METHODOLOGIES FOR SYSTEMS MODELING

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ABSTRACT: This paper presents a survey of modeling and simulation methodology which is useful in systems engineering functional modeling for policy analysis, evaluation, planning, and decision support. We discuss the need for systems engineering models, a structural taxonomy of modeling methods for issue formulation, impact analysis, and evaluation and interpretation of policy impacts. This is followed by a set of guidelines concerning selection of a modeling method and combinations of modeling methods.

1. INTRODUCTION

Issues need to be resolved, policies formulated, and decisions made and implemented every day at the individual, group, local, state, national, and international levels-in private, corporate, and public settings. In this survey paper, we will discuss modeling approaches to assist policy and decision-makers in the resolution of complicated issues. These modeling methods are equally appropriate in either the public or the private sector, as complicated issue resolution in all these areas displays many common characteristics.

Typically, policy formulation and choice making involves considerations of many affected individuals, groups, or institutions who often have conflicting or competitive desires. Resources are generally scarce in that resource availability is insufficient to satisfy the demands of all. Trade-offs have to be made, generally among incommensurate attributes of proposed policies. Various special interest groups often attempt to exert pressure on those responsible for making the trade-offs. At the same time, the impacts to be traded off are often poorly known. There are, typically, large uncertainties with respect to the future impacts of policies or decisions as many future developments are beyond the control of the policy or decisionmaker. And the values or needs to be satisfied may change in an often unpredictable way before a policy comes into effect. There will also often be concerns that transcend various classical disciplines of knowledge, and various institutions or responsible bodies. Institutional and organizational factors play an important, sometimes even crucial part in the realization of policies and decisions. Those responsible for policy and decisionmaking, whether they act as individuals or as groups, have to consider all these aspects: perhaps along with more personal concerns such as the desire to be reelected, renominated, or reappointed; to get a pet-project implemented; to fight a constituency or special interest group, to retain, obtain or consolidate influence, respect, or power.

Increased public and private sector interdependency and societal complexity is made manifest by the increased speed of changes, increased interdependence of actions taken in different areas, and increased numbers of vociferous special-interest groups. Due to these complexities, policy and decisionmakers in the private and public sector have, more and more, sought assistance in their difficult task. Typically, experts in a field related to an issue, and/or professional systems analysts or systems engineers have been consulted.

Experts in a relevant field are often consulted to utilize their experience with an issue and obtain their views on the feasibility and impacts of policy alternatives. Environmental scientists, for example, are typically consulted in the design and formulation of pollution control policies.

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The function of the analyst is generally to assist the policy or decisionmaker in dealing with the complexity of an issue. Analysts can provide assistance in structuring the information related to an issue, laying out the options, investigating the impacts of alternatives with the help of experts and stakeholders, and aiding in the evaluation and interpretation of alternative policies such as to enhance the selection of alternatives for action implementation that are consistent with the decisionmaker's or client's values or preferences. Systems engineers also play the role of information brokers, and of facilitators who provide a framework for information exchange and informed discussion between policy and decisionmakers, issue experts, and the various stakeholders.

Many believe that significant improvements can be made in the way in which policies are generated, selected, and implemented. They point to various problems with current process and practice. Among these problems are the following:

- Insufficient attention is given to long-range concerns.
- Many policy actions aim at temporary problem amelioration rather than fundamental problem resolution.
- Analysis efforts are often used to back up decisions already made rather than to aid in comparison and selection of policy alternatives.
- There is a serious communication gap between policy and decisionmakers on the one hand, and analysts on the other.
- There often is a mismatch between issue characteristics and the methods used to resolve the issues.
- Facts and values are often confounded; as are means and ends.
- Symptomatic concerns often dominate institutional and value concerns.
- Available methodology is often not used, resulting in unnecessary losses of funds, information, and time.

We shall now briefly elaborate on these problems.

The prevailing economic and political system strongly favors short-term improvement to long-term benefits. Political and corporate rewards appear often based on evidence of short-term results. Prevailing economic discounting practice, resulting from high inflation and opportunity cost of capital rates, effectively nullifies the impact of results expected more than 7-8 years into the future. As a result, immediate and short-term effects of policies receive virtually all the attention there is, with little importance attached to long-range impacts of policies.

This same over-emphasis on short-term results leads to the proliferation of superficial efforts at temporary problem and issue amelioration, rather than attempts to design and implement more fundamental solutions. Further, there appears little realization that attempts to produce a solution to one crisis may well be to the detriment of and the expense of a crisis in another problem area. As a result, problems keep on recurring, leaving no time for policy and decisionmakers to thoroughly investigate the issues.

There will typically be different experts and analysts with various technical capabilities offering support to policymakers and decisionmakers. Many of these are experts concerning the application of a small number of methods for issue analysis and resolution. In the prevailing competitive environment, these analysts will be likely to claim that their preferred method will yield results which exceed the quality of, or are more effective than approaches proposed by others. The policymaker often is not sufficiently familiar with the various methods to be able to judge which approach would be most appropriate for a particular issue. As a result, the choice of approach will often not be determined by the issue needs, but, rather, by the salesmanship of the competing analysts, and, perhaps, by prior experiences of the policy makers with analytical assistance. Precisely because there often is a mismatch between problem and method, and because many analysts are likely to overstate the potential power of their approach and raise higher expectations than is justified, many of those prior experiences are characterized by frustration. Policy makers have not always obtained what was promised. Often different, sometimes even conflicting conclusions concerning the same issue have been obtained by different analysts. This has added to the feeling that analysis results can be manipulated, and has generated mistrust among policy makers towards the objectivity of analysts and the utility of analytical methods.

On the other hand, many analysts are not aware of all the pressures and constraints under which policy and decisionmakers must act. At the same time, specialist analysts, often are not thoroughly familiar with the multitude of potentially helpful systemic methods that exist. Consequently they typically look for and distort problems to fit their proposed solutions approach rather than looking for solutions to given problems. They, too, are not well equipped to bring about an appropriate match between real problems and methods for resolution. Often the analyst does not take sufficient care to insure that proposed models and aids are matched to the cognitive style of the client and the contingency task structure in which the client must operate. The result of the client or policy makers' lack of sufficient methodological knowledge, and the narrowness of the scope of many analyst's knowledge result in many mismatches between issue needs and methods used to attack the issues. This will often lead to nonuse of systemic aids that can be truly helpful if used with sufficient skill [1, 2, 3].

We believe that the problems resulting from less than most cost effective use of systems analysis, which occur in various combinations, are very expensive to humankind. Among the consequences, we believe, is the expenditure of large sums of money to support studies and research, and sometimes ultimate development or policy implementation that do not lead to the best results that could be obtained for the same price or even at considerably lower cost in many cases.

The basic motivation behind this paper is to make a contribution to the resolution of the problems discussed above. We have assembled information that, we hope, will enable both the policy and decisionmakers and the analysts to make a better selection of the most appropriate available systemic modeling and analysis methods for assistance in issue resolution; and also to improve the communication between these two groups, as well as experts and stakeholders, by providing them a common resource. A much more complete document is in final stages of preparation [4] and this survey represents, in part, extracts from the larger more complete document. We hope that this survey and distribution and use of the material of [4] will lead to the following results:

a. Greater awareness of the important attributes and limitations of the systems approach for application to the resolution of complicated issues. We hope this will lead ultimately to a more systematic and purposeful course of action in policy formulation and selection, and to more fundamental, longer lasting solutions to public and private sector resource allocation issues facing society.

b. Greater awareness of the technical features, as well as the costs and benefits, of a wide variety of systemic methods of assistance for complex issue resolution.

c. Increased awareness of the fact that combinations of methods are typically more appropriate and effective for systematic issue resolution than concentration on a single approach.

d. Improved communication between policymakers, analysts, experts, and stakeholders.

e. More explicit formulation of objectives, alternatives, and values which might lead to increased participation in the policy process and, as a result, increased support for the policies chosen.

We feel that it is not fully useful to simply offer a catalog of modeling and analysis approaches without any indication of the general underlying principles and cost effectiveness guidelines concerning use of various methods. The advice we shall give here, however, cannot replace personal judgment in a particular analysis situation. But we feel it certainly can help the user of a modeling and analysis method, or methods, to develop an overall problem approach. It may save time in locating information on those methods that might be of use in a particular situation. The basic detailed information on which a selection of methods can be based remains to be found in the method descriptions of the original source literature. In this paper, we present the following:

a. A brief description of the systems engineering approach to large scale issue resolution. We present an introduction to the systems approach which serves as the underlying framework for this whole survey paper. It will help the user to place each method in proper perspective and to develop a systematic and comprehensive plan for overall problem resolution.

b. A list of considerations of importance in choosing from among the methods presented here.

c. A brief discussion concerning selection of appropriate combinations of methods.

2. SYSTEMS ENGINEERING

Systems engineering has been defined as application of a general set of guidelines and methods useful to assist clients in the resolution of real-world problems which are often of large scale and scope. Three fundamental steps may be distinguished in the approach:

a. problem or issue formulation,

b. problem or issue analysis,

c. interpretation of analysis results, including evaluation and selection of alternatives, and implementation of the chosen alternatives.

The systems engineering paradigm calls for an open process involving study of issues in relation with their environment, and with due consideration of causal or symptomatic, institutional or organizational, norms or values, of aspects of the problematique. The necessity of a systematic, rational, and purposeful course of action is emphasized. In contrast to many specialists who tend to overemphasize and promote particular approaches endemic to their professional organizations, systems engineers make an eclectic use of methods, theory, and data based on a variety of disciplines such as behavioral and cognitive psychology, operations research, economics, and systems theory. A serious attempt is made to consider as many relevant aspects of an issue as possible, cutting across various fields of knowledge, institutions, and traditional disciplinary boundaries. For example, an issue that initially might appear to be purely economic in nature, might, upon closer inspection, be interwoven with technological, social, political, and environmental problems. A systems engineer will attempt to take all these related fields into consideration when assisting the policy maker in laying out, analyzing, and evaluating the available options.

Also, systems engineers emphasize stakeholder participation in the policy analysis, and interpretation process. Several of the modeling approaches described in this survey facilitate interaction between policy and decisionmakers, issue experts, stakeholders, and analysts.

We believe that these and other characteristics make the systems engineering approach particularly appropriate to ameliorate or resolve many contemporary problems in the public and private sector. The emphasis on a comprehensive, systemic approach might lead to more fundamental and longer lasting solutions to problems; and this could very well be less costly and time consuming in the long run than application of superficial temporary and incremental solutions to recurring problems. Use of an appropriate systems engineering framework, and of the systemic methods useful within the framework, will lead to efficient and effective use of available methods for dealing with complexity, and to a more efficient and effective use of the time allocated to issue resolution; an efficient, effective, and also equitable resolution. Adoption of the eclectic approach leads to a better match of problems and techniques and hence makes the systems process more efficient by attaining better solutions at perhaps even lower costs than would otherwise be possible. Explicitation of alternatives, options, and values facilitates interaction between policy makers, analysts, issue experts, and stakeholders; and this enhanced degree of openness might lead to increased stakeholder support and political acceptability of the resulting policies or plans. The systems engineering process aims at separation of facts and opinions from values, and separation of means from ends, as part of the systemic divide and conquer approach. This separation encourages more informed discourse concerning contemporary issues, especially those in which there are questions of risk and hazard.

We have chosen a systems engineering framework involving the three-steps of formulation, analysis, and interpretation as the underlying structure ordering the modeling methods we discuss in this paper. We have also referred to this same framework in our modeling method descriptions to indicate the step of the systems framework in which a particular method is most useful.

We shall now briefly elaborate on each of the 3 systems engineering steps, and give particular attention to the methods appropriate for assistance in each step that are described in much greater detail in [4]. Figure 1 illustrates the 3 major steps in the systems process. This figure shows the systems engineering process only at the functional level of systems methodology and design. Supporting this level are various methods or approaches from systems science and operations research, many of which will be described in this survey paper. A systemic process is composed of human judgment and a methodology. The activity flows at the methodological level are controlled by a cognitive process functional level which consists of the system management functions. These include performance objectives for systemic problem solution, the contingency task structure, and decision rule selection. All of these are affected by the operational environment for systemic issue resolution. Figure 2 indicates some conceptual detail concerning this process model of systems engineering and indicates that the systems process involves the interaction of systems methodology (as supported by systems science and operations research methods) with human judgment (involving systems management and operational environment task characteristics).

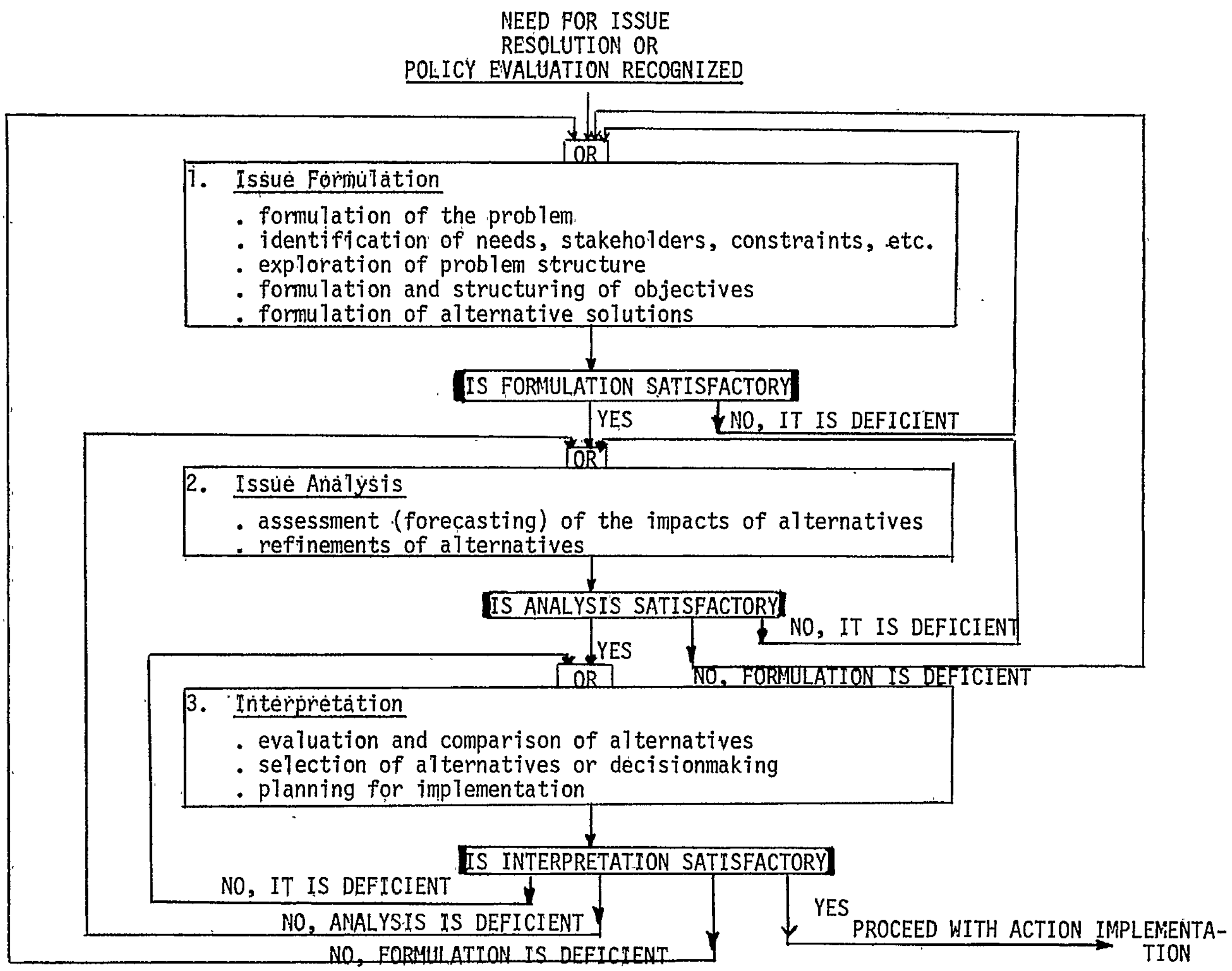
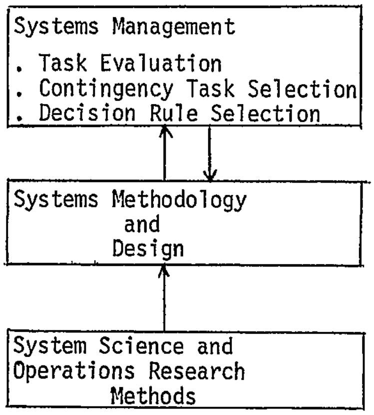


Figure 1: DELTA Chart of the Three-Step Systems Engineering Framework



OPERATIONAL ENVIRONMENT

Figure 2: Functional Components of a Systemic Process Model

3. SYSTEMS SCIENCE AND OPERATIONS RESEARCH METHODS

In this section we will present a brief description of a number of methods which can be used as part of the systems engineering process model of Figure 2.

3.1 Issue or Problem Formulation

The first part of a systems effort at problem resolution or policy evaluation is typically concerned with problem formulation, and identification of problem elements and characteristics such as stakeholders, their needs, relevant institutions, fields of knowledge, constraints, alterables, goals for the effort, policy instruments, actors involved, etc. Subsequently, a structuring or partitioning effort is undertaken to facilitate understanding and perception;and communication of the problem structure and the relations between the elements.

The first step in issue formulation is generally that of definition of the problem or issue to be resolved. Problem definition, regardless of whether we are discussing program planning or any of the other phases of a systems engineering problem, is generally an outscoping activity, as it enlarges the scope of what was originally thought to be the problem. Problem or issue definition will ordinarily be a group activity involving stakeholders in the problem, systems engineers, and government and management specialists. It seeks to determine the needs, constraints, alterables, and societal sectors affecting a particular problem and relationships among these elements. Relationships between elements of a given type can be readily shown using a self-interaction matrix. The relationships within other products such as alterables, constraints, and societal sectors are also identified in this manner. To show the interaction between any two products such as needs and alterables or alterables and constraints, a cross-interaction matrix is used. We may apply this technique to all four of the problem definition variables;needs, alterables, constraints, and societal sectors.

Of particular importance are the identification and structuring of objectives for the policy or alternative to be chosen. This is often referred to as "value system design."

Most philosophers will partition value into two levels called instrumental or extrinsic value, and intrinsic value. In complex large scale systems, resources must frequently be allocated among activities which compete for the same resources. If we denote these as activities A_1 and A_2 , for example, it is likely that some will place higher valuations upon A_1 and some upon A_2. It is also likely that the decision maker has little background or knowledge of A_1 and A_2. The evaluation of activities A_1 and A_2 by the decision maker can be often enhanced by an instrumental or extrinsic valuation. In order to do this effectively, it is necessary to distinguish ends from means or objectives from activities. This is effectively accomplished by the systems process. The objectives identified in "value system design" are effectively prioritized. This occurs as part of the issue evaluation and interpretation step. The analysis step will determine the impacts of proposed alternatives upon objectives. Thus the valuation of an alternative is determined in as objective a fashion as possible through the systemic divide and conquer process which separates means and ends.

Value is a relative term which is associated with various alternatives. We are primarily concerned with the relative values of an alternative policy, which denotes the degree to which we prefer it to other alternative policies. The term value system will be used to refer to the set of interacting elements which provides an ultimate basis for decision making. Value system design is therefore construed to be the transformation of the properties of a thing into a format amenable to instrumental or extrinsic valuation. Allocation of resources represents a value judgment. If we can characterize the value judgment in a manner that relates to human capabilities and human needs, then the judgment is amenable to reasoned criticism. The conclusion of the process of value judgment is an evaluation of alternatives and the decision to select one or more of them for implementation. Decision is the expression of preference for a particular option from a class of options. If a value judgment is an expression of preference, a proposed judgment which offers only one option must therefore be considered improper and incomplete, since preference implies comparison and this requires two or more class members. The do nothing at all alternative is, of course, one option in most issues.

Value judgments of either a public or a private nature are frequently difficult to discuss because such topics are often perceived in two simultaneous categories; subjective and objective. Two schools of philosophical thought concerning values and value judgments are subjectivism and objectivism. The subjectivist is the proponent of situational ethics, wherein we react dynamically to our perception of the existing situation at the time of decision. An afterthought often expressed when the situation has changed is, "We made the best decision at the time." The objectivist admits that feelings and the affective are a part, but not the central part, of value judgment. Clearly any real world judgment will have subjective and objective components.

Treatment of subjective topics using objective methodologies is a principal goal of value system design and of systems engineering in general. In fact, systemic methodologies can be exercised in an interative fashion to arrive at value judgments more palatable to the subjectivist. The objectivist approach to the value system design portion of a systems effort consists primarily of identifying. The identification of an objective or activity implies that it is possible to obtain value from the attainment of the objective or the pursuit of the activity. Selection of given objectives or activities to the exclusion of others is a value claim by the selector. Thus no claim can be made that the issue formulation step is value free. There is an effort however; through wide exposure, facilitation, and brokerage, to seek wide scope input into the issue formulation effort. This will, to the extent possible, make the results of the effort value free.

Selection of goals or objectives to be pursued represents a claim by the group devising the objectives that these goals have a possibility of value. The selection and implementation of specific goals in a given sequence is an interaction in the process of making a value claim. The method of selecting priorities by balloting becomes a subjective technique in which there is abundant opportunity for emotions to play a significant role. This does not, however, imply that priorities established on a subjective basis will be any better or worse or even different than those established on an objective basis in a given situation. One objective in value system design is defining objectives, obtaining an intent structure for them, and ordering them in a hierarchical structure. Value system design does not however, involve prioritizing or attaching priority weights to objectives. To the extent that this is needed, it occurs in the interpretation step.

It is very helpful to relate the objectives to the problem-definition linkages of needs, alterables, constraints, and societal sectors. After some self- and cross-interaction matrices have been determined, others can be generated mathematically by (Boolean) multiplication. This reduces the changes of getting inconsistencies in the cross-interaction matrices. Alternatively, all matrices may be determined first, and matrix multiplication may then be used to check for inconsistencies in reasoning.

Very essential also is the identification of alternatives or policies potentially capable of resolving needs. This activity may range from a simple listing of the actions or policies currently available to influence the system, to a comprehensive design effort to conceive systems structures or organizations that will be potentially responsive to the identified needs such as to achieve the identified objectives.

This system or policy synthesis step of issue formulation is concerned primarily with the answers to three questions: What are the alternative approaches for attaining objectives? How is each alternative approach described? How do we measure attainment of each alternative approach? The answers to these three questions lead to a series of alternative activities or policies and a set of activities measures.

Several of the methods that are particularly helpful in the identification of issue formulation elements are based on principles of collective inquiry. This means that a group of interested and motivated people is brought together in the hope that they will stimulate each other's creativity in generating elements. We may distinguish two groups of collective inquiry modeling methods here.

a. Brainwriting, Brainstorming, Synectics, Nominal Group Technique, and Charette.

   These approaches typically require a few hours of time, a group of knowledgeable people gathered in one place, and a group leader or facilitator. Brainwriting is typically better than Brainstorming in reducing the influence of dominant individuals. Both methods can be very productive: 50-150 ideas or elements might be generated in less than one hour. Synectics, based on problem analogies, might be very appropriate if there is a need for truly unconventional, innovative ideas. Considerable experience with the method is a requirement, however, particularly for the group leader. The Nominal Group Technique is based on a sequence of idea generation, discussion, and prioritization. It can be very useful when an initial screening of a large number of ideas or elements is needed. Charette offers a conference or workshop type format for generation and discussion of ideas and/or elements.

b. Questionnaires, Survey, and DELPHI

   These three methods of collective inquiry modeling do not require the group of participants to gather at one place and time, but they typically take more time to achieve results than the methods above. In Questionnaires and Surveys, a usually large number of participants is asked, on an individual basis, for ideas or opinions, which are then processed to achieve an overall result. There is no interaction among participants.

DELPHI usually provides for written interaction among participants in several rounds. Results of previous rounds are fed back to participants, and they are asked to comment, revise their views as desired, etc. A DELPHI can be very instructive, but usually takes several weeks or months to complete.

Use of most structuring methods, in addition to leading to greater clarity of the problem formulation elements, will typically lead also to identification of new elements and revision of element definitions. Most structuring methods contain an analytical component, and they may, therefore, be more properly labeled as analysis methods. The following element structuring aids are among the many modeling aids available:

- Interaction Matrices

  These may be useful to identify clusters of closely related elements in a large set, in which case we have a self interaction matrix; or to structure and identify the couplings between elements of different sets, for example objectives and alternatives. In this case we produce cross interaction matrices. Interaction matrices are useful for initial, comprehensive exploration of sets of elements. Learning about problem interrelationships during the process of constructing an interaction matrix is a major result of use of these matrices.

- Trees

  Trees are graphical aids particularly useful to portary hierarchical or branching-type structures. They are excellent for communication, illustration, and clarification. Trees may be useful in all steps and phases of a systems effort.

- Interpretive Structural Modeling (ISM)

  ISM is a computer-assisted structuring method designed for collective use; although it can also be of assistance to an individual desiring to structure a large set of elements. The computer is programmed to perform the more straight-forward bookkeeping tasks, thus allowing the user group to concentrate on the elements and their relations. ISM is particularly useful to assist a group of people in their effort to create clarity concerning their perceptions of a set of elements, and to structure their discussion concerning the relationships in the set. ISM has been used to structure objectives, attributes, activities, etc.

- Causal Loop Diagrams

  Causal loop diagrams, or influence diagrams, represent graphical pictures of causal interactions between sets of variables. They are particularly helpful to make explicit one's perception of the causes of change in a system, and can serve very well as communication aids.

The method described as Idea Management consists of a particular combination of a collective idea generation method, and a structuring method, typically ISM.

Two other descriptive methods, potentially useful for issue formulation, are:

- System Definition Matrix

  The System definition matrix or profile provides a framework for specification of the essential aspects, options, or characteristics of an issue, a plan, a policy, or a proposed or existing system. It can be helpful for the design and specification of alternative policies, designs, or other options or alternatives.

- Scenario Writing

  This method is based on narrative, across-the-board descriptions of existing or possible situations or developments. Scenario descriptions can be very helpful for clarification and communication of ideas and obtaining feedback on those ideas. Scenarios may also be helpful in conjunction with various analysis and forecasting methods where they may represent alternative or opposing views.

3.2 Analysis

The analysis portion of a systems effort typically consists of two steps: first, the options or alternatives defined in issue formulation are analyzed to assess the expected impacts of their implementation. This is often called impact assessment. Secondly, a refinement or optimization effort is often desirable. This is directed towards refinement or finetuning a viable alternative and parameters within an alternative so as to obtain maximum needs satisfaction, within given constraints, from a proposed policy.

Forecasting is an essential ingredient of impact assessment. There are many problems associated with forecasting in large-scale societal systems. Among these are: uncertainty concerning important future events, uncertainty concerning changes in the laws that attempt to govern society, uncertainty concerning institutional changes, and uncertainty concerning changes in human norms and values. Human behavior will, to a large extent, determine the course of society and hence affect the impacts of policies or plans; yet both individual and collective human behavior is very hard or impossible to predict.

A great variety of approaches have been designed and used for forecasting. There are basically two classes of methods that we describe here: expert opinion methods, and modeling and/or simulation models.

Expert opinion methods are based on the assumption that knowledgeable people will be capable of saying sensible things about the impacts of alternative policies on the basis of their experience with or insight into the issue or problem area. These methods are generally useful, and particularly appropriate when there are no established theories or data concerning system operation, precluding the use of more precise analytical tools. Among the most prominent expert-opinion based forecasting methods are Surveys, and DELPHI. In surveys, opin are collected and aggregated in one round. The DELPHI process is based on deliberation among an expert group in several, anonymous rounds, spread over several weeks or months. There are, of course, many other ways of asking experts for their opinion; for example hearings, meetings, conferences, etc. A particular problem with expert opinion models is that cognitive bias is wide spread; and incorporation of bias into these models often results in inconsistent and self-contradictory results.

Simulation and modeling methods are based on the conceptualization and use of an abstraction or model of the real world which hopefully behaves in a similar way as the real system. Impacts of policy alternatives are studied in the model, which will hopefully lead to increased insight into real-world policy impacts. Models are, of necessity, dependent on the value system and the purpose behind utilization of a model. We want to be able to determine the correctness of predictions based on usage of a model and thus be able to validate the model. Given the definition of a problem, a value system, and a set of proposed policies, we wish to be able to design a model consisting of relevant elements of these three sets and to determine the results of implementing proposed policies.

There are three essential steps in constructing a model:

1. Determine those issue formulation elements which are most relevant to a particular problem.
2. Determine the structural relationships among these elements.
3. Determine parametric coefficients within the structure.

We should not interpret the word model here in the sense of a paragon or prototype. A model is an abstract generalization of an object or system. Any set of rules and relationships that describes something is a model of that thing. When we model systems, we enhance our abilities to comprehend their nuances and to understand their interrelationships and our relationship to them. Science and engineering have made many contributions toward the improvement of clarity in modeling. A typical result of a systems engineering model is the opportunity to see a system from several viewpoints and perspectives such as economic, technical, political, environmental, etc. A system model may be viewed as a physical arrangement, as a causal flow diagram, and/or as a set of actions and consequences that can be shown graphically through time as a simplified picture of reality. Developments and improvements in the methodology of modeling have become more important as systems have become more complex. Usually resource and other socioeconomic systems evolve as an aggregate of subsystems interacting with one another to create an interdependent whole.

Gaming is a modeling method in which the real system is simulated by people taking on the roles of real-world actors. The approach is very appropriate for studying situations in which people's reactions to each others actions are of great importance, such as competition between individuals or groups for limited resources. It is also a very appropriate learning method. Thus, models often contain submodels.

Most simulation and modeling methods employ the power of mathematical formulations and computers to keep track of many pieces of information at the same time. Two methods in which the power of computers is combined with subjective expert judgments are Cross-Impact Analysis and Workshop Dynamic Models. Cross-impact analysis is useful when there is a need to take the interactions among a set of future events into account to separate the more likely outcomes from the less likely. Typically, experts provide subjective estimates of event probabilities and event interactions. These are processed by a computer to explore their consequences, and fed back to the analysts and thereafter to the experts for further study. Workshop dynamic modeling is a procedure in which a group of knowledgeable people interacts, through an analyst, with a computer to determine their perception of the basic mechanisms of change in a system. The computer derives the resulting behavior over time, giving rise to renewed discussion and revision of assumptions. This process can be very helpful as a group learning tool in a situation where causal interactions over time are of importance.

Expert judgment is virtually always included in all modeling methods. Scenario Writing can be an expert opinion modeling method. But typically this is done in a less direct and explicit way than in DELPHI, Survey, ISM, Gaming, Cross Impact, or Workshop Dynamic Models. As a result of this, internal inconsistency problems are reduced with those methods based upon mathematical modeling. The following other forecasting methods based on mathematical modeling and simulation are among those available. In these methods, a structural model is generally formed on the basis of expert opinion and physical or social laws. Information is then processed to determine parameters within the structure.

- Trend Extrapolation/Time Series Forecasting

  This method is particularly useful when sufficient data about past and present developments are available, but there is little theory about underlying mechanisms causing change. The method is based on the identification of a mathematical description or structure that will be capable of reproducing the data. Then, this description is used to extent the data series into the future, typically over the short to medium term.

- Continuous-time Dynamic Simulation

  A method based on postulation and quantification of a causal structure underlying change over time. A computer is used to explore long-range behavior as it follows from the postulated causal structure. The method can be very useful as a learning and qualitative forecasting device, but its application may be rather costly and time consuming.

- Input-Output Analysis has been especially designed for study of equilibrium situations and requirements in economic systems in which many industries are interdependent. Many economic data fit in directly to the method, which is, mathematically, relatively simple, and can handle many details.

- Econometrics is another method mainly applied to economic description and forecasting problems. It is based on both theory and data, with, usually, the main emphasis on specification of structural relations based upon economic theory and the derivation of unknown parameters in behavioral equations from available economic data. The method requires expertise in economics, statistics, and computer use and can be quite expensive and time consuming. It has been used widely for short to medium-term economic analysis and forecasting in many industrialized economies.

- Micro-economic Models represent an application of economic theories of firms and consumers. Behavior of economic agents in a free-market economy is described as that set of actions which will maximize total benefits or utility for the agent. Micro-economic Models are used to study and forecast economic quantities. Closely related to microeconomic models are welfare economic models, which incorporate equity concepts into microeconomic models and cost benefit analysis models.

- Welfare Economics Models are concerned with equity considerations in economic systems based on microeconomic theory. In particular, they examine the question: "What is the distribution of economic goods that will lead to maximum overall economic welfare?". For application of economic models, the utility or satisfaction derived by each economic agent from possession of certain economic goods must be expressed mathematically. Equity is a goal of welfare economic modeling.

- Queueing Theory and Discrete Event Simulation have been developed to study, analyze, and forecast the behavior of systems in which queueing phenomena, such as waiting lines, are of importance. Queueing theory is a mathematical, pencil and paper approach, while discrete-event simulation is based on computer simulation of queueing theory type models. The two methods are being used widely in the analysis and design of systems such as toll booths, service facilities, shipping terminals, etc.

There are at least three uses to which models may normally be put. Model categories corresponding to these three uses are: descriptive models, predictive or forecasting models, and policy or planning models. Representation and replication of important features of a given problem is the object of a descriptive model. Good descriptive models are of considerably value in that they reveal much about the structure of a complex issue and demonstrate how the issue formulation elements impact and interact with one other. An accurate descriptive model must be structurally and parametrically valid. One of the primary purposes behind constructing a descriptive model is to learn about the impacts of various policy alternatives.

In building a predictive or forecasting model, we must be especially concerned with determination of proper cause and effect, or input/output relationships. If the future is to be predicted with integrity, we must have a method with which to determine exogenous or independent "given" variables accurately and the model structure must be valid and parameters within the structure must be accurately identified. Often, it will not be possible to accurately predict all exogenous variables and, in that case, conditional predictions can be made from scenarios. Consequently predictive or forecasting models are often used to generate a variety of future scenarios, each a conditional prediction of the future.

Policy or planning models are much more than predictive or forecasting models although any policy or planning model is also a predictive or forecasting model. The outcome from a policy or planning model must ultimately be evaluated in terms of a value system. Policy or planning efforts must not only predict outcomes from implementing alternative policies, but they must also present these outcomes in terms of the value system that is in a form useful and suitable for the alternative ranking, evaluation, and decisionmaking that takes place in the interpretation step of systems engineering.

Verification of a model is necessary to ensure that the model behaves in a fashion and for the purpose intended by the model builder and, consequently, the client. If we can determine that the structure of the model corresponds to the structure of the elements obtained in the issue formulation steps, then the model is verified with respect to behaving in a gross fashion as intended. Even if a model is verified, there is still no assurance whatever that the model is valid in the sense that predictions made from the model will occur. Since data concerning results of not implemented alternative policies are generally not available, there is usually no way to completely validate a model used for other than descriptive purposes. Nevertheless, there are several efforts which can be undertaken to validate a model with respect to those policies that have been implemented. These include a reasonableness test in which we attempt to determine from knowledgeable people that the overall model, as well as model subsystems, respond to inputs in a reasonable way. The model should also be valid according to statistical time series used to determine or estimate parameters and variables within the model. Finally, the model should be epistemologically valid in that the policy interpretations of the various model parameters, structure, and recommendations are consistent with ethical, professional, and moral standards of the group affected by the model.

There are many areas for which particular types of simulation models have been developed, for example:

demography, ecology, energy, land use, transportation, water resource management, etc. The principles of these models are very similar to those we have described here. There are also many combinations of different models and modeling methods, for example, input-output analysis and econometrics, or continuous-time dynamic models and time series extrapolation and forecasting models.

The material we offer here is intended as a first guideline in assessing the potential merits of a variety of methods. The user is, however, strongly advised to consult with one or more analysts familiar with a wide variety of modeling analysis methods before deciding to use a particular modeling method. Risks of failure are extremely high when the analysis method chosen does not well fit the nature of the problem.

There are also many methods that are helpful in conjunction with mathematical modeling approaches. Among these are many of the idea generation and structuring methods discussed under issue formulation. Interpretive structural models and causal loop diagrams may represent the first step or input to construction of a quantitative, mathematically based, simulation models.

There are also a number of specific aids in the quantification of models. We describe two of these here: Hypothesis Testing and Regression Analysis and Estimation Theory.

Hypothesis Testing provides a widely accepted set of rules for deriving conclusions on the basis of samples of information rather than full information. The approach is used widely in social science, engineering, quality control, and in conjunction with Regression Analysis. Regression Analysis and Estimation Theory are methods very useful for the identification of mathematical relations and parameter values in these relations from sets of data or measurements. Regression and Estimation methods are used frequently in conjunction with mathematical modeling, in particular with Trend Extrapolation and Time Series Forecasting, and with Econometrics. These methods are often also used to validate models.

There exists a number of methods for finetuning, refinement, or optimization of specific alternative policies or systems. These are useful to determine the best (in terms of needs satisfaction) control settings or rules of operation in a well-defined quantitatively describable system. A single scalar indicator of performance or desirability, is typically needed. There are approaches to multiple objective optimization which are based on welfare economic type optimization concepts, however.

Mathematical Programming is used extensively in operations research and analysis practice, for resource allocation under constraints, resolution of planning or scheduling problems, and similar applications. It is particularly useful when the best equilibrium or one-time setting has to be determined for a given policy or system.

Optimum Systems Control addresses the problem of determining the best controls or actions when the system, the controls or actions, the constraints, and the performance index may change over time. A mathematical description of system change is necessary. Optimum Systems Control is particularly suitable for refining controls or parameters in systems in which trade-offs over time play an important part.

Markov Decision Models have been designed to assist in determining the best overall strategy in a system in which future change over time can be described as a succession of unpredictable events. Applications have been reported in the fields of maintenance strategies and inventory management.

Application of the various refinement or optimization methods like these described briefly here typically requires significant training and experience on the part of the analyst.

3.3 Interpretation

The third step in a systems effort starts with evaluation and comparison of alternatives, using the information gained by analysis. Subsequently, one or more alternatives are selected, and a plan for their implementation is designed.

The evaluation of alternative actions must typically be accomplished and implementation decisions made in an atmosphere of uncertainty. The outcome from any proposed policy is seldom known with certainty. One of the purposes of efforts in the analysis step is to reduce, to the extent possible, uncertainties associated with the outcomes of proposed policies. Decisionmaking, policy analysis, and planning will often involve a large number of decisionmakers who act according to their varied preferences. Often, these decisionmakers will have diverse and conflicting data available to them and the resulting decision situation will be quite fragmented. Further, outcomes resulting from actions can often only be adequately characterized by a large number of incommensurable attributes. Comparison among these attributes, by many stakeholders in an evaluation and choicemaking process, is typically most difficult. Also, inadvertent biases, such for example as those due to a nonconscious ideology, are systematic and prevalent in most unaided cognitive activities. Unaided evaluations, decisions, and judgments are influenced by many heuristic procedures which may lead to, in some cases, very inferior results. It is often quite difficult to disaggregate the valuation associated with policy outcomes from the causal and uncertain relations and events which determine these outcomes. This confounding of values with facts can lead to extreme difficulties in communication as well as choice making. The systems process attempts to reduce these difficulties through a divide and conquer process.

The interpretation step is first approached by disaggregating the evaluation and decision analysis problem of choosing one or more alternative actions or policies into four interacting phases. In the structuring phase, relevant system elements are determined, relationships among system elements are established, a formal model is obtained, and possible outcomes of alternative acts are determined. In the probabilistic phase, which is needed if there are uncertainties involved, probabilities of various outcomes following as a consequence of various alternative acts are determined and assigned to the relevant system elements. In the utility or valuation phase, the values placed by appropriate stakeholder groups upon outcomes of alternative policies or decisions, and the uncertainties associated with these, are determined.

It is important to note that there is a clear and distinct difference between the refinement of individual alternatives, or optimization step of analysis, and the evaluation of sets of refined alternatives. In some cases refinement of individual alternative policies is not needed in the analysis step. But evaluation of alternatives is always needed; for if there is but a single policy alternative, then there really is no alternative at all. It is especially important to avoid a large number of cognitive biases in the structuring, probabilistic and information phase of evaluation and decisionmaking. In the information phase, the economic value associated with reducing uncertainty concerning the important issue formulation elements is determined and the value of this information is contrasted with the cost of obtaining it. When it turns out that obtaining additional information is needed, it is generally necessary to repeat the four phases of evaluation and decisionmaking, in an iterative fashion, to determine an acceptable model for the ensuing valuation and choicemaking effort. Clearly, the efforts involved in evaluation and choicemaking interact most strongly with the efforts in the other steps of the systems process.

There are a number of methods for evaluation and choice making which are of importance. Among these are:

- Decision Analysis which is a very general approach to option evaluation and selection. As has just been described, it involves: identification of action alternatives and possible consequences, identification of the probabilities of these consequences, identification of the valuation placed by the decision maker upon these consequences, computation of the expected value of the consequences, aggregating or summarizing these values for all consequences of each action. In doing this we obtain an evaluation of each alternative act; and the one with the highest value is the most preferred action or option.
- Cost-Benefit Analysis is a well-known approach to systematic identification, specification, and comparison of the various costs or disadvantages, and benefits or advantages of the various alternative actions. A closely related variant of cost-benefit analysis is cost-effectiveness analysis.
- Economic Discounting provides a method to compare costs and benefits that are occurring at different points in time. It is very helpful in conjunction with cost-benefit analysis.
- Worth Assessment and Multi-Attribute Utility Theory have been designed to facilitate comparison and ranking of alternatives with many attributes or characteristics. The relevant attributes are identified, structured, and a weight or relative utility is assigned by the decisionmaker to each basic attribute. The attribute measurements for each alternative are used to compute an overall worth or utility for each attribute. Multi-Attribute Utility Theory allows for various types of worth structures, and for the explicit recognition and incorporation of the decisionmakers attitude towards risk in the utility computation. Worth assessment is a simpler, more straightforward process in which risk considerations are not taken into account. Both methods are very helpful to the decisionmaker in making values and preferences explicit, and making decisions that are consistent with those values.
- Policy Capture (or Social Judgment Theory) has also been designed to assist decisionmakers in making their values explicit, and their decisions consistent with their values. In policy capture, the decisionmaker is asked to rank order a set of alternatives directly or holistically. Then, alternative attributes and their attribute measures are determined by elicitation from the decisionmaker: and a mathematical procedure involving regression analysis is used to determine that relative importance of each attribute that will lead to a ranking as specified by the decisionmaker. The result is fed back to the decisionmaker, who, typically will express the view that his or her values are different. In an iterative learning process, preference weights and/or overall rankings are modified until the decisionmaker is satisfied with both the weights and the overall alternative ranking.

Two well known heuristic methods of selection of alternatives are often used in practice to evaluate or prioritize alternatives.

- Elimination by Aspects is a simple selection aid in which those alternatives not fulfilling certain minimum requirements on every aspect or attribute are eliminated from further consideration. Alternatively, only alternatives which exceed a minimum aspiration level on each attribute may be retained. This is an extensively used heuristic. It is used in many areas as a screening method to select only those options for further consideration that meet a number of minimum requirements.
- Voting is a well-known and widely used method of group decisionmaking. Different methods of voting may, and often will, lead to different results.

After the selection of an alternative action or policy has been made, implementation for action plans are determined. There are many methods, and tools for implementation for action planning. Three very prominent ones are worth mentioning here.

- DELTA Charts portray the events, activities, decisions, and actors in a process in their proper, logical and sequential order. The result is an attractive, easy to understand pattern. DELTA charts are very suitable for design and communication of the structure of and responsibilities in a proposed or actual systems engineering effort.

- Gantt Charts consist of a graphical representation of different activities in a project or plan, and the time during which they are (planned to be) carried out. Gantt charts are very useful for communication, and for monitoring progress during implementation of a plan.
- Network Planning Methods include a wide variety of more specialized tools for planning complicated projects consisting of many activities; some of which must preceed others to be meaningful. The method is used extensively in civil engineering projects, and has also received widespread acclaim in other areas. It is of great help in scheduling different activities, determining the expected duration of a project, estimating costs of reducing the project duration, identifying latest possible or necessary completion times of certain project tasks, scheduling activities to reduce overload, etc.

It should be emphasized here that many methods that we discuss as most appropriate for one step of a systems effort may very well be useful for other steps as well. For example, idea generation methods may be useful in all steps of a comprehensive policy formulation effort. Similarly, network planning methods can be useful analysis tools as they might indicate the feasibility of timely implementation of an alternative. Also, DELTA charts might be very helpful for the design and description of alternatives in issue formulation. And various forecasting methods might be very helpful in issue formulation when the issue is related to ancicipated needs rather than current needs or problems.

A systems effort is generally always conducted in an iterative rather than a sequenced manner. Typically, after some analysis has been accomplished, certain elements of issue formulation might be reconsidered, and a first preliminary evaluation and selection of alternatives may be made. Only viable alternatives that pass this initial screening will then be subjected to more detailed analysis, including exploration of possible implementation plans, before a further evaluation and selection is made. This was indicated in Figure 1 by the various feedback paths and in Figure 2 by the cognitive process level, or systems management, which represents the human judgment input to systems methodology that results in a systemic process.

4. CONSIDERATIONS IN THE CHOICE OF SYSTEMIC MODELING METHODS

Selection of an appropriate set of methods to attack a specific issue may be determined using a similar systemic approach as that used for policy evaluation and selection: First, assess the needs and constraints of the problem situation. Then, identify or design candidate approaches. Finally, study and compare the candidate approaches, select a subset, and use them in what we shall call a systems process. These are of the actions to which the cognitive process level of systems management is responsive. These suggestions, however, may not be very helpful to the policy and decisionmaker who typically is not an expert concerning systemic methods, and does not want to spend the time necessary to become familiar with a large set of possible approaches. A trained systems analyst or engineer can assist the policymaker or decisionmaker to these ends however. And this is one reason why systems engineering is solving problems with clients, not merely for clients.

There are, however, some general guidelines and thoughts concerning the identification of appropriate candidate methods for resolution of specific issues that are appropriate and useful. These guidelines should be used with an awareness of their limitations. They are necessarily global, and can be disputed in specific instances. The methods most appropriate for a given situation are very much dependent on the operational environment and contingency task structure that is present. Also, the guidelines refer to typical applications of most methods. But virtually every modeling method discussed in this survey can be used in a variety of ways. For example, construction of a dynamic simulation model is typically a rather time consuming and costly effort. It is, however, possible to construct and successfully use a simple model in a few days at a cost of only a few hundred dollars.

We shall now discuss some aspects of the choice of methods for each of the three basic steps in the systems approach.

4.1 Issue Formulation

In the issue formulation step, first a formulation of the problem is obtained, and various elements relevant to the problem are identified. Study of relevant literature is one approach towards element identification. This will typically be supported and augmented by use of systemic methods for idea or element generation by experts and knowledgeable people. The choice of method will primarily be determined by such contingency task structural concerns governing the choice of performance objectives for the systemic process as:

- The location, number, and personal characteristics of prospective participants;
- The time and funds available to carry out the issue formula elements for idea generation.

When there is little time available, and relatively limited monies, Brainwriting, Brainstorming, Synectics, or Nominal Group Technique might be appropriate. The personal characteristics of participants might determine the further choice: Brainwriting and Nominal Group Technique are better in reducing the influence of dominant individuals than the other two methods. Telephone polls or conferences could replace these when participants are widespread geographically.

When there are more time and funds, and when participants can easily get together at one time and place, Charette, a conference or workshop, or a similar approach might be the best alternative. When the number of participants is large, and they are geographically widespread, and there is sufficient time and financial support, Surveys; Questionnaires, and DELPHI might be appropriate approaches.

Table I provides a global set of guidelines:

		TIME AND MONEY	
		little time (days), funds ($1,000)	more time (months), funds (thousands to ten-thousands)
PEOPLE	5-25 people at one time, place	Brainwriting, Brainstorming Synectics Nominal Group Technique	Charette, conference other
PEOPLE	Participants widespread geographically; large number of participants (50-200)	Telephone polls, tele-conferencing	Surveys Questionnaires DELPHI

Table I: Appropriate element or idea generation methods for 4 different conditions

Creativity is a prime requirement for identification and synthesis of alternative actions or policies that are perceived as potentially capable of need resolution. In addition to creativity stimulating methods like the idea generation methods discussed above, standard frameworks such as the Systems Definition Matrix might be useful to ensure completeness and internal consistency of alternatives. DELTA charts are appropriate for description of an alternative which contains many options that might be exercized if various contingencies materialize.

4.2 Analysis

In a subsequent element structuring effort, typically undertaken as part of the impact analysis step, the purpose of the effort, the type of relation used for structuring, and the type of effort (individual analytic, or collective) will be major determinants in the choice of a method. When a collective inquiry effort is preferred, i.e. performed by a group of interacting people, Interpretive Structural Modeling, and, to a lesser degree, Causal Loop Diagrams and Interaction Matrices might be useful. When the contextual relation used is direct and causal, Causal Loop Diagrams are worth consideration. When the relation is transitive, i.e. when, if element A relates to element B, and element B relates to element C, then element A also relates to element C, then Interpretive Structural Modeling is a very appropriate method.

For general types of relations, and for identification of subsets of variables, or other characteristic patterns, Interaction Matrices, Cluster Analysis and Multidimensional Scaling might be very helpful.

Availability of data and theory, and the time horizon or type of forecast desired are, along with available time and funds, the prime determinants in the choice of an impact assessment or analysis method.

When little or no data or theory are available, methods based on expert opinion and feedback; such as DELPHI and Scenario descriptions; or on "real-life" simulation such as Gaming, are the prime learning, forecasting, and impact assessment tools for various kinds of time horizons and forecasting needs. When a forecast is needed which is related to a series of events and the uncertain occurence or non-occurence of these, Cross-Impact Analysis might also be useful. Workshop Dynamic Models are often useful for long-range exploration of interacting trends. Typically, the data needed in these two approaches are expert-provided, and the methods allow inclusion of both measurable as well as unmeasurable concepts or data.

When some theory about the system structure is available, but little data, Workshop Dynamic Models and Dynamic Simulation Models are useful for long-range exploration. Workshop Dynamic Modeling is generally the simpler, faster, cheaper, and less accurate method of the two.

When data are abundant, but theory is generally lacking, Trend Extrapolation or Time Series Forecasting can be very useful, particularly for short to medium-term forecasting.

Appropriate methods for different combinations of data and theory availability are indicated in Table II.

		data availability	
		low	fair-high
Existence of Theory	little	DELPHI, Scenarios, Cross-Impact, Workshop Dynamic, other expert-opinion	Trend-Extrapolation, time series forecasting, Regression Models
	Fair to sufficient	Workshop Dynamic, Dynamic Simulation Models	Various combinations and types possible; special purpose methods e.g. econometrics, demographic models, etc.

Table II: Appropriate analysis and forecasting modeling methods classified according to availability of data and theory

Another dichotomy in the systems analysis and modeling step refers to the nature of the mathematical models used: There are equilibrium models to study steady-state or equilibrium situations under a variety of different assumptions. There are dynamic models useful to study processes involving change over time. Typically, dynamic models are used for medium-term and long term forecasting.

A great many special-application-type models and modeling methods have been developed for situations in which both theory and data are available. There are a number of important economic impact assessment modeling methods: Input-Output Analysis, appropriate for detailed analysis of productive systems; Econometrics, mostly used for description and analysis of aggregate economic variables, or macroeconomic variables, on the national or state level; Micro-economics, designed for description and study of specific economic sectors on a more detailed level; Welfare Economics, which incorporates societal equity concepts into microeconomics; Queueing Theory and Discrete Event Simulation, especially appropriate for analysis and impact assessment in issues where queueing phenomena such as delays and waiting lines are important. As noted before, there are a wide variety of other special purpose analysis and forecasting methods not described here.

The most prominent methods for refinement or optimization of individual alternative policies are useful when, in addition to a reliable mathematical description of relevant aspects of the alternative, and other issue formulation elements being available, a single performance function can be formulated. The nature of the relevant mathematical description will determine the choice of method. When a best one-time or equilibrium setting has to be determined, mathematical programming can be used. This includes linear programming, a method widely used for resource allocation under constraints, and for operational optimization of existing systems. When the system and controls vary over time according to known principles, Optimum Systems Control is an appropriate method. When system evolution can be described by unpredictable transitions from one state to another, with known probabilities, Markov Decision Models might be appropriate.

4.3 Interpretation

In the third systems engineering step, user, analyst, and other stakeholders evaluate and compare alternatives, choose one or more of those, and prepare a plan for implementation of the selected alternative or decision.

Cost-Benefit Analysis provides a framework for systematic discussion of the advantages and disadvantages of alternatives, with emphasis on economic aspects. When advantages or disadvantages occur at different points in time, Economic Discounting concepts will be very helpful when there are costs and benefits distributed over time. Cost-effectiveness analysis is a term given to a modified form of cost benefit analysis in which other than economic considerations form the basis for resource allocations.

When a complicated decision situation has to be structured for greater clarity, Decision Analysis provides a framework for assistance. It is often difficult to make trade-offs between the particular advantages and disadvantages of various alternatives in a given issue under consideration. Several related methods have been developed to assist decisionmakers in this task. The choice of a particular decision analysis approach will typically be determined by the nature of the alternatives such as whether there exists uncertainty about the outcome states. The accuracy of available information, and the users willingness to spend time and money and to make values and preferences explicit also influence the particular decision analysis approach selected. When uncertainty is present and user and analyst feel it should explicitly be taken into account, multi-attribute utility theory is appropriate. When uncertainty is not thought to be important, Policy Capture or Worth Assessment may be used. The choice depends whether the users prefer to make values explicit first and then apply them to the decision problem (Worth Assessment or Multi-Attribute Utility Theory), or to rank alternatives and use this information to look into their values or preferences (Policy Capture).

Typically, Worth Assessment is the least costly and fastest method of the three we describe here, but provides less flexibility than Multi-Attribute Utility Theory. There is an even simpler version of Worth Assessment available that is denoted simple Multiple Attribute Rating Technique (SMART).

The result of use of one of these aids or adjuvants for planning and decision support is typically a ranking of alternatives which may be the basis for selection or elimination of alternatives. Another, far more simple heuristic method of selection is Elimination by Aspects-which is often used for screening an initially large set of alternatives. When groups rather than individuals are responsible for decisions, different types of Voting may be used but great care needs to be exercized to avoid various voting paradoxes in which group preference intransitivities, even with all individual preferences being transitive, make ordinal (ie. simple preferences) comparisons not fully useful. Although originally designed for individual use, the other selection and comparison aids discussed here are generally useful for group decision aiding as well; and due to the cardinal, or numerical, nature of the comparisons may avoid intransitivities associated with ordinal, or nonnumerical, preferences.

In planning for implementation of an alternative, different tasks or actions have to be distinguished, their proper sequence and timing identified, and responsibilities assigned. Network Planning methods are very useful for ordering, in proper logical sequence, different tasks or activities in a complicated endeavor. Gantt Charts are very appropriate for displaying time-related schedules, while DELTA Charts emphasize the process aspects, and responsibilities for activities and decisions in a process. All these three methods can be useful for virtually any planning for implementation effort.

5. ON THE CHOICE OF COMBINATION OF METHODS

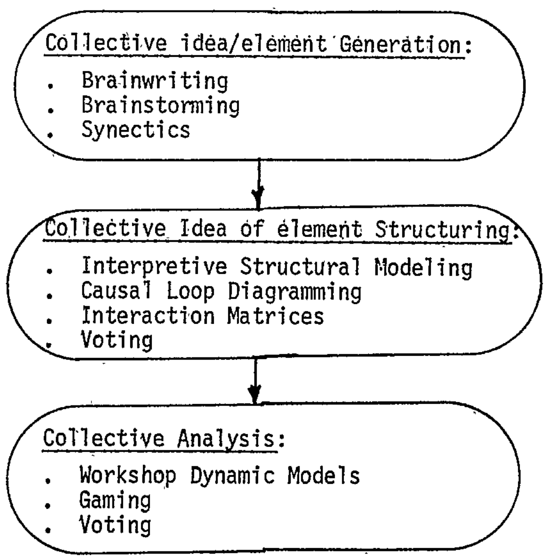
While each individual modeling and analysis method may be very useful, it will generally be more appropriate to use a combination of several methods for issue resolution and resource allocation efforts. But not all combinations of issue formulation methods, analysis methods, and interpretation methods yield acceptable or viable overall approaches. We have attempted to indicate some particular linkages of methods in each of the brief descriptions included here. Now, we shall briefly elaborate on possible combinations of the methods described.

There are several ways in which different systemic modeling and analysis methods might be used together. Use of one method might yield results useful as input, or starting information for another method. For example, element or idea generation methods produce lists of elements which serve as inputs to element structuring methods such as Interpretive Structural Modeling. Also, use of one method might be required as an essential part of another one; such as the use of Regression and Estimation methods in the construction of Time Series and Econometrics models. Finally, combination of two approaches might yield a more powerful overall approacn that takes both future events and trends into account in a computer simulation model. Similarly, DELTA Charts and Network Planning Methods might nicely compliment each other to analyze and document complicated implementation plans. The combination of Nominal Group Technique for formulation, Interpretative Structural Modeling for analysis and attribute tree determination, and Worth Assessment for evaluation and interpretation may represent a particularly useful complete set of methods for all three steps of the systems process.

We shall now, to further elucidate and elaborate these points, briefly discuss a number of typical clusters of methods which fit very well together. Let us first consider methods of collective inquiry in which a group of people get together at one place and time. Figure 3 shows a map or structural model illustrating how several of these methods might be used together. A group of people might very well engage in a collective element generation effort, and subsequently proceed, after editing of the elements, to a collective structuring effort. Voting might be useful as an aid in deciding about relations between individual elements of the structure, such a set of attributes. This structuring effort might be followed by collective analysis, for example as might be accomplished in a Gaming exercise, or from use of a Workshop Dynamic Model. Two of the methods described earlier provide examples of such combinations: Nominal Group Technique is essentially an idea generation effort followed by priority structuring of ideas carried out by voting. Idea Management is a combination of idea generation and idea structuring typically using Interpretive Structural Modeling. Other combinations than those illustrated here are, of course, possible.

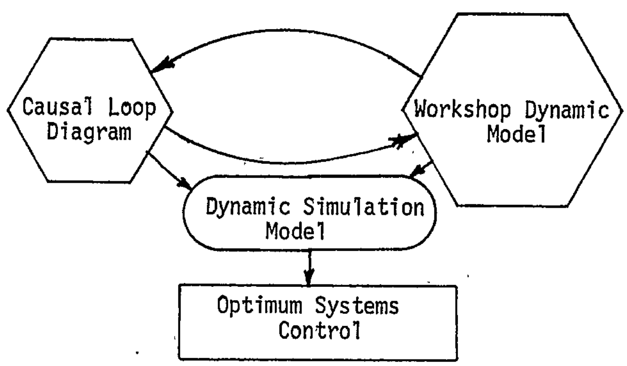
Figure 4 illustrates a very characteristic combination of methods for analysis of change over time. Causal Loop Diagramming may be used to display the major causes of change in a system. These may be represented and analyzed crudely in a Workshop Dynamic Model. Any of these two, or a combination, may be followed by construction and use of a more elaborate Dynamic Simulation Model. Finally, Optimum Systems Control is potentially useful to structure or optimize an alternative described by a dynamic model.

Another typical combination of analysis methods is shown in Figure 5. Cross-Impact Analysis and Workshop Dynamic Modeling might be used together. The results are potentially helpful in constructing viable scenario descriptions. These, in turn, might be helpful to represent various possible futures in connection with some other, more quantitative modeling effort.



(A)→(B) indicates: "Method A produces results useful in B, or supports in accomplishing B".

Figure 3: Appropriate combinations of collective inquiry methods for issue formulation and analysis



(A)→(B): Method A produces results useful in B, or supports accomplishing B.

Figure 4: Typical analysis methods combinations involving change over time

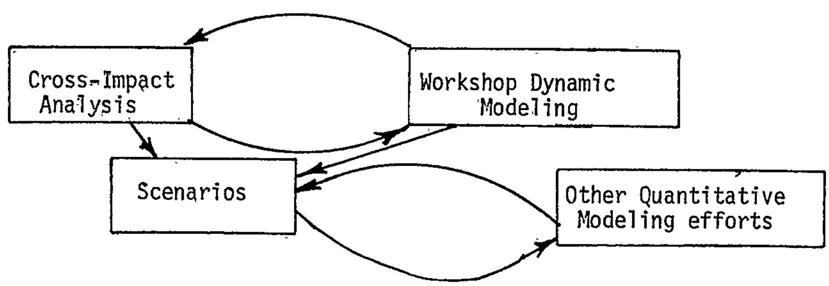


Figure 5: Illustration of combination of analysis methods

Figure 6 illustrates a third set of analysis methods that fit well together. Hypothesis Testing is used in Regression Analysis which, in turn, is one of the basic techniques used in both Econometrics and Trend Extrapolation/Time Series Forecasting. These two modeling approaches can be and are used together in the construction and analysis of economic models.

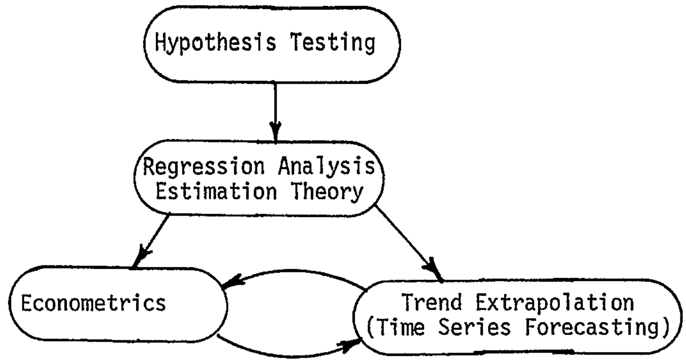


Figure 6: Illustration of combinations of algorithms for economic analysis and forecasting

Figure 7 shows typical combinations of methods centered around a complete-systems effort involving formulation analysis and interpretation. A brainwriting effort has been used to identify issue formulation elements. Attributes have also been identified . These are ordered using Interpretive Structural Modeling, which results in an Attribute Tree. A Decision Tree is used to structure the overall decision situation, and the information in both types of trees is used, together with analysis results, to assist the user in comparing and evaluating the decision alternatives using Worth Assessment, Multi-Attribute Utility Theory, or Policy Capture.

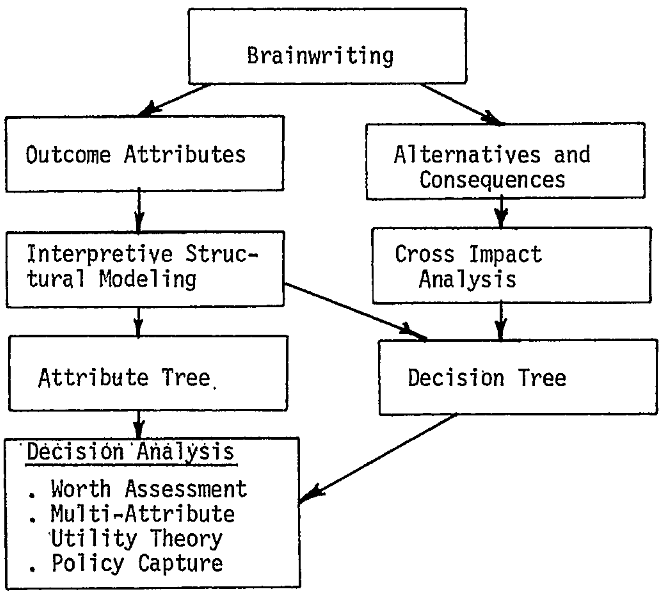


Figure 7: Possible method combinations for a complete planning and decision support system

A variety of methods can be used for exploration and determination of action plans for implementation. Among these are the ones shown in Figure 8. The basic activities in a plan might be identified using some element generation aids. Then, the activities are structured in a Network diagram-perhaps using Interpretive Structural Modeling. The Network Diagram can be used in conjunction with a great many other methods, notably Simulation, and Mathematical Programming for optimum scheduling given the constraints of the plan. Results of this may be displayed in the form of Gantt and DELTA Charts which support each other in clarifying an action plan.

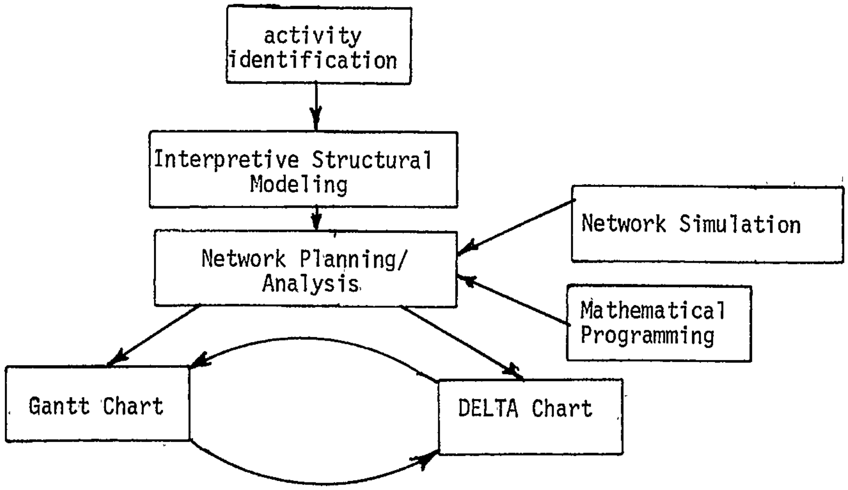


Figure 8: Possible method combinations for planning for action implementation

There are many more possible method combinations which might have to be designed especially for each specific problem. Thorough knowledge of what each method can accomplish under different conditions is a requirement for proper selection of a combination of modeling methods for a specific issue. Therefore, support of a knowledgeable broadly oriented systems analyst is very crucial in designing an overall issue resolution approach. In this regard it is especially critical that the operational environment and contingency task structure be given full consideration in the development of an appropriate methodology or combination of procedures for problem resolution. Without this consideration it is very possible that the resulting systemic process may be so ill matched to the real needs of the decision maker that far less than the best results obtainable, perhaps even very unacceptable results, may occur as a consequence of using the process. This caveat suggests a design approach for systemic processes which contains an operational evaluation phase as an essential feature [5].

6. SUMMARY

We have attempted a survey of systems engineering modeling methods. Our discussion of details of each method is necessarily space restricted as in our discussion of guidelines and use of methods. Considerably greater detail is provided concerning these methods in [6] and [7] and in [4].

7. REFERENCES

[1] A. P. Sage, "Systems Engineering: Fundamental Limits and Future Prospects", Proceedings of the IEEE, vol. 69, no. 2, February 1981.

[2] G. Majone and E. S. Quade, Pitfalls of Analysis, John Wiley, 1980.

[3] T. B. Green, S. M. Lee, and W. B. Newsom, The Decision Science Process, Petrocelli, 1978.

[4] W. A. Thissen, A. P. Sage, and J. N. Warfield, A Users Guide to Systems Methodology, Working Draft Report on NSF GRANT

[5] A. P. Sage, "A Methodology for System Design", Proceedings 1980 Conference on Cybernetics and Society, Boston, Ma., October 1980.

[6] A. P. Sage, Methodology for Large Scale Systems, McGraw-Hill, 1977.

[7] A. P. Sage, Systems Engineering: Methodology and Applications, IEEE Press and John Wiley & Sons, 1971.

[8] A. P. Sage, "Systems Engineering Linkages, Modeling, and Policy Analysis", Policy Analysis and Information Systems, vol. 2, no. 3, April 1979, pp. 55-67.