PART 2
SYSTEMS, CONTROLS, AND MEMS

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

CHAPTER 9

SYSTEMS ENGINEERING: ANALYSIS, DESIGN, AND INFORMATION PROCESSING FOR ANALYSIS AND DESIGN

Andrew P. Sage
School of Information Technology and Engineering
George Mason University
Fairfax, Virginia

1 INTRODUCTION **257**

2 THE SYSTEM LIFE CYCLE AND FUNCTIONAL ELEMENTS OF SYSTEMS ENGINEERING **260**

3 SYSTEMS ENGINEERING OBJECTIVES **266**

4 SYSTEMS ENGINEERING METHODOLOGY AND METHODS **267**
4.1 Issue Formulation 267
4.2 Issue Analysis 273
4.3 Information Processing by Humans and Organizations 278
4.4 Interpretation 282
4.5 The Central Role of Information in Systems Engineering 284

5 SYSTEM DESIGN **285**
5.1 The Purposes of Systems Design 285
5.2 Operational Environments and Decision Situation Models 287
5.3 The Development of Aids for the Systems Design Process 288
5.4 Leadership Requirements for Design 293
5.5 System Evaluation 293
5.6 Evaluation Test Instruments 296

6 CONCLUSIONS **296**

REFERENCES **298**

1 INTRODUCTION

Systems engineering is a management technology. Technology involves the organization and delivery of science for the (presumed) betterment of humankind. Management involves the interaction of the organization, and the humans in the organization, with the environment. Here, we interpret environment in a very general sense to include the complete external milieu surrounding individuals and organizations. Hence, systems engineering as a management technology involves three ingredients: science, organizations, and their environments. Information, and knowledge, is ubiquitous throughout systems engineering and management efforts and is, in reality, a fourth ingredient. Systems engineering is thus seen to involve science, organizations and humans, environments, technologies, and information and knowledge.

The process of systems engineering involves working with clients in order to assist them in the organization of information and knowledge to aid in judgment and choice of activities

Copyrighted Material
Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

that lead to the engineering of trustworthy systems. These activities result in the making of decisions and associated resource allocations through enhanced efficiency, effectiveness, equity, and explicability as a result of systems engineering efforts.

This set of action alternatives is selected from a larger set, in accordance with a value system, in order to influence future conditions. Development of a set of rational policy or action alternatives must be based on formation and identification of candidate alternative policies and objectives against which to evaluate the impacts of these proposed activities, such as to enable selection of efficient, effective, and equitable alternatives for implementation.

In this chapter, we are concerned with the engineering of large-scale systems, or *systems engineering.*[1] We are especially concerned with strategic-level systems engineering, or *systems management.*[2] We begin by first discussing the need for systems engineering and then providing some definitions of systems engineering. We next present a structure describing the systems engineering process. The result of this is a *life-cycle model* for systems engineering processes. This is used to motivate discussion of the functional levels, or considerations, involved in systems engineering efforts: *measurements, systems engineering methods and tools, systems methodology or processes,* and *systems management.* Considerably more details are presented in Refs. 1 and 2, which are the sources from which most of this chapter is derived.

Systems engineering is an appropriate combination of mathematical, behavioral, and management theories in a useful setting appropriate for the resolution of complex real-world issues of large scale and scope. As such, systems engineering consists of the use of management, behavioral, and mathematical constructs to identify, structure, analyze, evaluate, and interpret generally incomplete, uncertain, imprecise, and otherwise imperfect information. When associated with a value system, this information leads to knowledge to permit decisions that have been evolved with maximum possible understanding of their impacts. A central need, but by no means the only need, in systems engineering is to select an appropriate life cycle, or process, that is explicit, rational, and compatible with the implementation framework extant and the perspectives and knowledge bases of those responsible for decision activities. When this is accomplished, an appropriate choice of systems engineering methods and tools may be made to enable full implementation of the life-cycle process.

Information is a very important quantity that is assumed to be present in the management technology that is systems engineering. This strongly couples notions of systems engineering with those of technical direction or systems management of technological development, rather than exclusively with one or more of the methods of systems engineering, important as they may be for the ultimate success of a systems engineering effort. It suggests that *systems engineering is the management technology that controls a total system life-cycle process, which involves and which results in the definition, development, and deployment of a system that is of high quality, trustworthy, and cost-effective in meeting user needs.* This process-oriented notion of systems engineering and systems management will be emphasized here.

Among the appropriate conditions for use of systems engineering are the following:

- There are many considerations and interrelations.
- There are far-reaching and controversial value judgments.
- There are multidisciplinary and interdisciplinary considerations.
- The available information is uncertain, imprecise, incomplete, or otherwise flawed.
- Future events are uncertain and difficult to predict.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

- Institutional and organizational considerations play an important role.
- There is a need for explicit and explicable consideration of the efficiency, effectiveness, and equity of alternative courses of action.

There are a number of results potentially attainable from use of systems engineering approaches. These include:

- Identification of perceived needs in terms of identified objectives and values of a client group
- Identification or definition of a set of user or client requirements for the product system or service system that will ultimately be fielded
- Enhanced identification of a wide range of proposed alternatives or policies that might satisfy these needs, achieve the objectives of the clients in a high-quality and trustworthy fashion, and fulfill the requirements definition
- Increased understanding of issues that led to the effort and the impacts of alternative actions upon these issues
- Ranking of these identified alternative courses of action in terms of the utility (benefits and costs) in achieving objectives, satisfying needs, and fulfilling requirements
- A set of alternatives that is selected for implementation, generally by a group of content specialists responsible for detailed design and implementation, and an appropriate plan for action to achieve this implementation

Ultimately these action plans result in a working product or service, each of which is maintained over time in subsequent phases of the postdeployment efforts that also involve systems engineering.

To develop professionals capable of coping satisfactorily with diverse factors involved in widescope problem solving is a primary goal of systems engineering and systems engineering education. This does not imply that a single individual or even a small group can, despite its strong motivation, solve all of the problems involved in a systems study. Such a requirement would demand total and absolute intellectual maturity on the part of the systems engineer and such is surely not realistic. It is also unrealistic to believe that issues can be resolved without very close association with a number of people who have stakes, and who thereby become stakeholders, in problem solution efforts. Consequently, systems engineers must be capable of facilitation and communication of knowledge between the diverse groups of professionals, and their publics, that are involved in wide-scope problem solving. This requires that systems engineers be knowledgeable and able to use not only the technical methods-based tools that are needed for issue and problem resolution, but also the behavioral constructs and management abilities that are needed for resolution of complex, large-scale problems. Intelligence, imagination, and creativity are necessary but not sufficient for proper use of the procedures of systems engineering. Facility in human relations and effectiveness as a broker of information among parties at interest in a systems engineering program are very much needed as well.

It is this blending of the technical, managerial, and behavioral that is a normative goal of success for systems engineering education and for systems engineering professional practice. Thus, systems engineering involves:

- The sciences and the various methods, analysis, and measurement perspectives associated with the sciences
- Life-cycle process models for definition, development, and deployment of systems

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

- The systems management issues associated with choice of an appropriate process
- Organizations and humans and the understanding of organizational and human behavior
- Environments and understanding of the diverse interactions of organizations of people, technologies, and institutions with their environments
- Information and the way in which it can and should be processed to facilitate all aspects of systems engineering efforts

Successful systems engineering must be practiced at three levels: systems methods and measurements, systems processes and methodology, and systems management. Systems engineers must be aware of a wide variety of methods that assist in the formulation, analysis, and interpretation of contemporary issues. They must be familiar with systems engineering process life cycles (or methodology, as an open set of problem-solving procedures) in order to be able to select eclectic approaches that are best suited to the task at hand. Finally, a knowledge of systems management is necessary in order to be able to select life-cycle processes that are best matched to behavioral and organizational concerns and realities.

All three of these levels, suggested in Fig. 1, are important. To neglect any of them in the practice of systems engineering is to invite failure. It is generally not fully meaningful to talk only of a method or algorithm as a useful system-fielding or life-cycle process. It is ultimately meaningful to talk of a particular process as being useful. A process or product line that is truly useful for the fielding of a system will depend on the methods that are available, the operational environment, and leadership facets associated with use of the system and the system-fielding process. Thus systems management, systems engineering processes, and systems engineering methods and measurements do, separately and collectively, play a fundamental role in systems engineering.

2 THE SYSTEM LIFE CYCLE AND FUNCTIONAL ELEMENTS OF SYSTEMS ENGINEERING

We have provided one definition of systems engineering thus far. It is primarily a structural and process-oriented definition. A related definition, in terms of purpose, is that ''systems

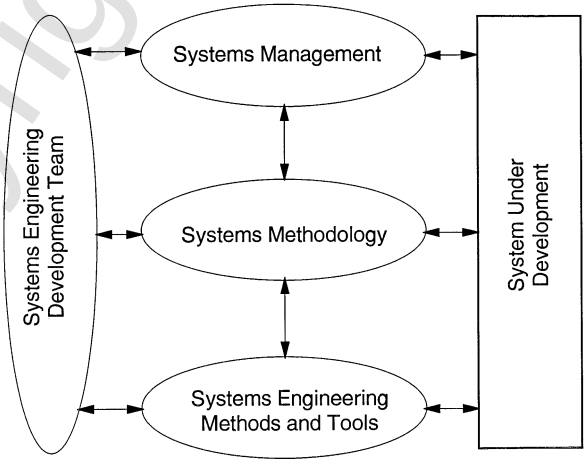


Figure 1 Conceptual illustration of the three levels for systems engineering.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

engineering is management technology to assist and support policy-making, planning, decision-making, and associated resource allocation or action deployment for the purpose of acquiring a product desired by customers or clients. Systems engineers accomplish this by quantitative and qualitative formulation, analysis, and interpretation of the impacts of action alternatives upon the needs perspectives, the institutional perspectives, and the value perspectives of their clients or customers.'' Each of these three steps is generally needed in solving systems engineering problems. Issue *formulation* is an effort to identify the needs to be fulfilled and the requirements associated with these in terms of objectives to be satisfied, constraints and alterables that affect issue resolution, and generation of potential alternative courses of action. Issue *analysis* enables us to determine the impacts of the identified alternative courses of action, including possible refinement of these alternatives. Issue *interpretation* enables us to rank in order the alternatives in terms of need satisfaction and to select one for implementation or additional study. This particular listing of three systems engineering steps and their descriptions is rather formal. Often, issues are resolved this way. The steps of formulation, analysis, and interpretation may also be accomplished on as ''as-if'' basis by application of a variety of often useful heuristic approaches. These may well be quite appropriate in situations where the problem solver is experientially familiar with the task at hand and the environment into which the task is imbedded.[1]

The key words in this definition are ''formulation,'' ''analysis,'' and ''interpretation.'' In fact, all of systems engineering can be thought of as consisting of formulation, analysis or assessment, and interpretation efforts, together with the systems management and technical direction efforts necessary to bring this about. We may exercise these in a formal sense throughout each of the several phases of a systems engineering life cycle or in an ''as-if'' or experientially based intuitive sense. These formulation, analysis, and interpretation efforts are the stepwise or microlevel components that comprise a part of the structural framework for systems methodology. They are needed for each phase in a systems engineering effort, although the specific formulation methods, analysis methods, and interpretation methods may differ considerably across the phases.

We can also think of a functional definition of systems engineering: ''Systems engineering is the art and science of producing a product, based on phased efforts, that satisfies user needs. The system is functional, reliable, of high quality, and trustworthy, and has been developed within cost and time constraints through use of an appropriate set of methods and tools.''

Systems engineers are very concerned with the appropriate *definition, development,* and *deployment* of product systems and service systems. These comprise a set of phases for a systems engineering life cycle. There are many ways to describe the life-cycle phases of the systems engineering process, and we have described a number of them in Refs. 1 and 2. Each of these basic life-cycle models, and those that are outgrowths of them, is comprised of these three phases of definition, development, and deployment. For pragmatic reasons, a typical life cycle will almost always contain more than three phases. Often, it takes on the ''waterfall'' pattern illustrated in Fig. 2, although there are a number of modifications of the basic waterfall, or ''grand-design,'' life cycles that allow for incremental and evolutionary development of systems life-cycle processes.[2]

A successful approach to systems engineering as an intellectual and action-based approach for increased innovation and productivity and other contemporary challenges must be capable of issue formulation, analysis, and interpretation at the level of institutions and values as well as at the level of symptoms. Systems engineering approaches must allow for the incorporation of need and value perspectives as well as technology perspectives into models and postulates used to evolve and evaluate policies or activities that may result in technological and other innovations.

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

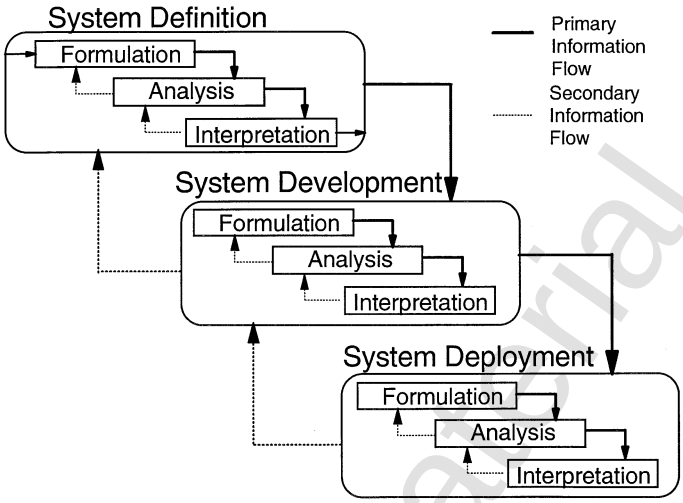


Figure 2 One representation of three systems engineering steps within each of three life-cycle phases.

In actual practice, the steps of the systems process (formulation, analysis, and interpretation) are applied iteratively, across each of the phases of a systems engineering effort, and there is much feedback from one step (and one phase) to the other. This occurs because of the learning that is accomplished in the process of problem solution. Underlying all of this is the need for a general understanding of the diversity of the many systems engineering methods and algorithms that are available and their role in a systems engineering process. The knowledge taxonomy for systems engineering, which consists of the major intellectual categories into which systems efforts may be categorized, is of considerable importance. The categories include systems methods and measurements, systems engineering processes or systems methodology, and systems management. These are used, as suggested in Fig. 3, to produce a *system,* which is a generic term that we use to describe a product or a service.

The methods and metrics associated with systems engineering involve the development and application of concepts that form the basis for problem formulation and solution in systems engineering. Numerous tools for mathematical systems theory have been developed, including operations research (linear programming, nonlinear programming, dynamic programming, graph theory, etc.), decision and control theory, statistical analysis, economic systems analysis, and modeling and simulation. Systems science is also concerned with psychology and human factors concepts, social interaction and human judgment research, nominal group processes, and other behavioral science efforts. Of very special significance for systems engineering is the interaction of the behavioral and the algorithmic components of systems science in the choice-making process. The combination of a set of systems science and operations research methods and a set of relations among these methods and activities constitutes what is known as a *methodology.* References 3 and 4 discuss a number of systems engineering methods and associated methodologies for systems engineering.

As we use it here, a methodology is an open set of procedures that provides the means for solving problems. The tools or the content of systems engineering consists of a variety of algorithms and concepts that use words, mathematics, and graphics. These are structured in ways that enable various problem-solving activities within systems engineering. Particular sets of relations among tools and activities, which constitute the framework for systems

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

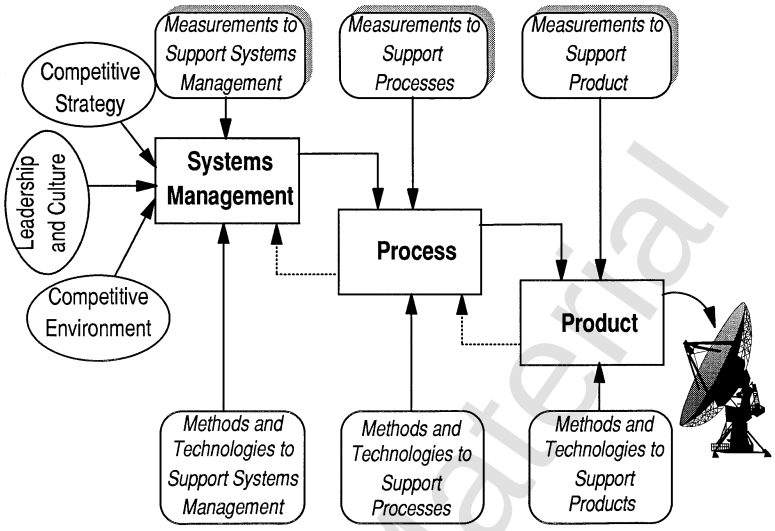


Figure 3 Representation of the structure systems engineering and management functional efforts.

engineering, are of special importance here. Existence and use of an appropriate systems engineering process are of considerable utility in dealing with the many considerations, interrelations, and controversial value judgments associated with contemporary problems.

Systems engineering can be and has been described in many ways. Of particular importance is a morphological description, that is, in terms of form. This description leads to a specific methodology that results in a process* that is useful for fielding a system and/or issue resolution. We can discuss the knowledge dimension of systems engineering. This would include the various disciplines and professions that may be needed in a systems team to allow it to accomplish intended purposes of the team, such as provision of the knowledge base. Alternatively, we may speak of the phases or time dimension of a systems effort. These include system definition, development, and deployment. The deployment phase includes system operation, maintenance, and finally modification or reengineering or ultimate retirement and phase-out of the system. Of special interest are the steps of the logic structure or logic dimension of systems engineering:

- Formulation of issues, or identification of problems or issues in terms of needs and constraints, objectives, or values associated with issue resolution, and alternative policies, controls, hypotheses, or complete systems that might resolve or ameliorate issues
- Analysis of impacts of alternative policies, courses of action, or complete systems
- Interpretation or evaluation of the utility of alternatives and their impacts upon the affected stakeholder group and selection of a set of action alternatives for implementation

* As noted in Refs. 1 and 2, there are life cycles for systems engineering efforts in research, development, test, and evaluation (RDT&E); systems acquisition, production, or manufacturing; and systems planning and marketing. Here, we restrict ourselves to discussions of the life cycle associated with acquisition or production of a system.

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

We could also associate feedback and learning steps to interconnect these steps one to another. The systems process is typically very iterative. We shall not explicitly show feedback and learning in our conceptual models of the systems process, although it is ideally always there.

Here we have described a three-dimensional morphology of systems engineering. There are a number of systems engineering morphologies or frameworks. In many of these, the logic dimension is divided into a larger number of steps that are iterative in nature. A particular seven-step framework, due to Hall,[5,6] involves:

1. *Problem definition,* in which a descriptive and normative scenario of needs, constraints, and alterables associated with an issue is developed. Problem definition clarifies the issues under consideration to allow other steps of a systems engineering effort to be carried out.
2. *Value system design,* in which objectives and objectives measures or attributes with which to determine success in achieving objectives are determined. Also, the interrelationship between objectives and objectives measures and the interaction between objectives and the elements in the problem definition step are determined. This establishes a measurement framework, which is needed to establish the extent to which the impacts of proposed policies or decisions will achieve objectives.
3. *System synthesis,* in which candidate or alternative decisions, hypotheses, options, policies, or systems that might result in needs satisfaction and objective attainment are postulated.
4. *Systems analysis and modeling,* in which models are constructed to allow determination of the consequences of pursuing policies. Systems analysis and modeling determine the behavior or subsequent conditions resulting from alternative policies and systems. Forecasting and impact analysis are, therefore, the most important objectives of systems analysis and modeling.
5. *Optimization or refinement* of each alternative, in which the individual policies and/or systems are tuned, often by means of parameter adjustment methods, so that each individual policy or system is refined in some ''best'' fashion in accordance with the value system that has been identified earlier.
6. *Evaluation and decision making,* in which systems and/or policies and/or alternatives are evaluated in terms of the extent to which the impacts of the alternatives achieve objectives and satisfy needs. Needed to accomplish evaluation are the attributes of the impacts of proposed policies and associated objective and/or subjective measurement of attribute satisfaction for each proposed alternative. Often this results in a prioritization of alternatives, with one or more being selected for further planning and resource allocation.
7. *Planning for action,* in which implementation efforts, resource and management allocations, or plans for the next phase of a systems engineering effort are delineated.

More often than not, the information required to accomplish these seven steps is not perfect due to information uncertainty, imprecision, or incompleteness effects. This presents a major challenge to the design of processes and for systems engineering practice as well.

Figure 4 illustrates a not-untypical 49-element morphological box for systems engineering. This is obtained by expanding our initial three systems engineering steps of formulation, analysis, and interpretation to the seven just discussed. The three basic phases of definition, development, and deployment are expanded to a total of seven phases. These seven steps, and the seven phases that we associate with them, are essentially those identified

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

Phases of Systems Engineering			Steps of Systems Engineering: Formulation: Problem Definition	Formulation: Value System Design	Formulation: System Synthesis	Analysis: Systems Analysis	Analysis: Alternative Refinement	Interpretation: Decision Making	Interpretation: Planning for Action
	Definition	Program Planning	1	2	3	4	5	6	7
		Project Planning	8						
	Develop-ment	System Development		16					
		Production							
	Deployment	Distribution							
		Operations			38				
		Reengineering or Retirement						48	49

Figure 4 The phases and steps in one 49-element two-dimensional systems engineering framework with activities shown sequentially for waterfall implementation of effort.

by Hall in his pioneering efforts in systems engineering.[5,6] The specific methods we need to use in each of these seven steps are clearly dependent upon the phase of activity that is being completed, and there are a plethora of systems engineering methods available.[3,4] Using a seven-phase, seven-step framework raises the number of activity cells to 49 for a single life cycle. A very large number of systems engineering methods may be needed to fill in this matrix, especially since more than one method will almost invariably be associated with many of the entries.

The requirements and specification phase of the systems engineering life cycle has as its goal the identification of client or stakeholder needs, activities, and objectives for the functionally operational system. This phase should result in the identification and description of preliminary conceptual design considerations for the next phase. It is necessary to translate operational deployment needs into requirement specifications so that these needs may be addressed by the system design efforts. As a result of the requirement specification phase, there should exist a clear definition of development issues such that it becomes possible to make a decision concerning whether to undertake preliminary conceptual design. If the requirement specification effort indicates that client needs can be satisfied in a functionally satisfactory manner, then documentation is typically prepared concerning system-level specifications for the preliminary conceptual design phase. Initial specifications for the following three phases of effort are typically also prepared, and a concept design team is selected to implement the next phase of the life-cycle effort. This effort is sometimes called *system-level architecting.*[7,8] Many[9,10] have discussed technical-level architectures. It is only recently that the need for major attention to architectures at the systems level has also been identified.

Preliminary conceptual system design typically includes, or results in, an effort to specify the content and associated architecture and general algorithms for the system product in question. The desired product of this phase of activity is a set of detailed design and architectural specifications that should result in a useful system product. There should exist a high degree of user confidence that a useful product will result from detailed design or the entire design effort should be redone or possibly abandoned. Another product of this phase is a refined set of specifications for the evaluation and operational deployment phases of the

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

life cycle. In the third phase, these are translated into detailed representations in logical form so that system development may occur. A product, process, or system is produced in the fourth phase of the life cycle. This is not the final system design, but rather the result of implementation of the design that resulted from the conceptual design effort.

Evaluation of the detailed design and the resulting product, process, or system is achieved in the sixth phase of the systems engineering life cycle. Depending upon the specific application being considered, an entire systems engineering life-cycle process could be called *design,* or *manufacturing,* or some other appropriate designator. *System acquisition* is an often-used term to describe the entire systems engineering process that results in an operational systems engineering product. Generally, an acquisition life cycle primarily involves knowledge practices or standard procedures to produce or manufacture a product based on established practices. An RDT&E life cycle is generally associated with an emerging technology and involves knowledge principles. A marketing life cycle is concerned with product planning and other efforts to determine market potential for a product or service and generally involves knowledge perspectives.

The intensity of effort needed for the steps of systems engineering varies greatly with the type of problem being considered. Problems of large scale and scope will generally involve a number of perspectives. These interact and the intensity of their interaction and involvement with the issue under consideration determines the scope and type of effort needed in the various steps of the systems process. Selection of appropriate algorithms or approaches to enable completion of these steps and satisfactory transition to the next step, and ultimately to completion of each phase of the systems engineering effort, are major systems engineering tasks.

Each of these phases of a systems engineering life cycle is very important for sound development of physical systems or products and such service systems as information systems. Relatively less attention appears to have been paid to the requirement specification phase than to the other phases of the systems engineering life-cycle process. In many ways, the requirement specification phase of a systems engineering design effort is the most important. It is this phase that has as its goal the detailed definition of the needs, activities, and objectives to be fulfilled or achieved by the process to be ultimately developed. Thus, this phase strongly influences all the phases that follow. It is this phase that describes preliminary design considerations that are needed to achieve successfully the fundamental goals underlying a systems engineering study. It is in this phase that the information requirements and the method of judgment and choice used for selection of alternatives are determined. Effective systems engineering, which inherently involves design efforts, must also include an operational evaluation component that will consider the extent to which the product or service is useful in fulfilling the requirements that it is intended to satisfy.

3 SYSTEMS ENGINEERING OBJECTIVES

Ten performance objectives appear to be of primary importance to those who desire to evolve quality plans, forecasts, decisions, or alternatives for action implementation:

1. Identify needs, constraints, and alterables associated with the problem, issue, or requirement to be resolved (problem definition).
2. Identify a planning horizon or time interval for alternative action implementation, information flow, and objective satisfaction (planning horizon, identification).
3. Identify all significant objectives to be fulfilled, values implied by the choice of objectives, and objectives measures or attributes associated with various outcome states, with which to measure objective attainment (value system design).

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

4. Identify decisions, events, and event outcomes and the relations among them such that a structure of the possible paths among options, alternatives, or decisions and the possible outcomes of these emerge (impact assessment).
5. Identify uncertainties and risks associated with the environmental influences affecting alternative decision outcomes (probability identification).
6. Identify measures associated with the costs and benefits or attributes of the various outcomes or impacts that result from judgment and choice (worth, value, or utility measurement).
7. Search for and evaluate new information, and the cost-effectiveness of obtaining this information, relevant to improved knowledge of the time-varying nature of event outcomes that follow decisions or choice of alternatives (information acquisition and evaluation).
8. Enable selection of a best course of action in accordance with a rational procedure (decision assessment and choice making).
9. Reexamine the expected effectiveness of all feasible alternative courses of action, including those initially regarded as unacceptable, prior to making a final alternative selection (sensitivity analysis).
10. Make detailed and explicit provisions for implementation of the selected action alternative, including contingency plans, as needed (planning for implementation of action).

These objectives are, of course, very closely related to the aforementioned steps of the framework for systems engineering. To accomplish them requires attention to and knowledge of the methods of systems engineering such that we are able to design product systems and service systems and also enabling systems to support products and services. We also need to select an appropriate process, or product line, to use for management of the many activities associated with fielding a system. Also required is much effort at the level of systems management so that the resulting process is efficient, effective, equitable, and explicable. Thus, it is necessary to ensure that those involved in systems engineering efforts be concerned with technical knowledge of the issue under consideration, able to cope effectively with administrative concerns relative to the human elements of the issue, interested in and able to communicate across those actors involved in the issue, and capable of innovation and outscoping of relevant elements of the issue under consideration. These attributes (technical knowledge, human understanding and administrative ability, communicability, and innovativeness) are, of course, primary attributes of effective management.

4 SYSTEMS ENGINEERING METHODOLOGY AND METHODS

A variety of methods are suitable to accomplish the various steps of systems engineering. We shall briefly describe some of them here.

4.1 Issue Formulation

As indicated above, issue formulation is the step in the systems engineering effort in which the problem or issue is defined (problem definition) in terms of the objectives of a client group (value system design) and where potential alternatives that might resolve needs are identified (system synthesis). Many studies have shown that the way in which an issue is resolved is critically dependent on the way in which the issue is formulated or framed. The

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

issue formulation effort is concerned primarily with identification and description of the elements of the issue under consideration, with, perhaps, some initial effort at structuring these in order to enhance understanding of the relations among these elements. Structural concerns are also of importance in the analysis effort. The systems process is iterative and interactive, and the results of preliminary analysis are used to refine the issue formulation effort. Thus, the primary intent of issue formulation is to identify relevant elements that represent and are associated with issue definition, the objectives that should be achieved in order to satisfy needs, and potential action alternatives.

There are at least four ways to accomplish issue formulation, or to identify requirements for a system, or to accomplish the initial part of the definition phase of systems engineering:

1. Asking stakeholders in the issue under consideration for the requirements
2. Descriptive identification of the requirements from a study of presently existing systems
3. Normative synthesis of the requirements from a study of documents describing what ''should be,'' such as planning documents
4. Experimental discovery of requirements, based on experimentation with an evolving system

These approaches are neither mutually exclusive nor exhaustive. Generally, the most appropriate efforts will use a combination of these approaches.

There are conflicting concerns with respect to which blend of these requirement identification approaches is most appropriate for a specific task. The asking approach seems very appropriate when there is little uncertainty and imprecision associated with the issue under consideration, so that the issue is relatively well understood and may be easily structured, and where members of the client group possess much relevant expertise concerning the issue and the environment in which the issue is embedded. When these characteristics of the issue—lack of imprecision and presence of expert experiential knowledge—are present, then a direct declarative approach based on direct ''asking'' of ''experts'' is a simple and efficient approach. When there is considerable imprecision or a lack of experiential familiarity with the issue under concern, the other approaches take on greater significance. The asking approach is also prone to a number of human information-processing biases, as will be discussed in Section 4.5. This is not as much of a problem in the other approaches.

Unfortunately, however, there are other difficulties with each of the other three approaches. Descriptive identification, from a study of existing systems of issue formulation elements, will very likely result in a new system that is based or anchored on an existing system and tuned, adjusted, or perturbed from this existing system to yield incremental improvements. Thus, it is likely to result in incremental improvements to existing systems but not to result in major innovations or totally new systems and concepts.

Normative synthesis from a study of planning documents will result in an issue formulation or requirement identification effort that is based on what have been identified as desirable objectives and needs of a client group. A plan at any given phase may well not exist or it may be flawed in any of several ways. Thus, the information base may well not be present or may be flawed. When these circumstances exist, it will not be a simple task to accomplish effective normative synthesis of issue formulation elements for the next phase of activity from a study of planning documents relative to the previous phase.

Often it is not easily possible to determine an appropriate set of issue formulation elements or requirements. Often it will not be possible to define an appropriate set of issue formulation efforts prior to actual implementation of a preliminary system design. There are many important issues where there is an insufficient experiential basis to judge the effect-

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

iveness and completeness of a set of issue formulation efforts or requirements. Often, for example, clients will have difficulty in coping with very abstract formulation requirements and in visualizing the system that may ultimately evolve. Thus, it may be useful to identify an initial set of issue formulation elements and accomplish subsequent analysis and interpretation based on these, without extraordinary concern for completeness of the issue formulation efforts. A system designed with ease of adaptation and change as a primary requirement is implemented on a trial basis. As users become familiar with this new system or process, additions and modifications to the initially identified issue formulation elements result. Such a system is generally known as a *prototype*. One very useful support for the identification of requirements is to build a prototype and allow the users of the system to be fielded to experiment with the prototype and, through this experimentation, to identify system requirements.[11] This heuristic approach allows users to identify the requirements for a system by experimenting with an easily changeable set of system design requirements and to improve their identification of these issue formulation elements as their experiential familiarity with the evolving prototype system grows.

The key parts of the problem definition step of issue formulation involve identification of needs, constraints, and alterables and determination of the interactions among these elements and the group that they impact. Need is a condition requiring supply or relief or is a lack of something required, desired, or useful. In order to define a problem satisfactorily, we must determine the alterables or those items pertaining to the needs that can be changed. Alterables can be separated into those over which control is or is not possible. The controllable alterables are of special concern in systems engineering since they can be changed or modified to assist in achieving particular outcomes. To define a problem adequately, we must also determine the limitations or constraints under which the needs can or must be satisfied and the range over which it is permissible to vary the controllable alterables. Finally, we must determine relevant groups of people who are affected by a given problem.

Value system design is concerned with defining objectives, determining their interactions, and ordering these into a hierarchical structure. Objectives and their attainment are, of course, related to the needs, alterables, and constraints associated with problem definition. Thus, the objectives can and should be related to these problem definition elements. Finally, a set of measures is needed whereby to measure objective attainment. Generally, these are called *attributes of objectives* or *objectives measures*. It is necessary to ensure that all needs are satisfied by attainment of at least one objective.

The first step in system synthesis is to identify activities and alternatives for attaining each of the objectives or the postulation of complete systems to this end. It is then desirable to determine interactions among the proposed activities and to illustrate relationships between the activities and the needs and objectives. Activities measures are needed to gauge the degree of accomplishment of proposed activities. Systemic methods useful for problem definition are generally useful for value system design and system synthesis as well. This is another reason that suggests the efficacy of aggregating these three steps under a single heading: *issue formulation*.

Complex issues will have a structure associated with them. In some problem areas, structure is well understood and well articulated. In other areas, it is not possible to articulate structure in such a clear fashion. There exists considerable motivation to develop techniques with which to enhance structure determination, as a system structure must always be dealt with by individuals or groups, regardless of whether the structure is articulated or not. Furthermore, an individual or a group can deal much more effectively with systems and make better decisions when the structure of the underlying system is well defined and exposed and communicated clearly. One of the fundamental objectives of systems engineering is to

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

structure knowledge elements such that they are capable of being better understood and communicated.

We now discuss several formal methods appropriate for ''asking'' as a method of issue formulation. Most of these, and other, approaches are described in Refs. 1, 3, and 4. Then we shall very briefly contrast and compare some of these approaches. The methods associated with the other three generic approaches to issue formulation also involve approaches to analysis that will be discussed in the next section.

Several of the formal methods that are particularly helpful in the identification, through asking, of issue formulation elements are based on principles of collective inquiry, in which interested and motivated people are brought together to stimulate each other's creativity in generating issue formulation elements. We may distinguish two groups of collective-inquiry methods:

1. *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 an hour. Synectics, based on problem analogies, might be 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.
2. *Questionnaires, Surveys,* 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 first group of methods. In questionnaires and surveys, a usually large number of participants are 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, who are asked to comment, revise their views as desired, and so on. A Delphi exercise 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 also typically lead to identification of new elements and revision of element definitions. As we have indicated, most structuring methods contain an analytical component; they may, therefore, be more properly labeled analysis methods. The following element-structuring aids are among the many modeling aids available:

- *Interaction matrices* may be used 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, such as objectives and alternatives. In this case, we produce cross-interaction matrices, such as shown in Fig. 5. 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* are graphical aids particularly useful in portraying 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. Figure 6 presents an

Copyrighted material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

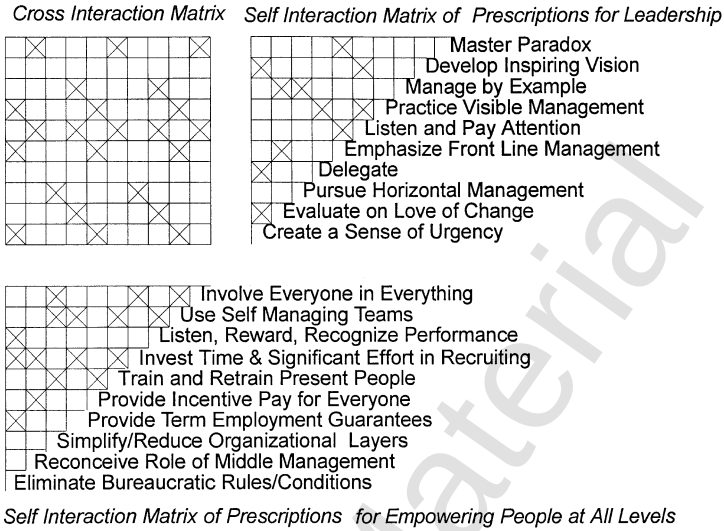


Figure 5 Hypothetical self- and cross-interaction matrices for prescriptions for leadership and for empowering people at all levels.

1. Understanding of Problem
   - 1.1 Navy Cost Credentialing Process
   - 1.2 NAVELEX Cost Analysis Methodology
   - 1.3 DoD Procurement Procedures
2. Technical Approach
   - 2.1 Establishment of a Standard Methodology
   - 2.2 Compatibility with Navy Acquisition Process
3. Staff Experience
   - 3.1 Directly Related Experience in Cost Credentialing, Cost Analysis, and Procurement Procedures
   - 3.2 Direct Experience with Navy R&D Programs
4. Corporate Qualification
   Relevant Experience in Cost Analysis for Navy R&D Programs
5. Management Approach
   - 5.1 Quality/Relevance
   - 5.2 Organization and Control Effectiveness
6. Cost
   - 6.1 Manner in which Elements of Cost Contribute Directly to Project Success
   - 6.2 Appropriate of Cost Mix to the Technical Effort

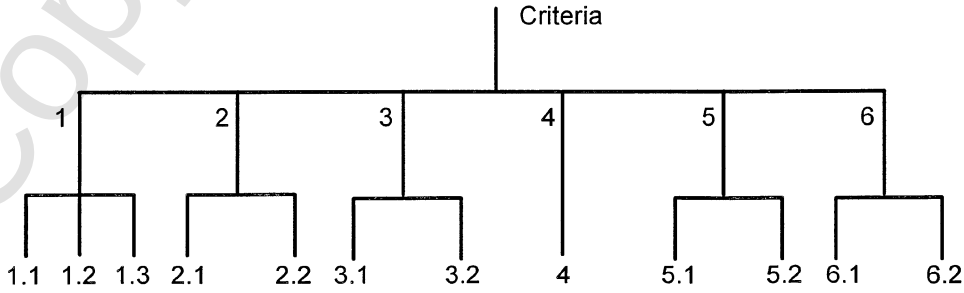


Figure 6 Possible attribute tree for evaluation of proposals concerning cost credentialing.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

attribute tree that represents those aspects that will be formally considered in the evaluation and prioritization of a set of proposals.

- *Causal loop diagrams,* or influence diagrams, represent graphical pictures of causal interactions between sets of variables. They are particularly helpful in making explicit one's perception of the causes of change in a system and can serve very well as communication aids. A causal loop diagram is also useful as the initial part of a detailed simulation model. Figure 7 represents a causal loop diagram of a belief structure.

Two other descriptive methods are potentially useful for issue formulation:

- The *system definition matrix,* options profile, decision balance sheet, or checklist 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. The system definition matrix is just a table that shows important aspects of the options that are important for judgment relative to selection of approaches to issue formulation or requirement determination.
- *Scenario writing* is based on narrative and creative descriptions of existing or possible situations or developments. Scenario descriptions can be 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.

Clearly, successful formulation of issues through ''asking'' requires creativity. Creativity may be much enhanced through use of a structured systems engineering framework. For example, group meetings for issue formulation involve idea formulation, idea analysis, and idea interpretation. The structure of a group meeting may be conceptualized within a systems engineering framework. This framework is especially useful for visualizing the trade-offs that

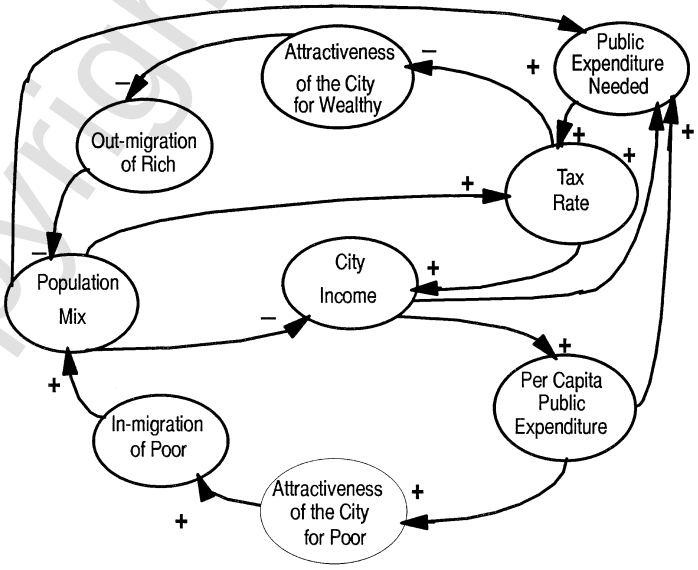


Figure 7 Causal loop diagram of belief structure in a simple model of urban dynamics.

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

must be made among allocation of resources for formulation, analysis, and interpretation of ideas in the issue formulation step itself. If there is an emphasis on idea formulation, we shall likely generate too many ideas to cope with easily. This will lead to a lack of attention to detail. On the other hand, if idea formulation is deemphasized, we shall typically encourage defensive avoidance through undue efforts to support the present situation or a rapid unconflicted change to a new situation. An overemphasis on analysis of ideas is usually time consuming and results in a meeting that seems to drown in details. There is inherent merit in encouraging a group to reach consensus, but the effort may also be inappropriate, since it may encourage arguments over concerns that are ineffective in influencing judgments.

Deemphasizing the analysis of identified ideas will usually result in disorganized meetings in which hasty, poorly thought-out ideas are accepted. Postmeeting disagreements concerning the results of the meeting are another common disadvantage. An emphasis on interpretation of ideas will produce a meeting that is emotional and people centered. Misunderstandings will be frequent as issues become entrenched in an adversarial, personality-centered process. On the other hand, deemphasizing the interpretation of ideas results in meetings in which important information is not elicited. Consequently, the meeting is awkward and empty, and routine acceptance of ideas is a likely outcome.

4.2 Issue Analysis

In systems engineering, issue analysis involves forecasting and assessing of the impacts of proposed alternative courses of action. In turn, this suggests construction, testing, and validation of models. Impact assessment in systems engineering includes system analysis and modeling and optimization and ranking or refinement of alternatives. First, the options or alternatives defined in issue formulation are structured, often as part of the issue formulation effort, and then analyzed in order to assess the anticipated impacts that may result from their implementation. Second, a refinement or optimization effort is often desirable. This is directed toward refinement or fine-tuning a viable alternative and parameters within an alternative, so as to obtain maximum needs satisfaction, within given constraints, from a proposed policy.

To determine the structure of systems in the most effective manner requires the use of quantitative analysis to direct the structuring effort along the most important and productive paths. This is especially needed when time available to construct structural models is limited. Formally, there are at least four types of self-interaction matrices: nondirected graphs, directed graphs (or digraphs), signed digraphs, and weighted digraphs. The theory of digraphs and structural modeling is authoritatively presented in Ref. 12 and a number of applications to what is called *interpretative structural modeling* are described in Refs. 3, 13, 14, and 15. Cognitive map structural models are considered in Ref. 16. A development of structural modeling concepts based on signed digraphs is discussed in Ref. 17. Geoffrion has been especially concerned with the development of a structured modeling methodology[18,19] and environment. He has noted[20] that a modeling environment needs five quality- and productivity-related properties. A modeling environment should:

1. Nurture the entire modeling life cycle, not just a part of it
2. Be hospitable to decision- and policy-makers as well as to modeling professionals
3. Facilitate the maintenance and ongoing evolution of those models and systems that are contained therein
4. Encourage and support those who use it to speak the same paradigm-neutral language in order to best support the development of modeling applications
5. Facilitate management of all the resources contained therein

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

Structured modeling is a general conceptual framework for modeling. Cognitive maps, interaction matrices, intent structures, Delta charts, objective and attribute trees, causal loop diagrams, decision outcome trees, signal flow graphs, and so on are all structural models that are very useful graphic aids to communications. The following are requirements for the processes of structural modeling:

1. An object system, which is typically a poorly defined, initially unstructured set of elements to be described by a model
2. A representation system, which is a presumably well-defined set of relations
3. An embedding of perceptions of some relevant features of the object system into the representation system

Structural modeling, which has been of fundamental concern for some time, refers to the systemic iterative application of typically graph-theoretic notions such that an easily communicable directed-graph representation of complex patterns of a particular contextual relationship among a set of elements results. There are a number of computer software realizations of various structural modeling constructs, such as cognitive policy evaluation (COPE), interpretive structural modeling (ISM), and various multiattribute utility theory-based representations, as typically found in most decision-aiding software.

Transformation of a number of identified issue formulation elements, which typically represent unclear, poorly articulated mental models of a system, into visible, well-defined models useful for many purposes is the object of systems analysis and modeling. The principal objective of systems analysis and modeling is to create a process with which to produce information concerning consequences of proposed actions or policies. From the issue formulation steps of problem definition, value system design, and system synthesis, we have various descriptive and normative scenarios available for use. Ultimately, as a part of the issue interpretation step, we wish to evaluate and compare alternative courses of action with respect to the value system through use of a systems model. A model is always a substitute for reality but is, one hopes, descriptive enough of the system elements under consideration to be useful. By posing a variety of questions using the model, we can, from the results obtained, learn how to cope with that subset of the real world being modeled.

A model must depend on much more than the particular problem definition elements being modeled; it must also depend strongly on the value system and the purpose behind construction and utilization of the model. These influence, generally strongly, the structure of the situation and the elements that comprise this structure. Which elements a client believes important enough to include in a model depend on the client's value system.

We wish to be able to determine correctness of predictions and forecasts that are based on model usage. Given the definition of a problem, a value system, and a set of proposed policies, we wish to be able to design a simulation model consisting of relevant elements of these three steps and to determine the results or impacts of implementing proposed policies. Following this, we wish to be able to validate a simulation model to determine the extent to which it represents reality sufficiently to be useful. Validation must, if we are to have confidence in what we are doing with a model, precede actual use of model-based results.

There are three essential steps in constructing a simulation model:

1. Determination of those problem definitions, value systems, and system synthesis elements that are most relevant to a particular problem
2. Determination of the structural relationships among these elements
3. Determination of parametric coefficients within the structure

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

There are 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 are the objects of a descriptive model. Good descriptive models are of considerable value in that they reveal much about the substance of complex issues and how, typically in a retrospective sense, change over time has occurred. One of the primary purposes behind constructing a descriptive model is to learn about the past. Often the past will be a good guide to the future.

In building a predictive or forecasting model, we must be especially concerned with determination of proper cause-and-effect relationships. If the future is to be predicted with integrity, we must have a method with which to determine exogenous variables, or input variables that result from external causes, accurately. Also, the model structure and parameters within the structure must be valid for the model to be valid. Often, it will not be possible to predict accurately all exogenous variables; in that case, conditional predictions can be made from particular assumed values of unknown exogenous variables.

The future is inherently uncertain. Consequently, predictive or forecasting models are often used to generate a variety of future scenarios, each a conditional prediction of the future based on some conditioning assumptions. In other words, we develop an ''if–then'' model.

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 be evaluated in terms of a value system. Policy or planning efforts must not only predict outcomes from implementing alternative policies but also present these outcomes in terms of the value system that is in a form useful and suitable for alternative ranking, evaluation, and decision making. Thus, a policy model must contain some provision for impact interpretation.

Model usefulness cannot be determined by objective truth criteria alone. Well-defined and well-stated functions and purposes for the simulation model are needed to determine simulation model usefulness. Fully objective criteria for model validity do not typically exist. Development of a general-purpose, context-free simulation model appears unlikely; the task is simply far too complicated. We must build models for specific purposes, and thus the question of model validity is context dependent.

Model credibility depends on the interaction between the model and model user. One of the major potential difficulties is that of building a model that reflects the outlook of the modeler. This activity is proscribed in effective systems engineering practice, since the purpose of a model is to describe systematically the ''view'' of a situation held by the client, not that held by the analyst.

A great variety of approaches have been designed and used for the forecasting and assessment that are the primary goals of systems analysis. There are basically two classes of methods that we describe here: expert-opinion methods and modeling and/or simulation methods.

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 system, as a result of their experience with or insight into the issue or problem area. These methods are generally useful, particularly 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. There are, of course, many other methods of asking experts for their opinion—for example, hearings, meetings, and conferences. A particular problem with such methods is that cognitive bias and value incoherence are widespread, often resulting in inconsistent and self-contradictory results.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

There exists a strong need in the forecasting and assessment community to recognize and ameliorate, by appropriate procedures, the effects of cognitive bias and value incoherence in expert-opinion-modeling efforts. Expert-opinion methods are often appropriate for the ''asking'' approach to issue formulation. They may be of considerably less value, especially when used as stand-alone approaches, for impact assessment and forecasting.

Simulation and modeling methods are based on the conceptualization and use of an abstraction or model of the real world intended to behave in a similar way to the real system. Impacts of policy alternatives are studied in the model, which will, it is hoped, lead to increased insight with respect to the actual situation.

Most simulation and modeling methods use 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 the computer is combined with subjective expert judgments are cross-impact analysis and workshop dynamic models. 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. The computer derives the resulting behavior of various model elements over time, giving rise to renewed discussion and revision of assumptions.

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, cross-impact, or workshop dynamic models. As a result, internal inconsistency problems are reduced with those methods based on mathematical modeling. The following list describes six additional forecasting methods based on mathematical modeling and simulation. In these methods, a structural model is generally formed on the basis of expert opinion and physical or social laws. Available data are then processed to determine parameters within the structure. Unfortunately, these methods are sometimes very data intensive and, therefore, expensive and time consuming to implement.

- Trend extrapolation/time-series forecasting 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 into the future, typically over the short to medium term.
- Continuous-time dynamic simulation is based on postulation and qualification 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.
- Discrete-event digital simulation models are based on applications of queuing theory to determine the conditions under which system outputs or states will switch from one condition to another.
- Input–output analysis has been specially 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 mathematically is relatively simple and can handle many details.
- Econometrics is a 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 on macroeconomic theory and the derivation of unknown parameters in behavioral equations from available economic data.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

- Microeconomic models represent an application of economic theories of firms and consumers who desire to maximize the profit and utility of their production and consumption alternatives.

Parameter estimation is a very important subject with respect to model construction and validation. Observation of basic data and estimation or identification of parameters within an assumed structure, often denoted as system identification, are essential steps in the construction and validation of system models. The simplest estimation procedure, in both concept and implementation, appears to be the least-squares error estimator. Many estimation algorithms to accomplish this are available and are in actual use. The subjects of parameter estimation and system identification are being actively explored in both economics and systems engineering. There are numerous contemporary results, including algorithms for system identification and parameter estimation in very-large-scale systems representative of actual physical processes and organizations.

Verification of a model is necessary to ensure that the model behaves in a fashion intended by the model builder. If we can determine that the structure of the model corresponds to the structure of the elements obtained in the problem definition, value system design, and system synthesis steps, then the model is verified with respect to behaving in a gross, or structural, fashion, as the model builder intends.

Even if a model is verified in a structural as well as parametric sense, there is still no assurance that the model is valid in the sense that predictions made from the model will occur. We can determine validity only with respect to the past. That is all that we can possibly have available at the present. Forecasts and predictions inherently involve the future. Since there may be structural and parametric changes as the future evolves, and since knowledge concerning results of policies not implemented may never be available, there is usually no way to validate a model completely. Nevertheless, there are several steps that can be used to validate a model. These include a reasonableness test in which we determine that the overall model, as well as model subsystems, responds to inputs in a reasonable way, as determined by ''knowledgeable'' people. The model should also be valid according to statistical time series used to determine parameters 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.

Once a model has been constructed, it is often desirable to determine, in some best fashion, various policy parameters or controls that are subject to negotiation. The optimization or refinement-of-alternatives step is concerned with choosing parameters or controls to maximize or minimize a given performance index or criterion. Invariably, there are constraints that must be respected in seeking this extremum. As previously noted, the analysis step of systems engineering consists of systems analysis and modeling and optimization or refinement of alternatives and related methods that are appropriate in aiding effective judgment and choice.

There exist a number of methods for fine tuning, refinement, or optimization of individual specific alternative policies or systems. These are useful in determining 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, however, approaches to multiple objective optimization that are based on welfare-type optimization concepts. It is these individually optimized policies or systems that are an input to the evaluation and decision-making effort in the interpretation step of systems engineering.

Among the many methods for optimization and refinement of alternatives are:

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

- *Mathematical programming,* which is used extensively for operations research and analysis practice, 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,* which 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 to use this approach. Optimum systems control is particularly suitable for refining controls or parameters in systems in which changes over time play an important part.

Application of the various refinement or optimization methods, like those described here, typically requires significant training and experience on the part of the systems analyst. Some of the many characteristics of analysis that are of importance for systemic efforts include the following:

1. Analysis methods are invaluable for understanding the impacts of proposed policy.
2. Analysis methods lead to consistent results if cognitive bias issues associated with expert forecasting and assessment methods are resolved.
3. Analysis methods may not necessarily lead to correct results since ''formulation'' may be flawed, perhaps by cognitive bias and value incoherence.

Unfortunately, however, large models and large optimization efforts are often expensive and difficult to understand and interpret. There are a number of possibilities for ''paralysis through analysis'' in the unwise use of systems analysis. On the other hand, models and associated analysis can help provide a framework for debate. It is important to note that small ''back-of-the-envelope'' models can be very useful. They have advantages that large models often lack, such as cost, simplicity, and ease of understanding and, therefore, explicability.

It is important to distinguish between analysis and interpretation in systems engineering efforts. Analysis cannot substitute, or will generally be a foolish substitute for, judgment, evaluation, and interpretation as exercised by a well-informed decision-maker. In some cases, refinement of individual alternative policies is not needed in the analysis step. But evaluation of alternatives is always needed, since, if there is but a single policy alternative, there really is no alternative at all. The option to do nothing at all must always be considered as a policy alternative. It is especially important to avoid a large number of cognitive biases, poor judgment heuristics, and value incoherence in the activities of evaluation and decision making. The efforts involved in evaluation and choice making interact strongly with the efforts in the other steps of the systems process, and these are also influenced by cognitive bias, judgment heuristics, and value incoherence. One of the fundamental tenets of the systems process is that making the complete issue resolution process as explicit as possible makes it easier to detect and connect these deficiencies than it is in holistic intuitive processes.

4.3 Information Processing by Humans and Organizations

After completion of the analysis step, we begin the evaluation and decision-making effort of interpretation. Decisions must typically be made and policies formulated, evaluated, and applied in an atmosphere of uncertainty. The outcome of any proposed policy is seldom known with certainty. One of the purposes of analysis is to reduce, to the extent possible,

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

uncertainties associated with the outcomes of proposed policies. Most planning, design, and resource allocation issues will involve a large number of decision-makers who act according to their varied preferences. Often, these decision-makers will have diverse and conflicting data available to them and the decision situation will be quite fragmented. Furthermore, outcomes resulting from actions can often only be adequately characterized by a large number of incommensurable attributes. Explicit informed comparison of alternatives across these attributes by many stakeholders in an evaluation and choice-making process is typically most difficult.

As a consequence of this, people will often search for and use some form of a dominance structure to enable rejection of alternatives that are perceived to be dominated by one or more other alternatives. An alternative is said to be "dominated" by another alternative when the other alternative has attribute scores at least as large as those associated with the dominated alternative and at least one attribute score that is larger. However, biases have been shown to be systematic and prevalent in most unaided cognitive activities. Decisions and judgments are influenced by differential weights of information and by a variety of human information-processing deficiencies, such as base rates, representativeness, availability, adjustment, and anchoring. Often it is very difficult to disaggregate values of policy outcomes from causal relations determining these outcomes. Often correlation is used to infer causality. Wishful thinking and other forms of selective perception encourage us not to obtain potentially disconfirming information. The resulting confounding of values with facts can lead to great difficulties in discourse and related decision making.

It is especially important to avoid the large number of potential cognitive biases and flaws in the process of formulation, analysis, and interpretation for judgment and choice. These may well occur due to flaws in human information processing associated with the identification of problem elements, structuring of decision situations, and the probabilistic and utility assessment portions of the judgmental tasks of evaluation and decision making.

Among the cognitive biases and information-processing flaws that have been identified are several that affect information formulation or acquisition, information analysis, and interpretation. These and related material are described in Ref. 21 and the references contained therein. Among these biases, which are not independent, are the following:

1. *Adjustment and Anchoring*. Often a person finds that difficulty in problem solving is due not to the lack of data and information but rather to an excess of data and information. In such situations, the person often resorts to heuristics, which may reduce the mental efforts required to arrive at a solution. In using the anchoring and adjustment heuristic when confronted with a large number of data, the person selects a particular datum, such as the mean, as an initial or starting point or anchor and then adjusts that value improperly in order to incorporate the rest of these data, resulting in flawed information analysis.
2. *Availability*. The decision-maker uses only easily available information and ignores sources of significant but not easily available information. An event is believed to occur frequently, that is, with high probability, if it is easy to recall similar events.
3. *Base Rate*. The likelihood of occurrence of two events is often compared by contrasting the number of times the two events occur and ignoring the rate of occurrence of each event. This bias often arises when the decision-maker has concrete experience with one event but only statistical or abstract information on the other. Generally, abstract information will be ignored at the expense of concrete information. A base rate determined primarily from concrete information may be called a *causal base rate,* whereas that determined from abstract information is an *inci-*

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

dental base rate. When information updates occur, this individuating information is often given much more weight than it deserves. It is much easier for the impact of individuating information to override incidental base rates than causal base rates.

4. *Conservatism*. The failure to revise estimates as much as they should be revised, based on receipt of new significant information, is known as *conservatism*. This is related to data saturation and regression effects biases.
5. *Data Presentation Context*. The impact of summarized data, for example, may be much greater than that of the same data presented in detailed, nonsummarized form. Also, different scales may be used to change the impact of the same data considerably.
6. *Data Saturation*. People often reach premature conclusions on the basis of too small a sample of information while ignoring the rest of the data, which is received later, or stopping acquisition of data prematurely.
7. *Desire for Self-Fulfilling Prophecies*. The decision-maker values a certain outcome, interpretation, or conclusion and acquires and analyzes only information that supports this conclusion. This is another form of selective perception.
8. *Ease of Recall*. Data that can easily be recalled or assessed will affect perception of the likelihood of similar events reoccurring. People typically weigh easily recalled data more in decision making than those data that cannot easily be recalled.
9. *Expectations*. People often remember and attach higher validity to information that confirms their previously held beliefs and expectations than they do to disconfirming information. Thus, the presence of large amounts of information makes it easier for one to selectively ignore disconfirming information such as to reach any conclusion and thereby prove anything that one desires to prove.
10. *Fact–Value Confusion*. Strongly held values may often be regarded and presented as facts. That type of information is sought that confirms or lends credibility to one's views and values. Information that contradicts one's views or values is ignored. This is related to wishful thinking in that both are forms of selective perception.
11. *Fundamental Attribution Error* (success/failure error). The decision-maker associates success with personal inherent ability and associates failure with poor luck in chance events. This is related to availability and representativeness.
12. *Habit*. Familiarity with a particular rule for solving a problem may result in reuse of the same procedure and selection of the same alternative when confronted with a similar type of problem and similar information. We choose an alternative because it has previously been acceptable for a perceived similar purpose or because of superstition.
13. *Hindsight*. People are often unable to think objectively if they receive information that an outcome has occurred and they are told to ignore this information. With hindsight, outcomes that have occurred seem to have been inevitable. We see relationships much more easily in hindsight than in foresight and find it easy to change our predictions after the fact to correspond to what we know has occurred.
14. *Illusion of Control*. A good outcome in a chance situation may well have resulted from a poor decision. The decision-maker may assume an unreasonable feeling of control over events.
15. *Illusion of Correlation*. This is a mistaken belief that two events covary when they do not covary.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

16. *Law of Small Numbers*. People are insufficiently sensitive to quality of evidence. They often express greater confidence in predictions based on small samples of data with nondisconfirming evidence than in much larger samples with minor disconfirming evidence. Sample size and reliability often have little influence on confidence.
17. *Order Effects*. The order in which information is presented affects information retention in memory. Typically, the first piece of information presented (primacy effect) and the last presented (recency effect) assume undue importance in the mind of the decision-maker.
18. *Outcome-Irrelevant Learning System*. Use of an inferior processing or decision rule can lead to poor results that the decision-maker can believe are good because of inability to evaluate the impacts of the choices not selected and the hypotheses not tested.
19. *Representativeness*. When making inference from data, too much weight is given to results of small samples. As sample size is increased, the results of small samples are taken to be representative of the larger population. The ''laws'' of representativeness differ considerably from the laws of probability and violations of the conjunction rule $P(A \cap B) < P(A)$ are often observed.
20. *Selective Perceptions*. People often seek only information that confirms their views and values and disregard or ignore disconfirming evidence. Issues are structured on the basis of personal experience and wishful thinking. There are many illustrations of selective perception. One is ''reading between the lines''—for example, to deny antecedent statements and, as a consequence, accept ''if you don't promote me, I won't perform well'' as following inferentially from ''I will perform well if you promote me.''

Of particular interest are circumstances under which these biases occur and their effects on activities such as the identification of requirements for a system or for planning and design. Through this, it may be possible to develop approaches that might result in debiasing or amelioration of the effects of cognitive bias. A number of studies have compared unaided expert performance with simple quantitative models for judgment and decision making. While there is controversy, most studies have shown that simple quantitative models perform better in human judgment and decision-making tasks, including information processing, than holistic expert performance in similar tasks. There are a number of prescriptions that might be given to encourage avoidance of possible cognitive biases and to debias those that do occur:

1. Sample information from a broad database and be especially careful to include databases that might contain disconfirming information.
2. Include sample size, confidence intervals, and other measures of information validity in addition to mean values.
3. Encourage use of models and quantitative aids to improve upon information analysis through proper aggregation of acquired information.
4. Avoid the hindsight bias by providing access to information at critical past times.
5. Encourage people to distinguish good and bad decisions from good and bad outcomes.
6. Encourage effective learning from experience. Encourage understanding of the decision situation and methods and rules used in practice to process information and make decisions so as to avoid outcome-irrelevant learning systems.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

A definitive discussion of debiasing methods for hindsight and overconfidence is presented by Fischhoff, a definitive chapter in an excellent edited work.[22] He suggests identifying faulty judges, faulty tasks, and mismatches between judges and tasks. Strategies for each of these situations are given.

Not everyone agrees with the conclusions just reached about cognitive human information processing and inferential behavior. Several arguments have been advanced for a decidedly less pessimistic view of human inference and decision. Jonathan Cohen,[23,24] for example, argues that all of this research is based upon a conventional model for probabilistic reasoning, which Cohen calls the ''Pascalian'' probability calculus. He expresses the view that human behavior does not appear ''biased'' at all when it is viewed in terms of other equally appropriate schemes for probabilistic reasoning, such as his own ''inductive probability'' system. Cohen states that human irrationality can never be demonstrated in laboratory experiments, especially experiments based upon the use of what he calls ''probabilistic conundrums.''

There are a number of other contrasting viewpoints as well. In their definitive study of behavioral and normative decision analysis, von Winterfeld and Edwards[25] refer to these information-processing biases as ''cognitive illusions.'' They indicate that there are four fundamental elements to every cognitive illusion:

1. A *formal operational* rule that determines *the* correct solution to an intellectual question
2. An intellectual question that almost invariably includes all of the information required to obtain the correct answer through use of the formal rule
3. A human judgment, generally made without the use of these analytical tools, that is intended to answer the posed question
4. A systematic and generally large and unforgivable discrepancy between the correct answer and the human judgment

They also, as does Phillips,[26] describe some of the ways in which subjects might have been put at a disadvantage in this research on cognitive heuristics and information-processing biases. Much of this centers around the fact that the subjects have little experiential familiarity with the tasks that they are asked to perform. It is suggested that as inference tasks are decomposed and better structured, it is very likely that a large number of information-processing biases will disappear. Thus, concern should be expressed about the structuring of inference and decision problems and the learning that is reflected by revisions of problem structure in the light of new knowledge. In any case, there is strong evidence that humans are very strongly motivated to understand, to cope with, and to improve themselves and the environment in which they function. One of the purposes of systems engineering is to aid in this effort.

4.4 Interpretation

While there are a number of fundamental limitations to systems engineering efforts to assist in bettering the quality of human judgment, choice, decisions, and designs, there are also a number of desirable activities. These have resulted in several important holistic approaches that provide formal assistance in the evaluation and interpretation of the impacts of alternatives, including the following:

- *Decision analysis,* which is a very general approach to option evaluation and selection, involves identification of action alternatives and possible consequence identification of the probabilities of these consequences, identification of the valuation placed by the decision-maker on these consequences, computation of the expected utilities of

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

the consequences, and aggregating or summarizing these values for all consequences of each action. In doing this, we obtain an expected utility evaluation of each alternative act. The one with the highest value is the most preferred action or option. Figure 7 presents some of the salient features involved in the decision analysis of a simplified problem.

- *Multiattribute utility theory* (MAUT) has been designed to facilitate comparison and ranking of alternatives with many attributes or characteristics. The relevant attributes are identified and structured and a weight or relative utility is assigned by the decision-maker to each basic attribute. The attribute measurements for each alternative are used to compute an overall worth or utility for each attribute. Multiattribute utility theory allows for explicit recognition and incorporation of the decision-maker's attitude toward risk in the utility computations. There are a number of variants of MAUT; many of them are simpler, more straightforward processes in which risk and uncertainty considerations are not taken into account. The method is very helpful to the decision-maker in making values and preferences explicit and in making decisions consistent with those values. The tree structure of Fig. 6 also indicates some salient features of the MAUT approach for the particular case where there are no risks or uncertainties involved in the decision situation. We simply need to associate importance weights with the attributes and then provide scores for each alternative on each of the lowest level attributes.
- *Policy capture* (or social judgment theory) has also been designed to assist decision-makers in making their values explicit and their decisions consistent with their values. In policy capture, the decision-maker is asked to rank order a set of alternatives in a gestalt or holistic fashion. Alternative attributes and associated attribute measures are then determined by elicitation from the decision-maker. A mathematical procedure involving regression analysis is used to determine that relative importance weight of each attribute that will lead to a ranking as specified by the decision-maker. The result is fed back to the decision-maker, 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 decision-maker is satisfied with both the weights and the overall alternative ranking.

There are many advantages to formal interpretation efforts in systems engineering, including the following:

1. Developing decision situation models to aid in making the choice-making effort explicit helps one both to identify and to overcome the inadequacies of implicit mental models.
2. The decision situation model elements, especially the attributes of the outcomes of alternative actions, remind us of information we need to obtain about alternatives and their outcomes.
3. We avoid such poor information-processing heuristics as evaluating one alternative on attribute A and another on attribute B and then comparing them without any basis for compensatory trade-offs across the different attributes.
4. We improve our ability to process information and, consequently, reduce the possibilities for cognitive bias.
5. We can aggregate facts and values in a prescribed systemic fashion rather than by adopting an agenda-dependent or intellect-limited approach.
6. We enhance brokerage, facilitation, and communication abilities among stakeholders to complex technological and social issues.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

There is a plethora of literature describing the decision assessment or decision-making part of the interpretation step of systems engineering. In addition to the discussions in Refs. 1, 2, and 3, excellent discussions are to be found in Refs. 27, 28, and 29.

4.5 The Central Role of Information in Systems Engineering

Information is certainly a key ingredient supporting quality decisions; all of systems engineering efforts are based on appropriate acquisition and use of information. There are three basic types of information, which are fundamentally related to the three-step framework of systems engineering:

1. Formulation information
   - **a.** Information concerning the problem and associated needs, constraints, and alterables
   - **b.** Information concerning the value system
   - **c.** Information concerning possible option alternatives
   - **d.** Information concerning possible future alternative outcomes, states, and scenarios
2. Analysis information
   - **a.** Information concerning probabilities of future scenarios
   - **b.** Information concerning impacts of alternative options
   - **c.** Information concerning the importance of various criteria or attributes
3. Interpretation information
   - **a.** Information concerning evaluation and aggregation of facts and values
   - **b.** Information concerning implementation

We see that useful and appropriate formulation, analysis, and interpretation of information is one of the most important and vital tasks in systems engineering efforts, since it is the efficient processing of information by the decision-maker that produces effective decisions. A useful definition of information for our purposes is that it is data of value for decision making. The decision-making process is influenced by many contingency and environmental influences. A purpose of the management technology that is systems engineering is to provide systemic support processes to further enhance efficient decision-making activities.

After completion of evaluation and decision-making efforts, it is generally necessary to become involved in planning for action to implement the chosen alternative option or the next phase of a systems engineering effort. More often than not, it will be necessary to iterate the steps of systems engineering several times to obtain satisfactory closure upon one or more appropriate action alternatives. Planning for action also leads to questions concerning resource allocation, schedules, and management plans. There are, of course, a number of methods from systems science and operations research that support determination of schedules and implementation plans. Each of the steps is needed, with different focus and emphasis, at each phase of a systems effort. These phases depend on the particular effort under consideration but will typically include such phases as policy and program planning, project planning, and system development.

There are a number of complexities affecting ''rational'' planning, design, and decision making. We must cope with these in the design of effective systemic processes. The majority of these complexities involve systems management considerations. Many have indicated that the capacity of the human mind for formulating, analyzing, and interpreting complex large-

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

scale issues is very small compared with the size and scope of the issues whose resolution is required for objective, substantive, and procedurally rational behavior. Among the limits to rationality are the fact that we can formulate, analyze, and interpret only a restricted amount of information; can devote only a limited amount of time to decision making; and can become involved in many more activities than we can effectively consider and cope with simultaneously. We must therefore necessarily focus attention only on a portion of the major competing concerns. The direct effect of these is the presence of cognitive bias in information acquisition and processing and the use of cognitive heuristics for evaluation of alternatives.

Although in many cases these cognitive heuristics will be flawed, this is not necessarily so. One of the hoped-for results of the use of systems engineering approaches is the development of effective and efficient heuristics for enhanced judgment and choice through effective decision support systems.[30]

There are many cognitive biases prevalent in most information acquisition activities. The use of cognitive heuristics and decision rules is also prevalent and necessary to enable us to cope with the many demands on our time. One such heuristic is satisfying or searching for a solution that is ''good enough.'' This may be quite appropriate if the stakes are small. In general, the quality of cognitive heuristics will be task dependent, and often the use of heuristics for evaluation will be both reasonable and appropriate. Rational decision making requires time, skill, wisdom, and other resources. It must, therefore, be reserved for the more important decisions. A goal of systems engineering is to enhance information acquisition, processing, and evaluation so that efficient and effective use of information is made in a process that is appropriate to the cognitive styles and time constraints of management.

5 SYSTEM DESIGN

This section discusses several topics relevant to the design and evaluation of systems. In order to develop our design methodology, we first discuss the purpose and objectives of systems engineering and systems design. Development of performance objectives for quality systems is important, since evaluation of the logical soundness and performance of a system can be determined by measuring achievement of these objectives with and without the system. A discussion of general objectives for quality system design is followed by a presentation of a five-phase design methodology for system design. The section continues with leadership and training requirements for use of the resulting system and the impact of these requirements upon design considerations. While it is doubtless true that not every design process should, could, or would precisely follow each component in the detailed phases outlined here, we feel that this approach to systems design is sufficiently robust and generic that it can be used as a normative model of the design process and as a guide to the structuring and implementation of appropriate systems evaluation practices.

5.1 The Purposes of Systems Design

Contemporary issues that may result in the need for systems design are invariably complex. They typically involve a number of competing concerns, contain much uncertainty, and require expertise from a number of disparate disciplines for resolution. Thus, it is not surprising that intuitive and affective judgments, often based on incomplete data, form the usual basis used for contemporary design and associated choice making. At the other extreme of the cognitive inquiry scale are the highly analytical, theoretical, and experimental approaches of the mathematical, physical, and engineering sciences. When intuitive judgment is appropriately skill based, it is generally effective and appropriate. One of the major challenges in

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

system design engineering is to develop processes that are appropriate for a variety of process users, some of whom may approach the design issue from a skill-based perspective, some from a rule-based perspective, and some from a knowledge-based perspective.

A central purpose of systems engineering and management is to incorporate appropriate methods and metrics into a methodology for problem solving, or a systems engineering process or life cycle, such that, when it is associated with human judgment through systems management, it results in a high-quality systems design procedure. By high-quality design, we mean one that will, with high probability, produce a system that is effective and efficient and trustworthy.

A systems design procedure must be specifically related to the operational environment for which the final system is intended. Control group testing and evaluation may serve many useful purposes with respect to determination of many aspects of algorithmic and behavioral efficacy of a system. Ultimate effectiveness involves user acceptability of the resulting system, and evaluation of this process effectiveness will often involve testing and evaluation in the environment, or at least a closely simulated model of the environment, in which the system would be potentially deployed.

The potential benefits of systems engineering approaches to design can be interpreted as attributes or criteria for evaluation of the design approach itself. Achievement of many of these attributes may often not be experimentally measured except by inference, anecdotal, or testimonial and case study evidence taken in the operational environment for which the system is designed. Explicit evaluation of attribute achievement is a very important part of the overall systemic design process. This section describes the following:

1. A methodological framework for the design of systems, such as planning and decision support systems
2. An evaluation methodology that may be incorporated with or used independently of the design framework

A number of characteristics of effective systems efforts can be identified. These form the basis for determining the attributes of systems and systemic design procedures. Some of these attributes will be more important for a given environment than others. Effective design must typically include an operational evaluation component that will consider the strong interaction between the system and the situational issues that led to the systems design requirement. This operational evaluation is needed in order to determine whether a product system or a service consisting of humans and machines:

1. Is logically sound
2. Is matched to the operational and organizational situation and environment extant
3. Supports a variety of cognitive skills, styles, and knowledge of the humans who must use the system
4. Assists users of the system to develop and use their own cognitive skills, styles, and knowledge
5. Is sufficiently flexible to allow use and adaptation by users with differing cognitive skills, styles, and knowledge
6. Encourages more effective solution of unstructured and unfamiliar issues, allowing the application of job-specific experiences in a way compatible with various acceptability constraints
7. Promotes effective long-term management

Copyrighted material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

It is certainly possible that the product, or system, that results from a systems engineering effort may be used as a process or life cycle in some other application. Thus, what we have to say here refers both to the design of products and to the design of processes.

5.2 Operational Environments and Decision Situation Models

In order to develop robust scenarios of planning and design situations in various operational environments and specific instruments for evaluation, we first identify a mathematical and situational taxonomy:

- Algorithmic constructs used in systemic design
- Performance objectives for quality design
- Operational environments for design

One of the initial goals in systems design engineering is to obtain the conceptual specifications for a product such that development of the system will be based on customer or client information, objectives, and existing situations and needs. An aid to the process of design should assist in or support the evaluation of alternatives relative to some criteria. It is generally necessary that design information be described in ways that lead to effective structuring of the design problem. Of equal importance is the need to be aware of the role of the affective in design tasks such as to support different cognitive styles and needs, which vary from formal knowledge-based to rule-based to skill-based behavior.[31] We desire to design efficient and effective physical systems, problem-solving service systems, and interfaces between the two. This section is concerned with each of these.

Not all of the performance objectives for quality systems engineering will be, or need be, fully attained in all design instances, but it is generally true that the quality of a system or of a systems design process necessarily improves as more and more of these objectives are attained. Measures of quality or effectiveness of the resulting system, and therefore systems design process quality or effectiveness, may be obtained by assessing the degree of achievement of these performance criteria by the resulting system, generally in an operational environment. In this way, an evaluation of the effectiveness of a design decision support system may be conducted.

A taxonomy based on operational environments is necessary to describe particular situation models through which design decision support may be achieved. We are able to describe a large number of situations using elements or features of the three-component taxonomy described earlier. With these, we are able to evolve test instruments to establish quantitative and qualitative evaluations of a design support system within an operational environment. The structural and functional properties of such a system, or of the design process itself, must be described in order that a purposeful evaluation can be accomplished. This purposeful evaluation of a systemic process is obtained by embedding the process into specific operational planning, design, or decision situations. Thus, an evaluation effort also allows iteration and feedback to ultimately improve the overall systems design process. The evaluation methodology to be described is useful, therefore, as a part or phase of the design process. Also, it is useful, in and of itself, to evaluate and prioritize a set of systemic aids for planning, design, and decision support. It is also useful for evaluation of resulting system designs and operational systems providing a methodological framework both for the design and evaluation of physical systems and for systems that assist in the planning and design of systems.

Copyrighted material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

5.3 The Development of Aids for the Systems Design Process

This section describes five important phases in the development of systems and systemic aids for the design process. These phases serve as a guide not only for the sound design and development of systems and systemic aids for design decision support but also for their evaluation and ultimate operational deployment:

- Requirements specification
- Preliminary conceptual design and architecting
- Detailed design, integration, testing, and implementation
- Evaluation (and potential modification)
- Operational deployment

These five phases are applicable to design in general. Although the five phases will be described as if they are to be sequenced in a chronological fashion, sound design practice will generally necessitate iteration and feedback from a given phase to earlier phases.

Requirements Specification Phase

The requirements specification phase has as its goal the detailed definition of those needs, activities, and objectives to be fulfilled or achieved by the system or process that is to result from the system design effort. Furthermore, the effort in this phase should result in a description of preliminary conceptual design considerations appropriate for the next phase. This must be accomplished in order to translate operational deployment needs, activities, and objectives into requirements specifications if, for example, that is the phase of the systems engineering design effort under consideration.

Among the many objectives of the requirements specifications phase of systems engineering are the following:

1. To define the problem to be solved, or range of problems to be solved, or issue to be resolved or ameliorated, including identification of needs, constraints, alterables, and stakeholder groups associated with operational deployment of the system or the systemic process
2. To determine objectives for operational system or the operational aids for planning, design, and decision support
3. To obtain commitment for prototype design of a system or systemic process aid from user group and management
4. To search the literature and seek other expert opinions concerning the approach that is most appropriate for the particular situation extant
5. To determine the estimated frequency and extent of need for the system or the systemic process
6. To determine the possible need to modify the system or the systemic process to meet changed requirements
7. To determine the degree and type of accuracy expected from the system or systemic process
8. To estimate expected effectiveness improvement or benefits due to the use of the system or systemic process
9. To estimate the expected costs of using the system or systemic process, including design and development costs, operational costs, and maintenance costs

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

10. To determine typical planning horizons and periods to which the system or systemic process must be responsive
11. To determine the extent of tolerable operational environment alteration due to use of the system or systemic process
12. To determine what particular planning, design, or decision process appears best
13. To determine the most appropriate roles for the system or systemic process to perform within the context of the planning, design, or decision situation and operational environment under consideration
14. To estimate potential leadership requirements for use of the final system itself
15. To estimate user group training requirements
16. To estimate the qualifications required of the design team
17. To determine preliminary operational evaluation plans and criteria
18. To determine political acceptability and institutional constraints affecting use of an aided support process and those of the system itself
19. To document analytical and behavioral specifications to be satisfied by the support process and the system itself
20. To determine the extent to which the user group can require changes during and after system development
21. To determine potential requirements for contractor availability after completion of development and operational tests for additional needs determined by the user group, perhaps as a result of the evaluation effort
22. To develop requirements specifications for prototype design of a support process and the operational system itself

As a result of this phase, to which the four issue requirements identification approaches of Section 4.1 are fully applicable, there should exist a clear definition of typical planning, design, and decision issues, or problems requiring support, and other requirements specifications, so that it is possible to make a decision whether to undertake preliminary conceptual design. If the result of this phase indicates that the user group or client needs can potentially be satisfied in a cost-effective manner, by a systemic process aid, for example, then documentation should be prepared concerning detailed specifications for the next phase, preliminary conceptual design, and initial specifications for the last three phases of effort. A design team is then selected to implement the next phase of the system life cycle. This discussion emphasizes the inherently coupled nature of these phases of the system life cycle and illustrates why it is not reasonable to consider the phases as if they are uncoupled.

Preliminary Conceptual Design and Architecting Phase

The preliminary conceptual design and architecting phase includes specification of the mathematical and behavioral content and associated algorithms for the system or process that should ultimately result from the effort as well as the possible need for computer support to implement these. The primary goal of this phase is to develop conceptualization of a prototype system or process in response to the requirements specifications developed in the previous phase. Preliminary design according to the requirements specifications should be achieved. Objectives for preliminary conceptual design include the following:

1. To search the literature and seek other expert opinion concerning the particular approach to design and implementation that is likely to be most responsive to requirements specifications

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

2. To determine the specific analytic algorithms to be implemented by the system or process
3. To determine the specific behavioral situation and operational environment in which the system or process is to operate
4. To determine the specific leadership requirements for use of the system in the operational environment extant
5. To determine specific hardware and software implementation requirements, including type of computer programming language and input devices
6. To determine specific information input requirements for the system or process
7. To determine the specific type of output and interpretation of the output to be obtained from the system or process that will result from the design procedure
8. To reevaluate objectives obtained in the previous phase, to provide documentation of minor changes, and to conduct an extensive reexamination of the effort if major changes are detected that could result in major modification and iteration through requirements specification or even termination of effort
9. To develop a preliminary conceptual design of, or architecture for, prototype aid that is responsive to the requirements specifications

The expected product of this phase is a set of detailed design and testing specifications that, if followed, should result in a usable prototype system or process. User group confidence that an ultimately useful product should result from detailed design should be above some threshold or the entire design effort should be redone. Another product of this phase is a refined set of specifications for the evaluation and operational deployment phases.

If the result of this phase is successful, the detailed design, testing, and implementation phase is begun. This phase is based on the products of the preliminary conceptual design phase, which should result in a common understanding among all interested parties about the planning and decision support design effort concerning the following:

1. Who the user group or responsive stakeholder is
2. The structure of the operational environment in which plans, designs, and decisions are made
3. What constitutes a plan, a design, or a decision
4. How plans, designs, and decisions are made without the process or system and how they will be made with it
5. What implementation, political acceptability, and institutional constraints affect the use of the system or process
6. What specific analysis algorithms will be used in the system or process and how these algorithms will be interconnected to form the methodological construction of the system or process

Detailed Design, Integration, Testing, and Implementation Phase

In the third phase of design, a system or process that is presumably useful in the operational environment is produced. Among the objectives to be attained in this phase are the following:

1. To obtain and design appropriate physical facilities (physical hardware, computer hardware, output device, room, etc.)
2. To prepare computer software

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

3. To document computer software
4. To integrate these effectively
5. To prepare a user's guide to the system and the process in which the system is embedded
6. To prepare a leader's guide for the system and the associated process
7. To conduct control group or operational (simulated operational) tests of the system and make minor changes in the aid as a result of the tests
8. To complete detailed design and associated testing of a prototype system based on the results of the previous phase
9. To implement the prototype system in the operational environment as a process

The products of this phase are detailed guides to use of the system as well as, of course, the prototype system itself. It is very important that the user's guide and the leader's guide address, at levels appropriate for the parties interested in the effort, the way in which the performance objectives identified in Section 5.3 are satisfied. The description of system usage and leadership topics should be addressed in terms of the analytic and behavioral constructs of the system and the resulting process as well as in terms of operational environment situation concerns. These concerns include the following:

1. Frequency of occurrence of need for the system or process
2. Time available from recognition of need for a plan, design, or decision to identification of an appropriate plan, design, or decision
3. Time available from determination of an appropriate plan, design, or decision to implementation of the plan, design, or decision
4. Value of time
5. Possible interactions with the plans, designs, or decisions of others
6. Information base characteristics
7. Organizational structure
8. Top-management support for the resulting system or process

It is especially important that the portion of this phase that concerns implementation of the prototype system specifically address important questions concerning cognitive style and organizational differences among parties at interest and institutions associated with the design effort. Stakeholder understanding of environmental changes and side effects that will result from use of the system is critical for ultimate success. This need must be addressed. Evaluation specification and operational deployment specifications will be further refined as a result of this phase.

Evaluation Phase

Evaluation of the system in accordance with evaluation criteria, determined in the requirements specification phase and modified in the subsequent two design phases, is accomplished in the fourth phase of systems development. This evaluation should always be assisted to the extent possible by all parties at interest to the systems design effort and the resultant systemic process. The evaluation effort must be adapted to other phases of the design effort so that it becomes an integral functional part of the overall design process. As noted, evaluation may well be an effort distinct from design that is used to determine usefulness or appropriateness for specified purposes of one or more previously designed systems. Among the objectives of system or process evaluation are the following:

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

1. To identify a methodology for evaluation
2. To identify criteria on which the success of the system or process may be judged
3. To determine effectiveness of the system in terms of success criteria
4. To determine an appropriate balance between the operational environment evaluation and the control group evaluation
5. To determine performance objective achievement of the system
6. To determine behavioral or human factor effectiveness of the system
7. To determine the most useful strategy for employment of the existing system
8. To determine user group acceptance of the system
9. To suggest refinements in existing systems for greater effectiveness of the process in which the new system has been embedded
10. To evaluate the effectiveness of the system or process

These objectives are obtained from a critical evaluation issue specification or evaluation need specification, which is the first, or problem definition, step of the evaluation methodology. Generally, the critical issues for evaluation are minor adaptations of the elements that are present in the requirements specifications step of the design process outlined in the previous section. A set of specific evaluation test requirements and tests is evolved from these objectives and needs. These must be such that each objective measure and critical evaluation issue component can be determined from at least one evaluation test instrument.

If it is determined that the system and the resulting process support cannot meet user needs, the systems design process iterates to an earlier phase and development continues. An important by-product of evaluation is the determination of ultimate performance limitations and the establishment of a protocol and procedure for use of the system that results in maximum user group satisfaction. A report is written concerning results of the evaluation process, especially those factors relating to user group satisfaction with the designed system. The evaluation process should result in suggestions for improvement in design and in better methodologies for future evaluations.

Section 5.6 will present additional details of the methodologies framework for evaluation. These have applicability to cases where evaluation is a separate and independent effort as well as cases where it is one of the phases of the design process.

Operational Deployment Phase

The last phase of design concerns operational deployment and final implementation. This must be accomplished in such a way that all user groups obtain adequate instructions in use of the system and complete operating and maintenance documentation and instructions. Specific objectives for the operational deployment phase of the system design effort are as follows:

1. To enhance operational deployment
2. To accomplish final design of the system
3. To provide for continuous monitoring of post implementation effectiveness of the system and the process into which the system is embedded
4. To provide for redesign of the system as indicated by effectiveness monitoring
5. To provide proper training and leadership for successful continued operational use of the system

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

6. To identify barriers to successful implementation of the final design product
7. To provide for ''maintenance'' of the system

5.4 Leadership Requirements for Design

The actual use, as contrasted with potential usefulness, of a system is directly dependent on the value that the user group of stakeholders associates with use of the system and the resulting process in an operational environment. This in turn is dependent, in part, on how well the system satisfies performance objectives and on how well it is able to cope with one or more of the pathologies or pitfalls of planning, design, and/or decision making under potentially stressful operational environment conditions.

Quality planning, design, and decision support are dependent on the ability to obtain relatively complete identification of pertinent factors that influence plans, designs, and decisions. The careful, comprehensive formulation of issues and associated requirements for issue resolution will lead to identification of pertinent critical factors for system design. These factors are ideally illuminated in a relatively easy-to-understand fashion that facilitates the interpretation necessary to evaluate and subsequently select plans, designs, and decisions for implementation. Success in this is, however, strongly dependent on adroitness in use of the system. It is generally not fully meaningful to talk only of an algorithm or even a complete system—which is, typically, a piece of hardware and software but which may well be a carefully written set of protocols and procedures—as useful by itself. It is meaningful to talk of a particular systemic process as being useful. This process involves the interaction of a methodology with systems management at the cognitive process or human judgment level. A systemic process depends on the system, the operational environment, and leadership associated with use of the system. A process involves design integration of a methodology with the behavioral concerns of human cognitive judgment in an operational environment.

Operational evaluation of a systemic process that involves human interaction, such as an integrated manufacturing complex, appears the only realistic way to extract truly meaningful information concerning process effectiveness of a given system design. This must necessarily include leadership and training requirements to use the system. There are necessary trade-offs associated with leadership and training for using a system and these are addressed in operational evaluation.

5.5 System Evaluation

Previous sections have described a framework for a general system design procedure. They have indicated the role of evaluation in this process. Successful evaluation, especially operational evaluation, is strongly dependent on explicit development of a plan for evaluation developed prior to, and perhaps modified and improved during the course of, an actual evaluation. This section will concern itself with development of a methodological framework for system evaluation, especially for operational evaluation of systemic processes for planning, design, and decision support.

Evaluation Methodology and Evaluation Criteria

Objectives for evaluation of a system concern the following:

1. Identification of a methodology for operational evaluation
2. Establishing criteria on which the success of the system may be judged

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

3. Determining the effectiveness of the support in terms of these criteria
4. Determining the most useful strategy for employment of an existing system and potential improvements such that effectiveness of the newly implemented system and the overall process might be improved

Figure 8 illustrates a partial intent structure or objectives tree, which contributes to system evaluation. The lowest level objectives contribute to satisfaction of the 10 performance objectives for systems engineering and systems design outlined in Section 3. These lowest level elements form pertinent criteria for the operational system evaluation. They concern the algorithmic effectiveness or performance objective achievement of the system, the behavioral or human factor effectiveness of the system in the operational environment, and the system efficacy. Each of these three elements become top-level criteria or attributes and each should be evaluated to determine evaluation of the system itself.

Subcriteria that support the three lowest level criteria of Fig. 8 may be identified. These are dependent on the requirements identified for the specific system that has been designed. Attainment of each of these criteria by the system may be measured by observation of the system within the operational environment and by test instruments and surveys of user groups involved with the operational system and process.

Algorithmic Effectiveness of Performance Objectives Achievement Evaluation

A number of performance objectives can be cited that, if achieved, should lead to a quality system. Achievement of these objectives is measured by logical soundness of the operational system and process; improved system quality as a result of using the system; and improvements in the way an overall process functions, compared to the way it typically functions without the system or with an alternative system.

Behavioral or Human Factors Evaluation

A system may be well structured algorithmically in the sense of achieving a high degree of satisfaction of the performance objectives, yet the process incorporating the system may seriously violate behavioral and human factor sensibilities. This will typically result in misuse or underuse. There are many cases where technically innovative systems have failed to achieve broad scope objectives because of human factor failures. Strongly influencing the acceptability of system implementation in operational settings are such factors as organizational slack; natural human resistance to change; and the present sophistication, attitude, and past experience of the user group and its management with similar systems and processes.

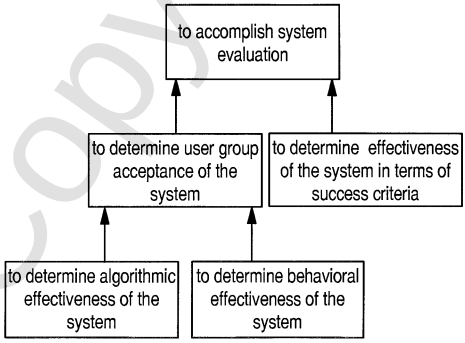


Figure 8 Objectives tree for evaluation of decision support system.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

Behavioral or human factor evaluation criteria used to evaluate performance include political acceptability, institutional constraint satisfaction, implementability evaluation, human workload evaluation, management procedural change evaluation, and side-effect evaluation.

Efficacy Evaluation

Two of the three first-level evaluation criteria concern algorithmic effectiveness or performance objective achievement and behavioral or human factors effectiveness. It is necessary for a system to be effective in each of these for it to be potentially capable of truly aiding in terms of improving process quality and being acceptable for implementation in the operational environment for which it was designed. There are a number of criteria or attributes related to usefulness, service support, or efficacy to which a system must be responsive. Thus, evaluation of the efficacy of a system and the associated process is important in determining the service support value of the process. There are seven attributes of efficacy:

1. *Time Requirements*. The time requirements to use a system form an important service support criterion. If a system is potentially capable of excellent results but the results can only be obtained after critical deadlines have passed, the overall process must be given a low rating with respect to a time responsiveness criterion.
2. *Leadership and Training*. Leadership and training requirements for use of a system are important design considerations. It is important that there be an evaluation component directed at assessing leadership and training needs and trade-offs associated with the use of a system.
3. *Communication Accomplishments*. Effective communication is important for two reasons. (1) Implementation action is often accomplished at a different hierarchical level, and therefore by a different set of actors, than the hierarchical level at which selection of alternative plans, designs, or decisions was made. Implementation action agents often behave poorly when an action alternative is selected that they regard as threatening or arbitrary, either personally or professionally, on an individual or a group basis. Widened perspectives of a situation are made possible by effective communication. Enhanced understanding will often lead to commitment to successful action implementation as contrasted with unconscious or conscious efforts to subvert implementation action. (2) Recordkeeping and retrospective improvements to systems and processes are enhanced by the availability of well-documented constructions of planning and decision situations and communicable explanations of the rationale for the results of using the system.
4. *Educational Accomplishments*. There may exist values to a system other than those directly associated with improvement in process quality. The participating group may, for example, learn a considerable amount about the issues for which a system was constructed. The possibility of enhanced ability and learning with respect to the issues for which the system was constructed should be evaluated.
5. *Documentation*. The value of the service support provided by a system will be dependent on the quality of the user's guide and its usefulness to potential users of the system.
6. *Reliability and Maintainability*. To be operationally useful, a planning-and-decision-support system must be, and be perceived by potential users to be, reliable and maintainable.
7. *Convenience of Access*. A system should be readily available and convenient to access or usage will potentially suffer. While these last three service support measures are

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

not of special significance with respect to justification of the need for a system, they may be important in determining operational usage and, therefore, operational effectiveness of a system and the associated process.

5.6 Evaluation Test Instruments

Several special evaluation test instruments to satisfy test requirements and measure achievement of the evaluation criteria will generally need to be developed. These include investigations of effectiveness in terms of performance objective attainment; selection of appropriate scenarios that affect use of the system, use of the system subject to these scenarios by a test group, and completion of evaluation questionnaires; and questionnaires and interviews with operational users of the system.

Every effort must be made to ensure, to the extent possible, that evaluation test results will be credible and valid. Intentional redundancy should be provided to allow correlation of results obtained from the test instruments to ensure maximum supportability and reliability of the facts and opinions to be obtained from test procedures.

The evaluation team should take advantage of every opportunity to observe use of the system within the operational environment. Evaluation of personnel reactions to the aid should be based on observations, designed to be responsive to critical evaluation issues, and the response of operational environment personnel to test questionnaires. When any of a number of constraints make it difficult to obtain real-time operational environment observation, experiential and anecdotal information becomes of increased value. Also, retrospective evaluation of use of a system is definitely possible and desirable if sufficiently documented records of past usage of an aided process are available.

Many other effectiveness questions will likely arise as an evaluation proceeds. Questions specific to a given evaluation are determined after study of the particular situation and the system being evaluated. It is, however, important to have an initial set of questions to guide the evaluation investigation and a purpose of this section to provide a framework for accomplishing this.

One of the important concerns in evaluation is that of those parts of the efficacy evaluation that deal with various ''abilities'' of a system. These include producibility, reliability, maintainability, and marketability. Figure 9 presents a listing of attributes that may be used to ''score'' the performance of systems on relevant effectiveness criteria.

6 CONCLUSIONS

In this chapter, we have discussed salient aspects concerning the systems engineering of large and complex systems. We have been concerned especially with systems design engineering and associated information-processing and analysis efforts. To this end, we suggested a process for the design and evaluation of systems and how we might go about fielding a design decision support system. There are a number of effectiveness attributes or aspects of effective systems. Design of an effective large-scale system necessarily involves integration of operational environment concerns involving human behavior and judgment with mechanistic and physical science concerns. An effective systemic design process should:

1. Allow a thorough and carefully conducted requirements specification effort to determine and specify needs of stakeholders prior to conceptual design of a system process to accomplish the desired task
2. Be capable of dealing with both quantitative and qualitative criteria representing costs and effectiveness from their economic, social, environmental, and other perspectives

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

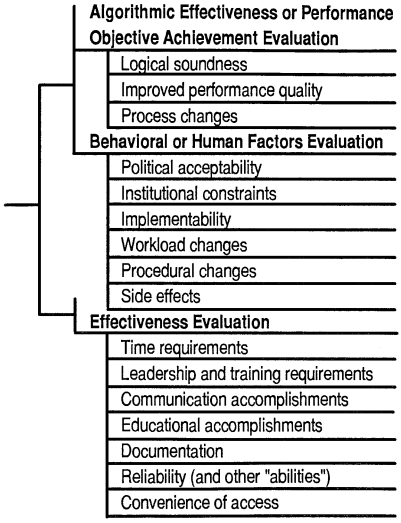


Figure 9 Attribute tree and criteria for evaluation of decision support system for design and other end uses.

3. Be capable of minimizing opportunities for cognitive bias and provide debiasing procedures for those biases that occur
4. Allow separation of opinions and facts from values, and separation of ends from means, or values from alternative acts
5. Provide an objective communicable framework that allows identification, formulation, and display of the structure of the issue under consideration as well as the rationale of the choice process
6. Allow for considerations of trade-offs among conflicting and incommensurate criteria
7. Provide flexibility and monitoring support to allow design process evaluation rule selection with due consideration to the task structure and operational environment constraints on the decision-maker
8. Provide an open process to allow consideration of new criteria and alternatives as values change and broad-scope awareness of issues grows

There are a number of potential benefits of the systems approach that should follow high achievement of each of the criteria for effective systems design processes. An appropriate systems design process will:

1. Provide structure to relatively unstructured issues
2. Facilitate conceptual formulation of issues
3. Provide cognitive cues to search and discovery
4. Encourage parsimonious collection, organization, and utilization of relevant data
5. Extend and debias information-processing abilities
6. Encourage vigilant cognitive style
7. Provide brokerage between parties at interest

There are many imperfections and limits to processes designed using the methodologies from what we know as systems engineering and systems analysis, design, and integration.[32] Some of these have been documented in this chapter. Others are documented in the references

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

provided here and in a recent handbook of systems engineering and management.[33] But what are the alternatives to appropriate systemic processes for the resolution of issues associated with the design of complex large-scale systems and are not the fundamental limitations to these alternatives even greater?

REFERENCES

1. A. P. Sage, *Systems Engineering,* Wiley, New York, 1992.
2. A. P. Sage, *Systems Management for Information Technology and Software Engineering,* Wiley, New York, 1995.
3. A. P. Sage, *Methodology for Large Scale Systems,* McGraw-Hill, New York, 1977.
4. J. E. Armstrong and A. P. Sage, *Introduction to Systems Engineering,* Wiley, New York, 2000.
5. A. D. Hall, *A Methodology for Systems Engineering,* Van Nostrand, New York, 1962.
6. A. D. Hall, "A Three Dimensional Morphology of Systems Engineering," *IEEE Transactions on System Science and Cybernetics* **5**(2), 156–160 (April 1969).
7. E. Rechtin, *Systems Architecting: Creating and Building Complex Systems,* Prentice-Hall, Englewood Cliffs, NJ, 1991.
8. E. Rechtin, "Foundations of Systems Architecting," *Systems Engineering: The Journal of the National Council on Systems Engineering* **1**(1), 35–42 (July/September 1994).
9. W. R. Beam, *Systems Engineering: Architecture and Design,* McGraw-Hill, New York, 1990.
10. D. N. Chorfas, *Systems Architecture and Systems Design,* McGraw-Hill, New York, 1989.
11. A. P. Sage and J. D. Palmer, *Software Systems Engineering,* Wiley, New York, 1990.
12. F. Harary, R. Z. Norman, and D. Cartwright, *Structural Models: An Introduction to the Theory of Directed Graphs,* Wiley, New York, 1965.
13. J. N. Warfield, *Societal Systems: Planning, Policy, and Complexity,* Wiley, New York, 1976.
14. D. V. Steward, *Systems Analysis and Management: Structure, Strategy, and Design,* Petrocelli, New York, 1981.
15. G. G. Lendaris, "Structural Modeling: A Tutorial Guide," *IEEE Transactions on Systems, Man, and Cybernetics* **SMC 10,** 807–840 (1980).
16. C. Eden, S. Jones, and D. Sims, *Messing about in Problems,* Pergamon, Oxford, 1983.
17. F. M. Roberts, *Discrete Mathematical Models,* Prentice-Hall, Englewood Cliffs, NJ, 1976.
18. A. M. Geoffrion, "An Introduction to Structured Modeling," *Management Science* **33,** 547–588 (1987).
19. A. M. Geoffrion, "The Formal Aspects of Structured Modeling," *Operations Research* **37**(1), 30–51 (January 1989).
20. A. M. Geoffrion, "Computer Based Modeling Environments," *European Journal of Operations Research* **41**(1), 33–43 (July 1989).
21. A. P. Sage (ed.), *Concise Encyclopedia of Information Processing in Systems and Organizations,* Pergamon, Oxford, 1990.
22. D. Kahneman, P. Slovic, and A. Tversky (eds.), *Judgment Under Uncertainty: Heuristics and Biases,* Cambridge University Press, New York, 1981.
23. L. J. Cohen, "On the Psychology of Prediction: Whose Is the Fallacy," *Cognition* **7,** 385–407 (1979).
24. L. J. Cohen, "Can Human Irrationality Be Experimentally Demonstrated?" *The Behavioral and Brain Sciences* **4,** 317–370 (1981).
25. D. von Winterfeldt and W. Edwards, *Decision Analysis and Behavioral Research,* Cambridge University Press, Cambridge, 1986.
26. L. Phillips, "Theoretical Perspectives on Heuristics and Biases in Probabilistic Thinking," in *Analyzing and Aiding Decision Problems,* P. C. Humphries, O. Svenson, and O. Vari (eds.), North Holland, Amsterdam, 1984.
27. R. T. Clemen, *Making Hard Decisions: An Introduction to Decision Analysis,* Duxbury, Belmont, CA, 1986.

Copyrighted material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com

28. R. L. Keeney, *Value Focused Thinking: A Path to Creative Decision Making,* Harvard University Press, Cambridge, MA, 1992.

29. C. W. Kirkwood, *Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets,* Duxbury, Belmont, CA, 1997.

30. A. P. Sage, *Decision Support Systems Engineering,* Wiley, New York, 1991.

31. J. Rasmussen, *Information Processing and Human–Machine Interaction,* North Holland, Amsterdam, 1986.

32. D. M. Buede, *The Engineering Design of Systems: Models and Methods,* Wiley, New York, 2000.

33. A. P. Sage and W. B. Rouse (eds.), *Handbook of Systems Engineering and Management,* Wiley, New York, 1999.

Copyrighted Material

Copyright © 2006 John Wiley & Sons Retrieved from: www.knovel.com