The use of systems concepts can be explicitly found in the River Basin Studies of Halter and Miller [1966], Hufschmidt and Fiering [1966] and Hamilton, et al. [1969]. In a number of respects these studies have drawn on the systems framework, specialized for resource problems by Maass, et al. [1962] and Dorfman [1965]. It should also be noted that this approach, although with a somewhat different terminology, was present in the early applied work on development of natural resources (Hufschmidt [1963]). Thus, from the appropriate framework for defining resources to that for developing physical and biological structures for use in applied work, systems concepts have occupied an important role.

The purpose of this paper is to document the importance of systems concepts in the analysis of resource economics problems. It will show that the modern work extending systems concepts to economic dimensions of natural resource problems has involved some expense in the sense that it extends beyond the range of available general economic theory. For this reason, results of the associated applications must often be viewed as highly specialized to the problems at hand and the persons developing the models. The discussion concludes by suggesting a solution to the dilemma presented by
the apparent suitability of the systems framework for studying natural re-
source problems in economics.

In order to provide an overview of the use of systems concepts in nat-
ural resource economics, and to offer suggestions of future directions, it
is useful to provide definitional frameworks for both systems concepts and
natural resource economics. In particular, since there is dazzling varia-
tion in definitions of concepts in the literature on systems methods, we
define in Section 2 the systems concepts as they will be used in the succeed-
ing discussion. Moreover, it should be useful, particularly to non-economists
to present a brief discussion on why natural resource economics is different
from other branches of economics; to identify those dimensions which distin-
guish it from the topics of the other papers in this issue. This treatment
is developed in Section 3. Selected, illustrative applications of systems
methods in the economics of natural resources are provided in Section 4 and
the final section, 5, provides an appraisal and assessment of future direc-
tions for modeling efforts and policy analysis for natural resources.
2. SYSTEMS METHODS, STRATEGIES FOR MODEL DEVELOPMENT AND APPLICATIONS

Natural resource systems and models are special in a number of respects. The basic features of these systems emphasize the importance of considering particular types of model construction and operational methods. First, problems of optimal utilization of natural resources are intrinsically dynamic. Current actions have delayed impacts on the objective functional. Moreover, they are sufficiently complex that assumptions facilitating simplifying decompositions are often restrictive. Planning horizons are long compared to those for most economic models, and there is often a comparatively substantial degree of uncertainty about the structure of the system and initial conditions (stocks) in the current time period. Finally, the models typically require the merging of physical, biological and economic systems. The result is that for most purposes, the models of such natural resources systems evolve through time whether actively or passively integrated into the optimization process.

As Mar [1973] suggests, a discussion of model development is difficult due largely to the diverse and inconsistent sets of nomenclature used to describe models, their characteristics, and uses in the various disciplines. Cited examples include Shubik and Brewer [1972], who view models as subroutines used in simulations; Raser [1969], who considers simulation a type of model; and Meier, Newell and Pazer [1969], who regard simulation as the manipulation of models. This section presents a cursory review of the basic systems concepts, model types, and model construction and application processes, with the purpose of establishing a consistent set of nomenclature.
2.1 Systems Methods and Model Construction. In the construction and use of quantitative economic systems models, activities which must be accomplished may be identified as analysis, synthesis, and design. Systems analysis is largely a descriptive stage of the model construction process; it is a process by which an investigator with a specific problem and objectives in mind initiates the modeling and/or research process. The system in question is observed and the investigator's perceptions of the problem under investigation is sharpened. Generally, this process is one in which the elements or components of the system are identified; the current and alternative institutional frameworks are isolated; the principal decision-makers are specified along with their decision variables, performance criteria measures, and the relationship between the decision variables and performance measures. The size and scope of the model, the level of abstraction appropriate for the question under study, and sources of information and data must be determined in the system's analysis phase. Finally, is the decision-maker or decision group's criterion function of all the relevant performance measures explicit or implicit?

Systems synthesis activities involve identifying and classifying the components as to function; specifying the environmental considerations; distilling the behavioral hypotheses; and determining the quantitative relationships between and within components of the system. This is the juncture at which the investigator's perception of the system in terms of modeling objectives must be formalized. In essence, it is the process which provides the model with a cohesive structure.

In the systems design stage, we generally find research objectives and elements of the model structured in such a way as to allow analysis of
alternative policy strategies. However, depending upon the objectives of the analysis, the design may be simply an hypothesis as to the working of the system, the structure of a decision model or a particular forecasting mechanism. In this regard, it is important to distinguish between the more utilitarian design problems within the model (strategic or tactical questions) and those which involve maintained hypotheses as to the function of the system (institutional questions). In essence, this process involves selecting the framework within which market, regulatory, structural, and institutional changes of systems are to be examined. Alternatively, design may be viewed as a process of choosing a format for combining the synthesized system components and relationships to satisfy modeling objectives. In any event, design determines the institutional framework, which in turn constrains the sorts of strategic or policy evaluations performed with the model representation. From an operational standpoint, design issues become particularly crucial in the use and construction of decision support systems based upon formal models.

The actual construction of the model can be viewed in terms of five essential steps. These steps are model specification, estimation, verification, validation, and revision. Specification generally occurs after the system has been analyzed and is one of the activities of systems synthesis. Structures deduced upon accepted normative propositions and established technical relationships have greater generality, given that the paradigm governing the modeling process is appropriate. Models of this type are more easily tested and are usually less complex structurally. Alternatively, there are highly specialized models of the type encountered in natural resource economics based largely on less refined propositions. The process is
one of observing the system and formulating (in abstract form) the behavioral and other structural relations. A difficulty with these more specialized models is that they can become highly personalized.

For quantitative models, specification involves a mathematical structure and an operating model. In the case of natural resource models, the relevant equations include behavioral, identity, and technical relationships. The behavioral equations attempt to represent the response of participants (represented by endogenous variables) within the system to economic and other signals (explanatory variables). The identity or technical equations imply exact relationships determined largely by engineering or physical phenomena.

Once the model has been specified, parameters summarizing the effects of certain variables on others must be estimated. Parameters may be estimated using a number of methods. Generally, systems models either rely heavily upon statistical methods, or reject the data because (i) it is inappropriate (Forrester [1961, 1968]); (ii) it involves substantial error (due to the sampling process generating the data); or (iii) of suspected structural change. Because of the diversity of possible estimation methods both in terms of information sources and iterative procedures involved (Wallace and Asher [1962]), a rather general framework is needed for viewing the process of estimation. Appropriate approaches include Bayesian (Zellner [1971] and Zellner and Chetty [1965]) or Mixed Estimation methods (Aitchison and Silvey [1958], Judge and Yancey [1969] and Theil [1970]). In both instances, sample data and extraneous information on parameter distributions are systematically combined to obtain estimates of the structure. Recent advances in Mixed and Bayesian estimation techniques also admit evolving structures with non-stationary parameters (Eldor and Koppell [1971], Freebairn
and Rausser [1976]). These data and non-data oriented estimation processes are essentially the same, with the difference a matter of the relative certainty with which the extraneous estimates of the parameters are held.

In addition to their appeal for the data source problem, the Bayesian and Mixed Estimation approaches are sufficiently general to provide for the incorporation of interactive procedures frequently used in choosing among model specifications (Rausser and Johnson [1975]). In the context of these difficulties, the Bayesian approach has been argued to be the more viable alternative for selecting among model specifications (Dhrymes, et al. [1972]). Leamer [1970] has explored the implications of alternative weighting functions in this context and Zellner [1971, pp. 306-317] has provided a general outline of Bayesian procedures for comparing and choosing among models. A useful summary and comparison of Bayesian and Classical procedures for discriminating among alternative specifications of single equation models, which reveals some promising developments, has been presented by Claver and Giesel [1972].

Lastly, parameter estimation is also influenced if models are adaptive. Many times systems models are constructed, estimated and simulated and while this process is evolving, additional data on the structure become available (indeed, may be actively sought). Results which may be of value in this context are contained in Aoki [1975], Chow [1975], Prescott [1972], Zellner [1971], Rausser and Freebairn [1974a], and Tse [1974].

Verification is the process by which the investigator determines whether or not the model performs in accordance with the intended purpose. For example, in algebraic models verification is concerned with completeness, existence of solutions, internal functioning and so forth. The most common
use of the term, however, appears in conjunction with digital computer models and/or analogs. Used in this connection the term relates to establishment of desired isomorphic relationships between system, model, and digital analog.

The process of corroborating the model with the system is called validation. This is clearly a judgmental process. First, if the requirement is a close corroboration with the system, how should data on the functioning of the system be summarized and compared to outputs of the model for tests of consistency? Secondly, how important is prior information relative to the data on the system and how should these two types of information be combined in corroborating the model? Third, at a more philosophical level, what framework should be employed to determine which hypotheses on the system are to be tested and which are maintained?

The four preceding steps may be final or provisional. In a provisional process the fifth or revision step is concerned with an assessment as to whether or not the model should be altered to make it more suitable for the intended objectives. Whatever the revisions, it is important to systematically specify the sources of information and the method for using the information to change the model. It is unfortunately not often recognized that such conditions are as much a part of the prior information used to construct the model as the more frequently discussed theoretical underpinnings and data sources.

Perhaps the single most important aspect of the modeling process is that it is an iterative one. If the model does not forecast the behavior of a particular variable reasonably well, or if the model does not provide the type of answers needed given the policy questions posed, then the construction should return to an earlier stage either to improve the model specification.
or to suggest that other types of policy questions be asked. To be sure, each of these phases is reversible; i.e., the research investigator can, for example, complete phases one and two and move back to a revision of phase one before going on to phase three. Nevertheless, it is important to recognize the opportunity cost in terms of inefficient strategies with respect to unstructured movements from one phase to another.

The cumulative implications of the above observations on the model construction process suggest that from a research strategy standpoint it is important to explicitly recognize the entire modeling process. Researchers begin with concepts from theory, results of other applied work, perhaps personal views and historical data on the system to develop a provisional specification. Given constraints which exist with respect to resources available for the research project, the time frame within which the research is planned, etc., the analyst proceeds from one provisional specification to another until a version of the model is available which, given the constraints, satisfies the objectives of the research endeavor. The objectives of the research projects are usually stated rather clearly, and research expense allocations, time and other constraints are also known with a fair degree of certainty.

By recognizing the process of proceeding from one provisional structure to another as a transition between states in the implicit control problem and making more explicit the policy or strategy governing the evolution to the final version of the model, research involving natural resource systems models can be placed on a sounder scientific footing. The availability of such information on model construction together with formalization of the implicit control problem provides a firm basis for critical appraisal of the
resulting formulation and at the same time establishes the foundation for a more systematic process of knowledge accumulation.

The entire model-building procedure is represented in Figure 1. As represented here, systems analysis is composed of isolating (i) the problem to be solved; (ii) alternative institutional frameworks; (iii) the decision-makers; (iv) the decision or policy variables; (v) the performance measures; (vi) the system's components and relationships, and (vii) the nature of the criterion function. System's synthesis is largely concerned with model construction activities while system's design is concerned with the actual use of the model as a decision-making aid on a timely and interactive basis. Finally, note the iterative nature of the modeling process.

2.2 Model Representations. The above steps in model construction are heavily conditioned upon the objectives or purposes for which model representations are developed. Clearly, models can be developed for a number of purposes, some of which do not necessarily correspond to the purposeful functioning of the system under examination. Depending upon research objectives, the investigator may use descriptive, explanatory, or predictive models.

Most descriptive models are exploratory in nature. The researcher observes a system and constructs a model designed to describe the functioning of the system. That is, "a descriptive model simply sets forth a set of relationships which have 'bound together' different variables in situations in which they have been previously observed" (Strotz and Wold [1960, pp. 417-418]. Information developed from the model is used to understand the workings of the system and support inferences under alternative assumptions as to conditioning by the environmental factors. Descriptive models have been
Figure 1
Modeling Process for Decision-Making Purposes

1. Problem to be solved
2. Alternative and current institutional setting
3. Who are the decision-makers?
4. Are the decision or policy variables explicit?
5. Are the performance measures explicit?
6. What are the components of the system, interactions among components, and relationships between decision variables and performance measures?
7. Is the criterion or objective function explicit or implicit?

1. Model specification
2. Data use and model estimation
3. Model verification
4. Model validation
5. Model revision
6. Model use
rather widely employed in studies of natural resource systems; a phenomenon in part attributable to the behavioral bent of the social sciences. Among those who have advanced and developed descriptive modeling techniques are Forrester [1971] and Meadows, Randers and Bhrens [1972].

Explanatory models are constructed with objectives similar to those for the descriptive case. The principal distinction is that explanatory models are causal in nature, where causality is defined in the Strotz and Wold [1960] sense. That is, in the statistical sense, "Z is a cause of Y if, by hypothesis, it is or 'would be' possible by controlling Z indirectly to control Y, at least stochastically". Relationships specified in these models involve assumptions as to the direction of influence of the variables. Hence, these models are chiefly concerned with the isolation and refinement of causal relationships and tests of implications vis-à-vis the observed system and the a priori theories. The objectives emphasized in these modeling endeavors are, therefore, internal consistency and tests of competing hypotheses on the behavioral or other mechanism driving the system.

Forecasting and prediction are important functions of modeling efforts in natural resource economics as in other policy sciences. Predictions of price movements, levels for stocks and usage, technology adoption rates, delayed impacts, maximum sustainable yields and similar policy questions are illustrative of the important roles of these modeling approaches. There is generally less concern with internal workings than with providing accurate forecasts in these models. This is particularly true in situations in which dynamic models are constructed to deal with short-run forecasting problems (Gross and Ray [1965]).
Decision problems for natural resource systems have a generally accepted set of components. As usually conceived, these problems involve controllable and environmental variables, objective functions and structures which relate the controlled and environmental variables to output variables (Fox, Sengupta and Thorbecke [1966]). The model specified as an optimizing problem, is used as a basis for policy prescriptions for the system. As a consequence research efforts are concerned with both the implications of the optimizing solutions and the accuracy with which the model portrays the system. When expressed in a dynamic context, these two problems can be productively viewed in adaptive and/or dual control theory frameworks (Rausser and Freebairn [1974a]; Tse [1974]).

Decision problems may be usefully grouped into two major types: regulatory and structural or institutional. Regulatory decision models are developed for policy questions given a particular institutional and environmental structure (Haitovsky and Wallace [1972]). For institutional decision models, the structure itself is allowed to vary and thus the larger questions on the organization of the general system within which the subsystems operate are considered. Frequently, these connections and identifications between subsystems have been prescribed by physical and economic paradigms (Kuhn [1970]). An example from economics is one in which time rates of discount have been mechanically applied to determine present values. In the final analysis, of course, the principal reason for constructing natural resource models is to improve public or private decision-making processes. For models to be useful in this regard, their causal or explanatory properties must be sound and their forecasting on predictive performance must be reasonably accurate.
2.3 Model Evaluation and Solution Methods. A number of alternative approaches for model evaluation and solving for one purpose or another are available. They might be characterized as analytical, analytical simulation, and ad hoc simulation methods. Although identified as alternatives, it is important to recognize that the options are simply points on a continuum—ranging from completely analytical (in the sense of closed-form solutions) to ad hoc or exploratory simulations. The usual approach to model analysis of systems would involve a combination of experimental methods with some structuring suggested by analytical considerations associated with the problem.

To indicate the framework in which these alternative approaches are employed, suppose that the system under consideration has been studied and that a model has been formulated. Furthermore, suppose that the checks on the functioning of the model or analog have been performed on the parameters of the estimated model and that the usual tests of predictive capability have been made. In many situations, even after these stock preliminaries, the researcher is likely to require further evidence on the adequacy of the model. That is, in addition to these preliminary tests and checks, a more extended evaluation of the model is necessary. The inconclusiveness of these preliminary checks and tests may be due to both model specification and data problems. In the former case, theory inadequacy and the related array of alternative models present substantial problems. Checks of logical consistency and classical statistical tests provide little guidance in such situations. To complicate matters further, economic data describing the system, but not used in the estimation—which itself may involve a nonsystematic combination of subjective and observed information—are often not available for evaluating
predictive performance. The application of classical statistical tests in these situations thus requires considerable confidence in their robustness.

The additional evaluations may be performed by one of the three alternative approaches suggested above. Once the researcher is satisfied with the corroborative power of the model, the decision analysis based on the model may be conducted, again, through application of one of the three alternative methods. As factors affecting the choice among these alternatives are in a number of instances similar, the discussion of approaches may be integrated with respect to function.

2.3.1 Analytical Methods. Analytical methods are those using information derived from isomorphic representations of the model structure or closed-form solutions. Evaluative procedures include those for determining properties of the models and for attempting to corroborate them with observed or prior information on the system. Decision analysis methods include the traditional optimization procedures for static and dynamic models.

The process of evaluation and analysis within this mode proceeds in accordance with clearly defined ground rules. Methods of mathematical analysis are applied in determining an isomorphic characterization of the response surface for the internally determined variables. Properties of the model's time dimension are inferred from solutions of the difference or differential equations represented. Properties so obtained are then compared to the prior or observed information on the system, summarized to conform to the analytically obtained results. This comparison provides the basis for conclusions drawn on the validity of the constructed model.
Once a valid structure for the model has been found, the decision problem may be contemplated. The element required for completeness of the model at this stage is an explicit utility or criterion function. With the explicit criterion or utility function an optimization method consistent with the structural characteristics of the model and objective function is employed to derive a solution or strategy.

2.3.2 Analytical Simulation Methods. These methods may be applied to models sufficiently complex that exact solutions or isomorphic representations for isolating internal properties and optimal decisions are not feasible or, as viewed from the opposite end of the aforementioned continuum, when the structure and objectives of the modeling process are sufficiently identified to suggest systematized experimental processes. Under these conditions response surfaces are "estimated" on the basis of outcomes of experiments designed according to a structure on the externally determined variables and parameters. Properties of the estimated response surface are then compared with prior and observed information (the latter again summarized in a comparable form) as a basis for corroborating the model. Procedures which are, in principle, similar to those suggested for the response surface examinations are employed for the assessment of dynamic properties.

Decision analysis can also be conducted in an analytical, experimental mode. Information developed through experiments with combinations of control and noncontrollable or externally determined variables, selected according to grid coordinates, may be used to approximate optimal solutions or strategies. Optimum seeking or policy improvement procedures used in connection with model experiments may also be viewed as types of analytical
solutions. As before, solution approximations obtained in this manner can be investigated for sensitivity to changes in model structure and criterion functions.

2.3.3 Ad Hoc Simulation Methods. This approach involves evaluation and decision analysis procedures which are explanatory or are applied without an explicitly formulated research strategy. Response surface properties and dynamic characteristics of the model in this case are usually inferred on the basis of experiments chosen in an intuitive rather than a structured fashion. Policy analysis proceeds similarly. Since there is no explicit objective function, experiments are made with settings of controls, parameters, and levels of externally determined variables which are intuitively based or suggested by past activities within the system. Policies or decisions are then somehow selected (by the policy maker, given his own preference patterns and those of the modeler which are implicit in the selection of the outcomes of the model presented as alternatives) on the basis of the comparative performance of the experiments or simulations conducted.

Advantages and disadvantages of the alternative approaches are, of course, dependent on the characteristics of the systems or models under examination. However, putting aside the capabilities of the research and/or costs associated with the alternative approaches identified, there are compelling reasons for research strategies which maximize the analytical content of the results. This point has been argued effectively in a Department of Defense critique [1973, pp. 19-22] which on pragmatic grounds suggests that ad hoc simulations of quantitative models fail to minimize dependence on intuition in decision making. A similar argument at a more abstract level
has been made by Chow [1973b] in developing a conceptual framework for the use of optimal control procedures in the analysis of economic policy problems.

The two most important characteristics with regard to types of models are (i) whether or not the model is stochastic and (ii) whether the model is linear or nonlinear. The choice of research strategy is highly dependent on these two characteristics of the model. As demonstrated elsewhere (Rausser and Johnson [1975]), when models become more stochastic and nonlinear, the comparative advantage of analytical simulation and ad hoc simulation methods increases. One should be careful, however, in concluding that, just because numerical results can be obtained for these more complicated models by ad hoc simulation, such an approach is more productive.

2.4 Model Use. Model construction and use are in principle similar problems. For the various model types, objectives of the application can be specified. Although this is most natural for decision models, it applies as well to the other model types. Because the natural resource systems models are often large and complicated in structure, the derivation of solutions for applied implications on an analytical basis is not a practical possibility. The result is a procedure whereby the solution is approximated by experimenting with different predetermined strategies; viz., simulation procedures. Methods for simulating solutions to natural resource systems models generally range from ad hoc trials to more highly structured procedures involving numerical approximations and directly employing techniques of optimum search and experimental design; i.e., analytical simulation. Given the purposeful intent of model applications, it is beneficial to systematize choices
of design points. This observation follows since the simulation processes are viewed in an optimizing or control theoretic framework.

Sensitivity analysis is simply the process of gathering information with which to evaluate the robustness of particular decisions taken in applying models (Maffei [1958]). Interest is directed to where doubt, uncertainty and ignorance are greatest. Policies very sensitive to changes in assumptions about which there is substantial uncertainty will warrant skepticism. In this regard, a useful distinction to keep in mind is the difference between local and global sensitivity (Zellner and Peck [1973]). In a local sense, many models may be insensitive to changes in exogenous factors, parameters, etc., but very sensitive to such changes in a global sense. Selecting the trials or experiments to be conducted in a sensitivity examination for particular policies involves a choice between *ad hoc* and formal experimental design settings (Hufschmidt [1962] and Hunter and Naylor [1970]). Application of experimental design methods to problems of model sensitivity have recently received increased attention. Naylor [1970], Ignall [1972], Naylor, et al. [1967], and Zellner and Peck [1973] are illustrative of these methods and the types of results that can be obtained. Methods employed in designing the related experiments have been routine. Complete factorial experiments are by far the most common, although more sophisticated designs can be employed (Kleijnen [1974]). The advantage of the more specialized design techniques is that trade-offs are known in advance (Handscomb [1968]). Since it is known in advance which hypotheses are maintained, the testable features of the design should be chosen accordingly (John [1971], Mendenhall [1970] and Kleijnen [1974, 1975]).
Response surfaces are simply functional relationships between parameters, environmental variables, structural choices, and perhaps, criterion functions and internally determined variables (Naylor and Budrick [1969], Box [1954], Burt [1966, 1967, 1964], Hufschmidt [1962]). Such surfaces are useful in applying models for several purposes; especially forecasting and decision uses. As with sensitivity analysis it is important to recognize that when such relationships cannot be obtained as closed-form solutions, numerical approximation procedures must be employed. The more recent work on response surfaces dates from important papers by Box and Wilson [1951] and Box [1954]. These and related works contain clear statements of the approach to response surface examination and sequential experimental designs (Davies [1954], Hill and Hunter [1960], Chernoff [1972]). Less structured types of procedures are due to Box [1957] and Box and Hunter [1959]. These designs explore response surfaces by first estimating them for restricted regions and then moving to estimate other regions on the basis of the information obtained.\(^6\) In a related context, a number of policy improvement or optimizing techniques are available (Emshoff and Sisson [1970]). These often involve sequential designs which begin with an extensive search via simple exploratory experiments arranged so as to converge towards some peak (or valley) of the surface and subsequently switch to intensive search methods as the optimum is approached (Cochran and Cox [1957], Mihram [1972], and Conlisk and Watts [1969]).

The connection between response surfaces and solutions to resource systems models is easily seen when it is recognized that the surface may be defined in terms of the application objective. For decision problems, these objectives are easily determined. For forecasting, behavioral and descriptive
models application objectives are generally specific to the problem at hand. Since natural resource research is undertaken with a purpose, the uses of response surface and sensitivity analysis techniques in achieving this purpose are obvious once it is formalized. Moreover, it should be apparent that an optimization problem is implicitly involved in all model applications.
3. SPECIAL FEATURES OF RESOURCE SYSTEMS AND POLICY PROBLEMS

It was indicated earlier that there are certain characteristics of natural resource systems and policy problems which combine to distinguish them from most other economic models. These include complexity, external effects, long planning horizons, and problems of information bases for structures and initial conditions. Some elaboration and further enumeration of the special characteristics of resource systems and models are presented in this section.

3.1 Resource Systems. As previously noted, natural resources are typically regarded as renewable or non-renewable (exhaustible). Each of these classes of extractive resources possesses its own peculiar characteristics relevant to the topic at hand. These are treated seriatim below.

Fisheries, forests, and water serve as examples of renewable resources; resources which exhibit economically significant rates of regeneration. Following the lead of Peterson and Fisher (1976), we use fisheries to illustrate the distinguishing characteristics of the renewable resource. While Clark and Munro (1975) highlight the resemblance of fisheries models to modern capital theory, there are critical differences as well. The first peculiarity of models involving biological species related to their natural regeneration processes, or biological growth functions. Thus, extraction of these resources differs from other production processes since yields in any period influence subsequent yields by changing the stock of remaining resources. Indeed, production functions for a single renewable resource typically include three factors: time, to allow for technological progress; some measure of effort (say, fishing); and resource stocks. Much of this
literature is of the exploratory type, since the production functions in this class of natural resources literature have been assigned all sorts of functional forms, with justification seldom provided.

In response to questions like: (1) What is the optimal rate of fishing effort? (2) Does this rate correspond with maximum sustainable yield? (3) Will extinction occur under normal conditions? (4) Is this bad? (5) Does optimal behavior correspond with behavior under a competitive regime?, some of the most intricate and interesting models in economics have been developed. These models exhibit multiple equilibria, involve dynamic optimization, recognize externalities, and examine resource exploitation under various institutional structures and policies.

Another distinguishing characteristic of natural resource models is the presence and importance of the user cost concept--the decrease in the value of an asset associated with use. In the fisheries example, the marginal user cost (shadow price) of fish in their natural state is the quantity by which the present value of the fishery at that point in time is diminished by the removal of one unit of the fish resource. This quantity is not generally observable, but rather must be imputed using present and projected prices, technologies, and stocks of the resource.

The prevalence of the common property status and problem is a further distinguishing characteristic, which interacts with and magnifies some of the other peculiarities of natural resources problems. Gordon's [1954] seminal paper on this subject shows that in the absence of cooperative agreements, firms in a common property fishery will enter and exit freely and drive rents to zero in the process. Congestion externalities created and user costs associated with depleting fish stocks will be ignored by the
individual firms, generally resulting in greater effort and lower stocks than are optimal.

More formally, the essence of the renewable resource use problem can be illustrated with a simple model of a single biological species. The type of illustration which follows is generally attributed to Schaefer [1954] and is rather widely used in recent natural resource economics literature. It assumes that the rate of change of the species stock, \( \frac{dS}{dt} \), is a function of the current stock:

\[
(1) \quad \frac{dS}{dt} = g(S),
\]

such that \( g(S) \) has two roots; viz., the species stock is in equilibrium \( \left( \frac{dS}{dt} = 0 \right) \) at \( S = S_e \), the minimum biologically viable species stock below which extinction would occur, and at \( S = S_m \), the maximum species population sustainable by the environment. The functional \( \frac{dS}{dt} \) is positive for stocks between \( S_e \) and \( S_m \) and is maximum at \( S_s \), the maximum sustainable yield for the species. It is worth noting that a fairly sizable amount of literature has been devoted to showing why when \( S_s \) is the maximum rate of exploitation of a species that can be sustained indefinitely, it may not be the economically optimal rate of resource use.

Since the extraction of renewable resources involves an instance in which current yields affect future yields by altering the remaining species stock, it has become commonplace to use a production function to describe the extractive process. This function generally takes the form \( f(E, S, t) \), where \( E \) is an index of capital, labor, and other input quantities used in extraction, and referred to simply as effort, and the presence of time, \( t \), allows for the possibility of technical progress. The inclusion of \( S \) is for
the reason suggested above, and when the resource is a common property this presence leads to inefficiencies and conflict.

The present value of the resource can then be expressed by the integral:

\[ (2) \int_{0}^{\infty} [p f(E, X, t) - w E] e^{-rt} dt, \]

where \( r \) is the discount rate and \( p, w \) are respectively output and effort prices assumed constant (competitive product and factor markets). This present value is then maximized subject to the system equation:

\[ (3) \frac{dS}{dt} = g(S) - f(E, S, t), \]

and side constraints that \( S_m > S > 0 \) and \( E > 0 \). For this, it is necessary that the current value Hamiltonian:

\[ (4) H = p f(E, S, t) - w E + \lambda [g(S) - f(E, S, t)] \]

be instantaneously maximized, where \( \lambda \) is the marginal user cost of the species in its habitat; i.e., the reduction in the present value of the species at time \( t \) occasioned by the removal of an additional unit of the species.

To maximize (4), the partial derivative with respect to the control variable, effort, is set to zero:

\[ (5) H_E = p f_E - w - \lambda f_E = 0. \]

Clearly, price \( p \) equals marginal extraction cost \( w + f_E \) plus marginal user cost \( \lambda \). The presence of the value \( \lambda \) in this condition then clearly differentiates this case from the optimizing conditions with non-extractive commodities.

To maximize the present value of the resource (2), it is also necessary that the time path of \( \lambda \) be governed by the differential equation:
This equation provides that the capital gain from an additional unit of the species \(\frac{d\lambda}{dt} = -H_S + r \lambda = -p f_S - \lambda g_S + \lambda f_S + r \lambda\) plus the marginal revenues generated \((p f_S)\) plus the value of the additional growth \((\lambda g_S)\) equals the user cost of the extra output generated \((\lambda f_S)\) plus the opportunity cost of the natural species \((r \lambda)\). If not, if the species were more or less attractive as compared with other investments, then the price \(\lambda\) would be bid up or down by the investors.

Models of non-renewable resources, like oil, coal, and minerals, also possess a number of distinguishing characteristics. Frameworks for these resources involve optimally depleting a stock, with no significant natural regenerative possibilities and recycling (artificial regeneration) limited by economic as well as natural processes. For this reason, the theory underlying these models have been termed "theory of the mine".

One characteristic for this class of resources which is similar to renewable resources but not other production processes is that user costs should be considered alongside extraction costs in deciding stock depletion rates. That is, for non-renewable resources user costs (determined by the future time paths of prices and costs) represent an endogenous depreciation cost as contrasted with the usual notion of depreciation which depends only on the passage of time.

The essence of the exhaustible resource extraction problem can be illustrated by a simple model. For comparison with the renewable resources problem we again adopt the production function approach of Peterson and Fisher [1977] rather than the cost function models of Gordon [1967] and Cummings [1969].
Using the same notation, yield for a particular tract, \( f(E, S, t) \), depends on effort, time, and stock of remaining resources. At \( t \), the tract has its initial stock \( S_0 \) less cumulative extraction; so that

\[
S(t) = S_0 - \int_0^t Y(\gamma) \, d\gamma
\]

For the exhaustible resource problem, the conditions are the same as for the renewable resource model except for the biological growth function. Denoting again by \( p \) and \( w \) the prices of output and effort, (2) is the present value integral, (3) is the system equation, (4) is the Hamiltonian, and (5) and (6) are the necessary conditions, where \( g(S) \) is omitted from each equation. The interpretations are similar as well. For example, (5) determines the rate of mineral extraction and (6) provides for an adjusting \( \lambda \) which maintains the attractiveness of mineral stocks equally with other investment goods.

If exploration is important in a particular exhaustible resource, models of extraction become more complex (Koopmans [1973], Peterson and Fisher [1976]). There are numerous motives for exploration, of course. Monopolists may wish to discover deposits in part to raise barriers to entry by keeping these stocks out of the market. Alternatively, firms may devote too few resources to exploration due to the uncompensated external benefits of the information they supply others in the process.

While uncertainty is not exclusive to the domain of natural resource systems, it is difficult to imagine areas in which uncertainty plays as large a role as, for example, drilling decisions for oil and natural gas. The uncertainties of supply--location, quantities, quality--are enormous. The rather substantial volume of recent literature on bidding models is
relevant here. A potential lessee of a mineral bearing property wishes to
know its worth and how much to pay. When the price is determined by auction,
a bidding strategy is involved. Recent studies to assess the implications
of factors such as number of bidders, whether bidders collude, and whether
bids are open or closed include Wilson [1975], Williams [1975], Gaskins and
Vann [1975], and Leland [1975]. One interesting suggestion from this work
is that asymmetries in information among firms can lead to inefficiencies
and that often prospective lessees are led to inefficiently gather excessive
duplicate information to reduce uncertainty and gain an edge in sales of
leases. There is strong evidence of this phenomenon of excessive informa-
tion gathering preparatory to development of the U. S. outer continental
shelf.

In addition, since the value of a stock depends on the stream of future
prices, there are substantial uncertainties on the demand side as well.
But this is just the beginning—uncertainty as regards future demands is
compounded by the fact that substitutes and new technologies may develop
(Dasgupta and Stiglitz [1975], Peterson and Fisher [1976]).

One type of substitute for some of these extractive resources is repre-
sented by the secondary materials from recycling. Some have argued (e.g.,
Weinstein and Zeckhauser [1974]) that in the absence of externalities asso-
ciated with waste disposal, the free market results in optimal levels of
recycling activities. However, such absences are not often in the real
world and thus these externalities are clearly important and should be taken
into account. Since recycling acts in both the role of substituting for ex-
ahaustible resources and in reducing pollution, failure to recognize these
externalities leads to an under-allocation of resources to the recycling
activity. We will return to this link between extraction and the environment below.

A characteristic of some of the most recent contributions to the literature in extractive resources is that rather than operating from the paradigm of the behavior of a firm out to maximize the present value of a resource, they presume the view of a planner seeking to optimize some more broadly conceived social welfare function. Questions arise concerning inter-generational welfare. Should utilities be discounted? How can we justify depriving one generation because of a greater gain to another? What are the consequences of the Rawls [1971] notions of distributive justice wherein a "maxi-min" criterion is adopted, where social welfare is established on the basis of the least privileged generation, for growth, capital formation, etc.?

Finally, a distinguishing characteristic of models of natural resources is the importance of information from other disciplines. As Peterson and Fisher [1976] suggest, economists presently employ geological and engineering information in their natural resource models and recently "there has been a flurry of activity". Examples include: Franklin Fisher [1964], Bradley [1967], Kuller and Cummings [1974], and MacAvoy and Pindyck [1975, pp. 65-79].

In brief, renewable and non-renewable natural resources have special characteristics which distinguish them from other economic processes, which stimulate different problems, questions to be posed, and give rise to more complicated modeling efforts. If a resource is exhaustible, but has a close substitute given current or foreseen technology, is it appropriate to discuss policy problems in the narrow context of exhaustibility? Is the net
effect of technology to make primary factors more suitable, as would seem

The problem of changing resource concepts is also real. Scarcity of
natural resources is a function of current technology as well as many other
social factors which are not economic in nature. As societies evolve, the
focus on particular primary inputs for production may change. How do pres-
ent policy models accommodate these types of shifts? Finally, natural re-
source issues cannot be intelligently analyzed without reference to common
property problems and external effects.

What this discussion suggests is that natural resource models are
grossly incomplete representations of the systems they attempt to duplicate.
Most ignore the substitutability problem, evolving production and consumption
decisions, and numerous externalities of production and consumption. The
models though complex and including economic, biological and physical compo-
nents are generally oversimplified. Given their future looking orientation,
current perspectives on model adequacy and even the characteristics of nat-
ural resource problems may change. In fact, changing model structures for
system representation and policy problems would seem the usual situation
rather than the exception. This means that models must include provision
for reflecting these possible changes and for updating.
4. RESOURCE SYSTEMS APPLICATIONS: A REVIEW

In the previous sections systems methods were defined, categorized and discussed and natural resource economics frameworks were characterized with special reference to identifying those special characteristics which distinguish these problems from other economic models. The present purpose is to provide a flavor of the range of applications of systems methods in natural resources. Reference is made to studies which employ simulation methods, analytical optimization, and analytical simulation. The critique of this literature is reserved for Section 5.

4.1 Simulation. In natural resources frameworks, as with other types of models, the modern applications of systems concepts and simulation methods have much historical significance. Furthermore, in contrast to the importance of simulation in the early development of other models, the emphasis in the resource literature was initially on the concept of a system. Systems concepts, growing out of the physical aspects of the problems studied and the engineering literature, found a very natural application in studies of resource problems.

Systems and simulation applications to natural resource and regional development problems often involve the public sector. As Kain and Meyer [1968] have noted, simulation is particularly useful when evaluating investments characterized by important externalities, broad social objectives and durable installations. When we add to these features, the importance of uncertainty, technological change, research and development strategies, and the sequential aspects of natural resource decision-making, computer simulation becomes an even more appealing tool (Rausser and Dean [1971a, 1971b]).
In a mechanistic sense, models of resource systems are generally dynamic and nonlinear. Some nonlinearities are fairly substantial including those involving artificial, time-counter relationships. Dynamic structures of these models are often characterized by lagged internally determined and conditioning variables and are represented by a system of difference equations. Approximately one-half of these models are simulated in stochastic form. Most stochastic simulations are limited, however, in the sense that only additive stochastic (disturbance) elements are recognized, i.e., only first moments of sampling distributions of the structural parameter estimates are used. A large number of the stochastic simulations were developed for the physical models representing hydrologic phenomena.

In Table 1, a number of empirical studies are described in terms of the authors, the situation modeled, objectives and decision variables. Reported model characteristics include model type, type of simulation, computer language used, validation procedures, and information on whether the model is dynamic, stochastic, and nonlinear. For the most part, the table is self-explanatory with respect to the listed characteristics. The three characteristics for which the conventions adopted may require elaboration are validation, type of simulation and the competitive versus non-competitive classification for gaming models. Terms used to describe the validation process are active and passive. All researchers are, of course, concerned with corroborating model representations with systems and, in fact, are probably implicitly doing such at all stages of the construction process. Such implicit corroborative activities are described as passive validation in the tabled information on the studies surveyed. Studies in which the verification
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<tr>
<th>References</th>
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<th>Components</th>
<th>Decision variables</th>
<th>Model Characteristics</th>
<th>Computer Language</th>
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<tbody>
<tr>
<td>Anderson and Moog,</td>
<td>To develop and test procedures by which operators and builders of irrigation systems can compare and evaluate alternative methods of distributing water among farmers</td>
<td>Production benefits, water allocation, water supply</td>
<td>Crop levels, water sequencing, operating procedure to deliver water, selection of crops to be irrigated</td>
<td>Passive Decision</td>
<td>FORTRAN</td>
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<td>[1971]</td>
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<tr>
<td>Acklaw et al.,</td>
<td>To simulate critical periods of drought to assist in the planning and construction of reservoirs and to compare generating techniques</td>
<td>Rivers, stream flow</td>
<td>Maximum permissible extraction rate, duration of low stream flow and the accumulated deficiency relative to the mean flow</td>
<td>Active Behavioral</td>
<td>FORTRAN</td>
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<tr>
<td>[1971]</td>
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<tr>
<td>Ciesiak [1971]</td>
<td>To develop a costing procedure which will be practical and useful tool in planning of cottage resorts</td>
<td>Investment, cost</td>
<td>Type of accommodation, secondary business facilities, and outdoor recreational facilities, length of season</td>
<td>Active Behavioral</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>Glazan and Fereinotis, [1973]</td>
<td>To formulate a mathematical model of a stochastic hydrologic system</td>
<td>Precipitation, runoff, storage</td>
<td>Conceptual watershed storage, stream flow</td>
<td>Passive Behavioral</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>Fritschi et al.,</td>
<td>To estimate the long-term optimal area to develop for irrigation given the size of a reservoir</td>
<td>Water supply, water demand, crops, moisture, costs</td>
<td>Acresage to be developed for irrigation</td>
<td>Passive Decision</td>
<td>Ad Hoc</td>
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<td>[1974]</td>
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<tr>
<td>Ellis [1960]</td>
<td>To present a system model of recreational activity in Michigan that can be utilized to predict the outcome of proposed changes or innovation</td>
<td>Population centers, transportation, destination</td>
<td>Activity by type recreation and location</td>
<td>Passive Decision</td>
<td>Ad Hoc</td>
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<tr>
<td>Table 1</td>
<td>Tabular Survey of Resource Models</td>
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Table 1 (Con't.)
Tabular Survey of Resource Models

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<thead>
<tr>
<th>References</th>
<th>Objectives</th>
<th>Components</th>
<th>Decision Variables</th>
<th>Model Characteristics</th>
<th>Simulation</th>
<th>Computer Language</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walter and Miller, [1966]</td>
<td>To test the applicability of simulation in evaluating water resource development projects and to test alternate resource management policies for an actual river basin</td>
<td>Hydrologic flows, upstream and downstream flows, costs, benefits, drainage</td>
<td>Size of proposed reservoir and channel capacity, channel improvements</td>
<td>yes, yes, yes, linear</td>
<td>Passive, Decision</td>
<td>DYNAMO</td>
</tr>
<tr>
<td>Hamilton, et. al., [1969]</td>
<td>To apply systems simulation to regional analysis, specifically the Susquehanna River Basin</td>
<td>Demographic, employment, water (quantity and quality), spatial</td>
<td>Base levels, migration levels, workers productivity, population levels</td>
<td>yes, no, yes, Active, Forecasting</td>
<td>Passive, Decision</td>
<td>DYNAMO</td>
</tr>
<tr>
<td>Keitt, et. al., [1974]</td>
<td>To predict the impact of changing water quality in the Salton Sea of California on the recreational use and the investment climate for recreational facilities</td>
<td>Water quality, recreation activities and facilities</td>
<td>Fishing and non-fishing participation, investment in recreational facilities</td>
<td>yes, no, yes, Passive, Decision</td>
<td>Adaptive, FORTRAN</td>
<td></td>
</tr>
<tr>
<td>Patrocinio, [1963]</td>
<td>To find an optimal design for a given river basin system</td>
<td>Reservoirs, hydro-power plants, irrigation system, flood damage system</td>
<td>Reservoir storage capacity, active and inactive storage capacity, installed capacity at alternative power plant sites, output levels for irrigation water</td>
<td>yes, yes, yes, Passive, Decision</td>
<td>Passive, Decision</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>Bremig and Hertig, [1966]</td>
<td>To outline a procedure for water resource simulation with an application to the Texas river basin</td>
<td>Supply of water, demand for water-derived products and services, flood, energy, temporal, benefits</td>
<td>Hydrologic conditions, dam and reservoir capacities, type of irrigation works, size of power plants, levels of flood damage alleviation</td>
<td>yes, yes, yes, Passive, Decision</td>
<td>Passive, Decision</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>References</td>
<td>Objectives</td>
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<tr>
<td>Ruggles and Sonke, [1968]</td>
<td>To develop a model to simulate the surface runoff from catchments by de-aggregating the model to a grid of small, independent elements</td>
<td>Rainfall, runoff</td>
<td>Rainfall interception, infiltration</td>
<td>no, no, yes</td>
<td>yes, yes, yes</td>
<td>Passive, Behavioral, Historical</td>
</tr>
<tr>
<td>Jacoby, [1961]</td>
<td>To develop a model to evaluate major investment and operating decisions for electric power planning using West Pakistan as an example</td>
<td>Costs, agricultural sector, irrigation water, electric power, foreign exchange rates, power demand, spatial markets</td>
<td>Size and location of multi-purpose hydropower and irrigation development, operating rules, type of plant</td>
<td>yes, no, yes</td>
<td>Passive, Behavioral, Designed</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>Lelisritz, [1970]</td>
<td>To determine forces that have major influence on farm real estate market</td>
<td>Supply, demand, farm size</td>
<td>Land purchases, land prices, land rental rates</td>
<td>yes, no, yes</td>
<td>Passive, Behavioral, Designed</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>March, et al., [1971]</td>
<td>To develop a set of interrelated water-quality models capable of routine water-quality parameters through a stream subsystem</td>
<td>Thermal behavior, waste assimilation, routing of conservative minerals, spatial, water quality, runoff</td>
<td>Location of waste loadings and withdrawals</td>
<td>yes, no, yes</td>
<td>Active, Behavioral, Designed</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>Maurer and Hiller, [1971]</td>
<td>To demonstrate the proper use of a first-order non-linear Markov model with shower data in the synthetic generation of stream flows</td>
<td>Hydrologic flow</td>
<td>N.A.</td>
<td>yes, yes, yes</td>
<td>Active, Behavioral, Historical</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>Mrdnyk, [1969]</td>
<td>To develop a model and a basis for long-range projections of economic activity in the Colorado River basin with water quality and quantity constraints</td>
<td>Water supply, water demand, spatial, production, agricultural, commercial, industrial, and municipal sectors</td>
<td>Crop production levels, water purchases, water (purification) treatment</td>
<td>no, no, no</td>
<td>Passive, Forecasting, Designed</td>
<td>FORTRAN</td>
</tr>
<tr>
<td>References</td>
<td>Objectives</td>
<td>Components</td>
<td>Decision variables</td>
<td>Model Characteristics</td>
<td>Notes</td>
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<tr>
<td>Pisano, [1966]</td>
<td>To provide a set of options to be used in river basin planning for water quality management</td>
<td>Water quality, stream flows, reservoir levels, pollutant concentrations</td>
<td>Various combinations of reservoir sizes, reservoir releases and waste input schedules, water quality standards</td>
<td>yes yes yes</td>
<td>Active, Behavioral</td>
<td></td>
</tr>
<tr>
<td>Raupser, et al., [1972]</td>
<td>To determine the probability distribution of the external benefits, costs, and how water quality standards influence capital investments and water allocation</td>
<td>Recycling, desalting plants, costs, external benefits, fresh water transport, reservoirs, new sectors and their demand for water</td>
<td>Public subsidies, investment sequencing of alternative water source developments, water allocation</td>
<td>yes yes yes</td>
<td>Passive, Decision</td>
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<tr>
<td>Raupser and Ellis [1974]</td>
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<tr>
<td>Rodhegistorke, et al., [1971]</td>
<td>To compare various Markovian models with respect to their adequacy in the preservation of the required reservoir storage characteristics of the historical record</td>
<td>Stream flows</td>
<td>Seasonal structure, periodicity, cyclic variation, random factors</td>
<td>yes yes yes</td>
<td>Active, Behavioral</td>
<td></td>
</tr>
<tr>
<td>Sato, [1968]</td>
<td>To use a hybrid computer simulation model to solve the three-dimensional nonuniform diffusion equation for determining evaporation from finite areas of water</td>
<td>Mean, temperature, humidity, atmospheric pressure</td>
<td>S.A.</td>
<td>no no yes</td>
<td>Passive, Behavioral, Historical</td>
<td></td>
</tr>
<tr>
<td>Stillson, [1969]</td>
<td>To outline a regional trade model to determine the economic impact of proposed pollution abatement programs for the Western Basin of Lake Erie</td>
<td>Tradable commodities, intraregional commodities, transportation system, costs, prices, final demand, spatial</td>
<td>Type of abatement program (size and technology), taxes</td>
<td>no no no</td>
<td>Passive, Decision, Historical</td>
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</tbody>
</table>
processes are more systematic and for which results of tests and associated procedures are reported are classified as active validation processes.

Simulation of the models are classified as historical, *ad hoc*, and designed. Historical simulations refer to experiments with models in which the conditioning variables are entered as historical data series. *Ad hoc* simulations refer to experiments in which the design points (values for conditioning variables, parameters, etc.) have been chosen in an intuitive or non-systematic fashion. Designed simulations are those in which the experiments with the models have been developed using an experimental design. This implies the inclusion of an implicit or explicit response or objective function and the choice of a method of selecting design points which will produce the information required to identify the associated relationship.

It should also be noted that in the decision variable column we report for behavioral and forecasting models the variables (endogenous) which refer to actions taken by the behavioral units while for decision models we report those variables (exogenous) which refer to policy actions that might be taken by public or private decision-makers. Second, the procedures for classifying models as linear or nonlinear are arbitrary; some models in which only weak departures from linearity exist are classified as linear models. Third, in the fifth column we classify as stochastic those models which are simulated stochastically and not constructed models which incorporate stochastic elements. Last, for the computer language designation we classify all simulation models for which the computer language is not reported or it was not possible to infer the actual computer language utilized as Fortran.

Simulation experiments for natural resource models are typically more sophisticated than for other economics models. A number of factorial and
factorial-factorial designs have been employed to examine response surface questions. Some designs also involve optimum seeking methods. Validation procedures, however, are less precise. Only eight of the surveyed studies went beyond graphical comparisons of sample or historical and simulated values of selected output variables. Predictive properties of the models were typically neglected in corroborating them with the systems in question.

The models specified in Halter and Miller [1966], Hufschmidt and Fiering [1966], Hamilton, et al. [1969], Rausser, et al. [1972, 1975], Jacoby [1967], Dudley, et al. [1972], and Chow and Kareliotis [1970] are viewed as representative of this group and are selected for further discussion. The first three models concern river basin systems. The Halter and Miller model represents an early application of industrial dynamics to water resource development projects. Proposed projects are dam construction and channel improvements in the Calapoolia River Basin. Benefits included irrigation, flood control, fishing, and drainage. A particularly interesting aspect of this model was the treatment of the temporal distribution for hydrologic flows. These flows were generated internally in the model by a random number generator process. Considerable care was taken in attempts to assure that the simulated hydrologic data conformed to historical flows. The experimental design used for the decision problem was reasonably simple with no indication as to how the combinations of project size and operating rules were selected and evaluated.

The Hufschmidt and Fiering [1966] model is more general than the one advanced by Halter and Miller. This study presents the steps and procedures for a simulation program including aspects related to collecting and organizing hydrologic and economic data. An interesting development for
synthesizing hydrologic events is provided. Pollution is considered along with abatement costs. For decision applications, economic consequences (benefits and costs) associated with design variables and outputs were evaluated under several assumed interest rates, static and dynamic investment patterns, as well as different discounting methods. An explicit criterion function was specified, a few basic plans were investigated and, from knowledge accumulated, improvements were made upon the basic plans and the search continued.

The third river basin study conducted by Hamilton, et al. [1969], contains more of a regional flavor than either of the other two. The principal objective of the work was to advance the state of the systems simulation art for regional analysis, particularly where social and technological factors form an integral part of the system under examination. Important features of this model are: (i) inclusion of demographic and economic components in a single model; (ii) explicit application of economic and engineering concepts to regional water resource problems; (iii) dynamic aspects in the form of feedbacks and lagged variables within the various components as well as between components; and (iv) ability of the model to facilitate sensitivity analysis. One of the more interesting results of the simulation analysis was that water shortages emanate not from the scarcity of the water resource itself but from current water treatment, storage, and distribution systems.

Turning from river basin applications, recent studies by Rausser, et al. [1972], Willis and Rausser [1973] were advanced in an attempt to determine the proper level of public subsidies for water desalting plants, the investment levels and sequencing of various water source developments, and the allocation of water across different use sectors. Bases for the public
subsidies are the external benefits which result from "learning" or knowledge accumulation of desalting techniques. Experience gained in the construction and operation of a particular desalting plant is presumed to lead to more efficient production for future plants. Since it was not possible to derive the marginal density function for benefits analytically, computer simulation experiments were employed. Given the approximated external benefit distributions, appropriate levels of public (state and federal) subsidies were derived for alternative sets of assumptions.

The model developed by Jacoby [1967] emphasizes alternative investment and operating decisions for electric power plants in West Pakistan. Potential investments in generation facilities for each of several electric power markets are analyzed. Each plan was constrained to satisfy predetermined power demands. Associated temporal patterns of operating costs were specified. The computer simulation model generates outputs of various plants, ranges of fuel prices, transmission constraints for each year, the distribution of foreign exchange rates, and the distribution of opportunity costs of capital. The opportunity cost information is particularly important given the multipurpose nature of hydroelectric and irrigation developments in the regions investigated. Experimental designs employed in this simulation analysis involved both multistage techniques and partial factorial designs. On the basis of a single basic demand projection, a variety of plans were tested, some of which were eliminated from further analysis. This initial analysis provided a new set of combinations to be investigated. Unfortunately, no real attempt was made to validate the constructed model.

The Dudley, et al. [1972] model was intended to determine the "best" area size for irrigation. This decision is presumed to take place in
conjunction with a reservoir of a given capacity. The specified criterion function involves a twenty-year planning horizon, net revenue derived from irrigated cropland, net revenue derived from dryland crops, and fixed costs of capital items. The actual effects of varying acreages were determined by simulating over a twenty-year period, for both stochastic demand and supply structures. Sensitivity analysis was employed in an attempt to determine how the selected acreage should be altered under varying opportunity costs. No attempt to verify the constructed model was advanced and the experimental design is simple.

4.2 Analytical Optimization. Many applications in natural resource systems have used analytical optimization rather than simulation methods. We list below some examples to illustrate the variety of problems addressed and make only general remarks about the groups of applications.

In the renewable resources class, in addition to the burgeoning numbers of studies of optimal rates of exploitation of fisheries (e.g., Bell [1972], Mohring [1974]), the biological growth functions discussed earlier have been incorporated into empirical systems models to address waterfowl management issues, forests, game animals, human populations, and even insects and bacteria. For example, Brown and Harnack [1972, 1973, 1974] use dynamic programming procedures to suggest management schemes for migratory waterfowl, Beddington, et al. [1975] develop a model to reveal optimal rates for harvesting deer, and Spence [1973] studies the blue whale. The Spence paper is an excellent example of the use of the calculus of variations to suggest optimum regulations for an endangered species. After estimating a growth equation and a production function for blue whales, Spence adopts the present
value of the differences between the market value of the blue whales harvested and the associated costs as the relevant criterion. Calculus of variations is then employed to find the best intertemporal patterns for whale harvesting and the economic value of the resource when these optimum strategies are adopted. In brief, the optimum strategy was to forbid blue whaling for some period of from seven to twenty-one years (depending upon cost assumptions).

Applications to water are the most ubiquitous of all. Examples include Cummings [1971] and Burt [1970], who examine optimal conjunctive use of ground and surface water; Dudley and Burt [1973] who advance a stochastic dynamic programming model for reservoir management purposes; and Rausser and Willis [1976] and Armstrong and Willis [1977] who combine integer and nonlinear programming procedures to determine both the sequencing of water resource investments and water allocations. The paper by Rausser and Willis serves as a useful example illustrating methods of resolving several of the more important problems in the design of water resource systems which have been neglected in the literature. Their framework includes a method for dealing explicitly with technological progress (in this instance, learning and new desalting processes), with staging and sequencing of multiple supply sources, with the simultaneous selection of rate of investment in the capital complex used to exploit the resource along with the allocation of this water once the capital complex is in place, and price sensitive demands for water. In a modeling context, we have found that generally more than two of these issues are explicitly addressed; the others are simply neglected. However, it is clear that each of these issues plays an important role in the design of water resource systems and should be formally examined. The
paper advances a decision framework for solving large-scale investment sequencing and water allocation problems, formally demonstrates the robustness and convergence properties, and applies the framework to an empirical situation in California.

As Peterson and Fisher [1976] conclude, these models, particularly for the biological species, are limited as management tools largely "... because their functional forms are too simple and their empirical content too low". Owing to the weakness of the database, parameters of growth and production functions are not known with any degree of precision. The need for an expanded data base is suggestive of the potential value of improved cooperation of economists with natural scientists.

Another weakness in this empirical work is that these studies of renewable resources are often not based upon dynamic models. Other studies, although based on aspects of a dynamic growth concept, use static optimization methods to derive policy implications. Mohring [1974] and Bell [1972] serve as examples of this approach. Only a few of these applications are fully dynamic (e.g., Brown and Hammack [1974]).

In the exhaustible resources category, a number of approaches have been taken. Much of the early work (Barnett [1950], Landsberg, et al. [1963], Schurr and Netschert [1960]) was based on the input-output model, although it was not until 1972 that the first full scale input-output model was used to forecast mineral demand and compare these with reserves (Ridker [1972]). Econometric procedures based upon macro-economic growth models were used by Hudson and Jorgenson [1974] and by MacAvoy and Pindyck [1975] to estimate demand and supply for energy sources in the United States.
Indeed, for this class of resources, unlike the renewable resources, the empirical applications do not explicitly model long run optimizing behavior. Presumably, it is the difficulty of solving realistic cases of many variables, the presence of inequality constraints, and the exaggerated assumptions made necessary to obtain estimates which has led to a propensity to use linear programming and similar models. An example of these types of applications in the field of energy is provided by Nordhaus (1973).

4.3 Analytical Simulation Methods. Recent applications which follow an earlier suggestion by Dorfman (1965) to combine the use of analytical optimization and simulation methods, include the models developed by Jacoby and Loucks (1972) and Dudley and Burt (1973). The first study involves construction of a river basin planning model where the number of available development opportunities is extremely large. To analyze the resulting framework in a tractable fashion, these authors employ analytical optimization models to screen the set of possible plans and select a smaller number for detailed simulation analysis. Stochastic aspects of the problem are explicitly recognized both in this study and in the Dudley and Burt model. The Dudley-Burt model, following the earlier work of Dudley, et al. (1972), uses a simulation model to compute state transition probabilities which in turn are utilized in a stochastic dynamic programming model to determine optimal: (1) inter-temporal water application rates; (2) abandonment of irrigated acreage for the remainder of the season; and (3) the acreage to plant for potential irrigation at the beginning of the season.

Manne's work provides another useful example of the incorporation of technical progress in a decision model and the explicit recognition of
uncertainty. He concentrates on one of the many important aspects of the energy problem—viz., the race between development of breeder fission and the economic exhaustion of natural uranium resources. His approach involves the use of sequential probabilistic linear programming to define optimum electricity plant-mix decisions during the 1980's (the planning horizon extends through nine 5-year periods through the year 2025), given the uncertainty surrounding the date of availability of the breeder reactor and allowing for the possibility that future shortages of uranium resources will cause an increase in electricity prices and this to a reduction in demands. The approach provides a good illustration of the analytical simulation method since a decision tree was structured and used to screen the range of possible options and hence to enable the development of a linear programming formulation for solution of the decision problem. An interesting result of his analysis is that early decisions are not very sensitive to distant future uncertainties in this instance, and relatedly, there was a rather low value of information attached to the date of availability of the resource-saving breeder technology. These results are connected with the adoption of an assumed ten percent discount rate. Other results suggest that the U. S. has enough stocks of coal to enable electricity generation from this exhaustible fossil fuel until well after the 2025 horizon, so that coal is regarded as a "backstop technology" for the event of failure to achieve a safe and competitive breeder. Further, by this date the chances are good that either fusion or solar energy will be on-line in a large scale, so that natural resource scarcities are not seen by Mann as a bottleneck to the electricity sector and are then not "essential" limits to growth.
The above natural resource models are generally advanced relative to their counterparts in other application areas, particularly as regards their detail and the methods employed in using simulation for decision analysis. However, they might be characterized as often deficient in terms of model validation and theoretical foundations. Owing to their complexity, this is not an unexpected result. A trend of recent vintage that will hopefully continue and experience further growth is explicit recognition of risk and uncertainty. Illustrative applications of these efforts may be found in the occasional staff paper series of the World Bank (e.g., Pouliquen [1970] and Reutlinger [1970]). Applications of these methods along with other approaches to uncertainty in a water resource context are treated in Rausser and Dean [1971a, 1971b].
5. CRITIQUE AND APPRAISAL

The impact on models of the natural resources of the modern development of systems analysis and simulation techniques is apparent. New and ambitious approaches to problems posed in the context of existing paradigms and exploratory work with less confined constructs have been stimulated by the development of systems and simulation methods. Grappling with the difficulties presented by applications of this highly flexible approach and attempting to refine them has and should continue to provide resource economists with the basis for a stream of useful results.

Advantages provided by the use of systems analysis and simulation can be more fully exploited if the two processes are themselves more systematically employed. Moreover, the appropriate framework to be utilized as a basis for systematizing the processes of model construction and use appears to involve concepts of stochastic control. In what follows, we describe the stochastic control process in its most general context, establish the link between model construction and application with control as the unifying force, and offer an assessment of some promising avenues for future modeling efforts in natural resources.

5.1 Stochastic Control. Stochastic control problems involve: (i) Specification of the relevant decision maker(s) and the control or instrument variables available for manipulation. Decision points and procedures for revision of policy actions in the light of new information are also important to this component of the specification. (ii) Specification of an objective function, possibly as a representation of collective preferences, which ranks the different states of the system. Arguments in this function are key
performance variables, including those endogenous and controlled variables considered by policy makers to have important implications for the problem under study. (iii) Specification of constraints or a policy possibility set which includes (a) state transformation functions relating the internally determined variables in each period to the policy variables, other exogenous variables, and lagged variables describing previous states of the system, (b) initial conditions for the system, and (c) other constraints delineating the feasible control variable and endogenous variable spaces. (iv) Specification of the processes of information generation, together with prescriptions for the analysis of data by policy makers as the decision sequence proceeds. The latter embraces active learning processes whereby the additional information may be used to lessen initial uncertainties about objectives, the constraint functions, and states of the system.

Stochastic control methods are thus dynamic optimizing procedures (applied to multi-period decision problems) in which imperfect knowledge is a key characteristic. Usually a discrete-period, sequential decision making process is assumed. In each decision period, a maximizing policy is selected from a set of feasible actions. The constraint functions delineate the feasible policy space and specify the endogenous variables included in the objective function conditioned on instrument, environmental or conditioning variables, and the initial state of the system.

Stochastic dual control methods explicitly recognize that as a system progresses through the sequence of periods, data become available which can be used to update or revise the decision-maker's perception of the policy possibility set. These revisions, in general, should not be regarded as separate from the derivation of an optimal policy. Alternative policy
decisions may reveal more or less information about the system. Inherent benefits of the additional information depend upon whether or not an "improved" representation of the structure results in superior future control. Costs of such information emanate, in part, from choosing a current policy which is less than optimal from a pure control point of view. The important aspect of this approach, from the standpoint of natural resources, is that the dual feature admits an experimental component which probes the system to learn more about the nature of reserves, structural growth or biological yields, the effects of technological change and the like. For this probing component, formal experimental procedures must be designed to determine whether the losses associated with current decisions can be recovered in subsequent periods by utilizing improved information on the structure.

5.2 Control, Model Construction and Application. As the foregoing discussion would suggest, the separation of model construction and application procedures is in some respects artificial. Models of natural resource systems and the systems themselves evolve through time. Applications of the models are made on an ongoing basis for policy and information purposes. The sequential process of model revision application, revision on the basis of added information, is obviously one which lends itself to the stochastic control framework.

Methods for applying techniques in the construction and application of natural resource models are at present, and probably will remain, available in an analytical context only for overly simplistic models. This does not, however, preclude the use of dual control principles in more realistic situations. From an operational viewpoint, an important issue in application or
model use is to understand the sequential nature of the model development and solution process. Specializations of applied models for use in designing search and revision strategies (models of models) are suggested as useful in this context. So are methods for more completely investigating information generating processes, which are, or should be, very much a part of natural resource modeling because of the large amount of uncertainty existing regarding model specification. The list of such techniques includes preposterior analysis (Raiffa and Schlaifer [1961], Anderson and Dillon [1968]) and artificial intelligence (Meier [1969], Shubik [1960]). The two techniques, in an applied context, involve selecting solutions to generate increased information on the model structure, perhaps at some expense in terms of net benefits in the current period.

5.3 Promising Directions. One of the much emphasized attributes of systems and simulation methods relates to the use of the approach as a substitute for more expensive and/or larger scale physical experiments. Within the adaptive control framework, problems resulting from attempts to formulate and investigate such models have a natural criterion function. That is, maximize the information content of the results less costs of complexity, given physical, institutional, time and budget constraints. Policy or control variables for problems formulated in this context are, however, less apparent. At present they would seem to be discrete types of choices such as methods of parameter estimation, the complexity of the model, scale of prototype, choices of paradigm, verification procedures and the like. Choices of control variables would, of course, vary with the problem being studied and the purpose of the modeling exercise.
An interesting method for handling problems of this type is the pre-posterior analysis developed by Raiffa and Schlaifer [1961]. Viewed in connection with biological growth function estimation, this approach provides a means of more effectively positioning actual physical experiments. As a consequence, model complexity and the cost of the physical experimentation can be reduced. In this exercise the control variables relate to the extent of pre-posterior analysis and choices of physical experiments based on such information. Although not fully exploiting the sequential nature of such problems, the structured approach advanced by these authors has wide areas of potential application. Surfaces generated by criterion functions in decision models, predictive performance functions, and measures of appropriate behavior characterization can obviously be viewed in a response type framework. Accordingly, the associated response functions can be explored at least conceptually, using methods of pre-posterior analysis.

A promising application of systems concepts and models is in the development of artificial intelligence. These models attempt to recreate decision-makers' thought and discovery processes, rules of thumb applied to complex real world systems, intelligent behavior, and effective problem-solving or search methods. They embrace a philosophy for approaching problems heuristically rather than with an organized and definable set of techniques. For many problems not solvable by classic mathematical and statistical models, these methods may be useful. They involve attempts to move towards optimum solution procedures rather than optimal solutions (Kuehn and Hamburger [1963]).

Although systems models and allied techniques were suggested early as means for generating information about economic systems (Simon and Norvell
related heuristic programming and learning constructs have received little attention by agricultural economists. The process of constructing and simulating any model of a system can be viewed loosely as a process of developing artificial intelligence. Hence, the observed lack of associated applications is based mainly on the absence of formal consideration of these processes.

The connection of these processes with the theory of learning (Bush and Estes [1959]) is apparent. Heuristic programming and learning theory have been most popular in the study of games (Shubik [1960]). However, they have wide potential applicability in exploratory research associated with the eclectic models employed in agricultural economics. From an economic point of view and in relation to decision models, learning theory is an allocation problem. Hence, applications of heuristic programming and the generation of artificial intelligence fit nicely with the overall adaptive control theory framework. These and our previous comments on the use of synthetically generated data and preposterior analysis present a formal basis on which learning about economic structures and technical response surfaces can proceed. In a more decision oriented context, dual control provides a framework within which exploratory models and policies can be developed.

In addition to those already mentioned or implied, there are other areas of possible application for heuristic methods. One is experimental economics (Castro and Weingarten [1970]; MacCrimmon and Tota [1969]; Naylor [1972]; Smith [1962, 1965]; and Watts [1969]). Most of these studies are closely connected with the gaming models in which learning and heuristic programming methods found initial application. Few propositions of the traditional economic theories of individual behavior have been tested in controlled
experiments; the few tests available refer mostly to the equilibrating process of simple competitive markets (Kagel, et al. [1975]). In comparison with other social sciences where theoretical foundations are not as unified, this is a striking statement. Applications of systems methods in obtaining information about how agents learn and operate within various economic systems would appear to have substantial potential. Of course, simulation methods can be and have been applied advantageously to generate artificial intelligence about the behavior of these economic agents. However, in the context of natural resource systems, much remains to be done.

Model construction is another activity in which an adaptive framework can be advantageously applied. Currently, a major limitation associated with the flexibility of systems analysis and simulation, particularly in the context of exploratory modeling, is the close identity of model and researcher. Stochastic control procedures employed in moving from provisional to final models of systems can be quite helpful in depersonalizing research results. In this manner, the sequential modeling approach can aid in making research results reproducible, and thus verifiable by other investigators. Concerns associated with this aspect of systems models and results of simulations (D.O.D. [1972] and Rausser and Johnson [1975]) are likely to provide strong incentives for developing models on the basis of more structured processes.

A related development concerns the process of verifying models. The discussion of the applications indicates with some notable exceptions (e.g., Singh and Day [1971]) that economists have been somewhat lax in corroborating models with systems. Methods of accomplishing this task are developing rapidly (Rausser and Johnson [1975]). As these advances represent an
additional means of evaluating comparative models, they should find wider application as systems analysis and simulation become more commonly applied in natural resource economics research.

These advances in verification techniques have in large part been made possible by more structured rationalizations for the process of estimating or specializing systems models for particular situations. In this regard, the debate surrounding the Forrester [1961] contention that sample and/or past data on the system are not useful in constructing models has been grossly unproductive. Instead of reaching for an estimation method sufficiently general to incorporate the Forrester argument, many researchers have apparently chosen instead to reject statistical and econometric approaches to model construction. The unfortunate result was, and is, that the associated models have little generality. If one cannot establish a correspondence of the parameters of a systems model to the underlying system, then the foundations for generalizing the results and verifying the model simply are not present. In view of these problems, the Mixed (Theil [1971]) and Bayesian (Zellner [1971]) estimation methods and associated generalizations to the sequential processes involved in model construction (Leamer [1974]) represent most promising developments.

Applications of the systems models as well are likely to benefit from more highly systematized simulations. The shopworn and increasingly suspect argument that systems analysis presents a method for analyzing problems without a criterion function will soon lose its acceptance. It is clear that all models (since they are readily admitted to be purposeful) involve some type of criterion function (Rausser and Freebairn [1974b]). Recognition and incorporation of the criterion function can provide a basis for conducting
experiments with the systems models which are considerably more informative. In this regard, the works of Zusman and Amiad [1965], Schechter and Heady [1970] and Jacoby and Loucks [1972] represent examples of methods of model application which are likely to prevail in future work.

The same observations, of course, apply to behavioral and predictive models. That is, given a criterion for the research exercise, experimental designs can be advantageously applied to enhance the value of simulated results. Applications of these methods are likely to produce results of the type developed by Candler and Cartwright [1971]. Incentives for explicitly identifying criterion functions are also likely to occur as a result of difficulties arising in summarizing simulations. Without a method of summarizing these experiments, the output from model simulations can quickly become unmanageable. However, if summarization is to be useful and accurately represent the outcomes of the experiments, the specification of a criterion function is required.

Given these comments concerning the structuring of model development and applications, one might counter by suggesting that past applications of the systems approach, in the sense that they were new or novel, were justified in proceeding in an unsystematized manner because they were heuristic. Here again, however, there are well-established counter arguments. In fact, the major points associated with the gathering of artificial intelligence and heuristic modeling (Kuehn and Hamburger [1963] and Neier [1969]) are themselves based on systematized search techniques. Their implications for learning about systems through systems analysis and simulation are therefore consistent with the methods which have identified the stochastic control framework with promising developments.
What are we to infer from these observations on promising developments and their identification with adaptive control processes? Obviously, they do not imply that everyone should rush out and purchase a copy of the latest text on stochastic control. Systems and simulation applications, although effectively viewed within the control framework, often present problems which are not currently mathematically tractable. Even in these instances, the conceptual basis of control (rather than actual solutions to these adaptive control problems) should be advanced as providing a basis on which systems analysis and simulation can be systematized.

Changes resulting from applications of systems and simulation are most encouraging. They foretell the merger of the theories of individual behavior with data or empirical evidence and methods of estimation. It would be unfortunate not to acknowledge the debt of these advancements to the concepts of systems analysis in the context of natural resource problems. The questions raised by the development and application of these methods have had a substantial impact in stimulating interest in refining techniques of estimation and in extending the theory. At the same time our discussion has hopefully indicated that systems analysis of natural resource problems as currently applied is itself in for some rather substantial alterations.
Footnotes

1/ A number of surveys documenting the development of the economic theory for natural resources and the environment are available; viz., Ciriacy-Wantrup [1952], Fisher and Peterson [1976], Mishan [1971], Peterson and Fisher [1977], and Herfindahl and Kneese [1974].


3/ The more frequently used definitional frameworks may be found in Chorafas [1965], Churchman [1960, 1968], Emory [1969], Orcutt [1960], and more recently, Churchman [1971] and Mihrim [1971].

4/ Lucid and detailed discussions of this process are given by Anderson [1974] and Mihrim [1972].

5/ On a more philosophical level, our perspective for the importance of this aspect of economic models has been greatly improved by the development of the notion of a paradigm (Kuhn [1970]).

6/ Anderson [1974, p. 25] points out that "it is possible to program the automatic location of successive experiments (according to some steepest ascent procedure) and the automatic switching to the intensive search which may be accomplished by simply supplementing the last factorial or triangle design into a composite or hexagonal second-order design, respectively".
As Starrett [1974, p. 2] recently argued, "... one can think of externalities as synonymous with nonexistence of markets, and define an externality to occur whenever the private economy does not have sufficient incentives to create a potential market." The usual definition of an externality, viz., a decision variable of one economic agent which enters into the production function (or utility function) of some other agent, is far too broad; it defines all commodities in a barter economy as externalities.

Artificial intelligence is characterized by Meier, et al. [1969, p. 150] as "... efficient use of the computer to obtain apparently intelligent behavior rather than to attempt to reproduce the step-by-step thought process of a human decision-maker". It is concerned with computer-oriented heuristics designed to accomplish such items as search, pattern recognition, and organization planning (Chan [1971], Hane [1967], and Lee [1974]). In a more sophisticated setting it may also include learning and inductive inference.
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