METHODOLOGY FOR LARGE-SCALE SYSTEMS

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To
LaVerne

PREFACE

The words *systems engineering* are perhaps used in a special way in this text. We use the word *systems* to refer to the application of system science and methodologies associated with this science for problem solving. We use the word *engineering* not only to mean the mastery and manipulation of physical data but also to imply social and behavioral considerations as inherent parts of the engineering design process. Thus by systems engineering we refer not only to physical systems and devices but to human and social systems as well. Thus we must consider the total impact of any technological system on society as an inherent part of "systems engineering."

There appear to be two fundamental features of systems engineering that can be of considerable utility in the solution of societal problems. Modern society is strongly dependent upon technology, and it would appear that fundamental and lasting solutions to societal problems in a society that is dominated by technology can ill afford to proceed without the use of technology. It may well be argued that technology has caused some of today's societal problems and that technology by itself will not solve fundamental societal issues. We postulate that societal problems cannot be solved, however, without the use of new or existing technology or without directing or redirecting technological applications.

Secondly, the systems engineering approach to problem solving emphasizes interactions and interrelations among the diverse parts of problems. Therefore it may be used to approach large and complex societal problems in a unified fashion. This should be contrasted with the fragmented approach to eliminating symptoms of societal ills that is so often taken.

In this text, we discuss methodologies that will, hopefully, be of value in achieving these ends. No attempt has been made to document all existing systems engineering methodologies, but we have presented some of the existing methodologies that appear to be especially pertinent to the solution of complex technological and societal systems engineering problems. These societal and sociotechnological problems are typically large and complex, and hence this text has been called *Methodology for Large-Scale Systems*.

Chapter 1 is devoted to an overview of the methodologies for large-scale systems that are incorporated in this text. Chapters 2 and 3 describe the phases and steps of systems engineering. Particular stress is placed upon problem definition, and upon the design and synthesis of objectives and policies for program planning. Emphasis is placed upon the considerable utility of graphical approaches to these steps of systems engineering. Chapter 4 is the first of three chapters devoted to models of complex systems. Chapter 4 is concerned with graphical and structural models, whereas Chaps. 5 and 6 are concerned more with quantitative and analytical models. Chapter 7 is concerned with the role of decision analysis in the overall systems engineering problem. Chapter 8 presents a brief introduction to the use of systems engineering methodology in technology forecasting and assessment.

There are several ways in which this text can be utilized. There is approximately 50 percent more material in the text than can be covered in one 3-semester hour course for beginning graduate students. If the entire text is to be covered in a single semester, it is suggested that some of the more specialized points in Chaps. 4 and 7 be deleted and that not all the modeling methodologies in Chaps. 5 and 6 be covered. Alternatively, some of the later chapters in the text can be deleted without loss of continuity, and these chapters can then be discussed in a second semester course. For example, this author has had success using Chaps. 1 through 4 and 7 and 8 in a one-semester three-credit-hour course in "planning and decision analysis." Chapters 5 and 6 have been used in a subsequent course concerning "large-scale systems simulation" in which students were requested to write a term paper expanding upon one of the modeling methodologies discussed in these chapters.

Very little specific preparation or specific prerequisites are needed to take the course(s) for which this text is designed. Essentially an undergraduate engineering background that includes differential equations, elementary probability theory, and some discussion of basic system concepts should be entirely sufficient. Solutions to a large number of the problems posed at the end of each chapter are available to professors who adopt the text in the form of an *Instructor's Manual*, obtainable directly from the publisher.

ACKNOWLEDGMENTS

I am indebted to many people in connection with this text. I wish, first of all, to express considerable gratitude to John N. Warfield, who not only has been an original driving force in the development of many of the systems engineering methodologies documented here, but has given me considerable encouragement to begin studies and research in this area. Thomas L. Martin, Jr., must be thanked for administrative encouragements, allowing the expansion of the scope of the electrical engineering department at the SMU Institute of Technology

to include public and societal systems engineering. Several of the detailed simulation results in this text have been developed by students taking courses associated with this text at the SMU Institute of Technology and more recently at the University of Virginia. I particularly wish to acknowledge Jim Smith and Dave Sundstrom for their development of the SMU Fortran version of several system dynamics models, including the detailed simulations associated with the urban dynamics model. Don Farris, Bob Hawthorne, Rob Kolstad, and Joe Cole must be thanked for their assistance in the computer development of the SMU version of interpretive structural modeling and other graphical tools used in the early chapters of this work. A very preliminary version of this text has been used by the SMU Institute of Technology, but the final version of the text was written and class-tested at the University of Virginia. Hugo Bonuccelli, Dave Rajala, and Dan Visanescu have been especially helpful in pointing out difficulties associated with earlier versions of the manuscript. John E. Gibson is to be thanked for his continuing interest in my career, which resulted in my affiliation with the University of Virginia and the opportunity to work with a master at the art of systems engineering practice. Portions of this text are based upon research which has been supported by the National Science Foundation under grants GK33348, GK40320, and ENG 74–21679. I am especially indebted to former doctoral students at the SMU Institute of Technology Joe Cole, Don Farris, and Bob Hawthorne, who, through their considerable persistence, have truly taught me and improved my perception of systems engineering and its methodologies. In particular, Chaps. 4 and 7 contain examples and discussions that have resulted from joint efforts with these outstanding young systems engineering professionals. Discussions in these chapters represent, in part, extensions of our efforts previously reported in *Computers and Electrical Engineering* (vol. 2, no. 2, 1975, pp. 149–174), *Socio-Economic Planning Sciences* (vol. 9, 1975, pp. 31–43), *Journal of the Franklin Institute* (vol. 299, no. 4, Apr. 1975, pp. 245–268), *IEEE Transactions on Systems, Man, and Cybernetics*, (vol. SMC-5, no. 3, May 1975, pp. 346–358), *International Journal of Systems Sciences*, (vol. 6, no. 12, 1975, pp. 1135–1178), and *Information Sciences* (vol. 10, Jan. 1976, pp. 31–57). I wish to thank Joe, Don, and Bob as well as the publishers of these journals for their kind permission to incorporate some of the results of our research in this effort. Despite the very generous assistance of so many, there are doubtless many failures in this text, and for these I alone accept full responsibility.

ANDREW P. SAGE

CONTENTS

CHAPTER
ONE
OVERVIEW

1.1 INTRODUCTION

We conjecture that a systemic method of dealing with complex systems has much to offer with respect to ameliorating many problems confronting us today. This chapter presents an overview of the set of tools, the set of activities, and the proposed relations between the tools and the activities which constitute a methodology for large-scale systems.

1.2 NEED FOR SYSTEMS ENGINEERING

Many have recently been led to the conclusion that something is seriously wrong with technology and our use of technology in the solution of complex, large-scale problems facing society. Others would not go quite this far, but would argue that the classical methods of using technology to deal with societal problems are no longer adequate. Within recent times we have been especially concerned with problems involving:

Health care
Crime
Urban transportation
Environmental pollution

Energy resources
Food resources
Social and emergency service delivery
Excessive inflation
Recession

All of these have been called crises in various quarters, and diverse portions of national and international resources have been devoted to resolving them.

It would appear that many of these problems are rather tightly coupled by feedbacks of various types. Indeed, attempts to produce a solution to one crisis may well be to the detriment of and at the expense of a crisis in another problem area. Lack of understanding of the structure of the underlying system often leads us to the wrong conclusion regarding problem solution. Further, there are questions of time involved. Even when policies to resolve a crisis have been developed, the time needed to implement them may be so great that counter-intended results may occur as the correct policy for one time is applied at some other time.

We strongly believe that technology is necessary to ameliorate the problems just delineated. However, it would appear that successful application of technology to societal problem areas must consider three levels (Chen, Ghausi, and Sage, 1975):

Symptoms
Institutions
Values

or we will be continually confronted with technological solutions looking for problems. Too often, we approach problems only at the level of symptoms: bad housing, inadequate health-care delivery to the poor, pollution, hunger, etc. "Technological fixes" are developed, and the resulting hardware creates the illusion that solution of societal problems requires merely the outpouring of huge quantities of public funds. Attacking problems at the level of institutions would allow the design of new institutions to make full and effective use of new technologies. Recent work in technology assessment appears to be directed at this level. Also of vital importance is the need to deal with societal problems at the level of values. It would appear that technologists serious about resolving societal problems must appreciate the significance of values and be able to identify basic issues in terms of conflicting values. Further, value elements and systems, as well as institutions and purely technological components, must be utilized in determining useful problem solutions.

This book will bring together a set of concepts and methodologies from systems engineering and illustrate how they might potentially be employed to improve planning and implementation of technology for the future improvement of society. Most of the theoretical systems engineering techniques developed here are exceptionally useful for science-based policy analysis as a participative methodology for public system planning, design, and operation.

Some necessary ingredients which must exist in order to develop large systems, solve large and complex problems, or manage large systems are:

1. A way to deal successfully with problems involving many considerations and interrelations
2. A way to deal successfully with areas in which there are far-reaching and controversial value judgments
3. A way to deal successfully with problems the solutions to which require knowledge from several disciplines
4. A way to deal successfully with problems in which future events are difficult to predict
5. A way to deal successfully with problems in which structural and institutional elements are given full consideration

We demonstrate in the sequel that systems engineering possesses these necessary characteristics. Thus, systems engineering is potentially capable of exposing not only technological perspectives associated with large-scale systems but also needs and value perspectives.

1.3 THE FRAMEWORK FOR SYSTEMS ENGINEERING

Systems engineering has three major dimensions. The *time* dimension of systems engineering includes the gross sequences or phases that are characteristic of systems work and extends from the initial conception of an idea through system retirement or phaseout. The *logic* dimension deals with the steps that are carried out at each of the systems engineering phases. The *knowledge* dimension refers to specialized knowledge from various professions and disciplines. These are the dimensions of the Hall (1969) morphological[1] box of systems engineering; they are illustrated in Fig. 1.3-1. The following discussion will be specifically concerned with the *activity plane* of systems engineering, consisting of the time and logic dimensions. Most of our efforts in this text will concern the logic dimension of systems engineering.

The seven phases (Hall, 1969) of systems engineering are given in Table 1.3-1. This discussion will be especially concerned with the program and project planning phases. The seven steps of systems engineering, illustrated in Table 1.3-2, are carried out in an iterative fashion. This means that it is possible to go back to

[1] Morphology is the study of structure or form employing a definite behavioral approach and methodology.

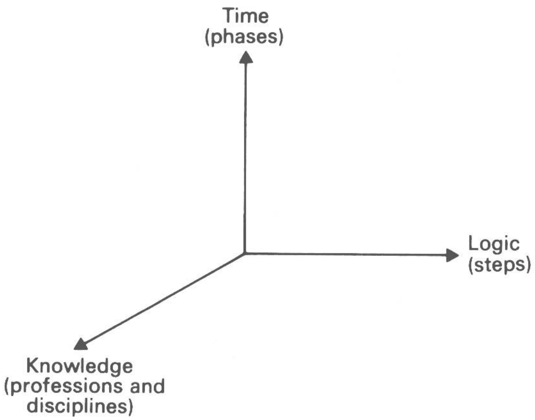

Figure 1.3-1 Three-dimensional systems engineering framework.

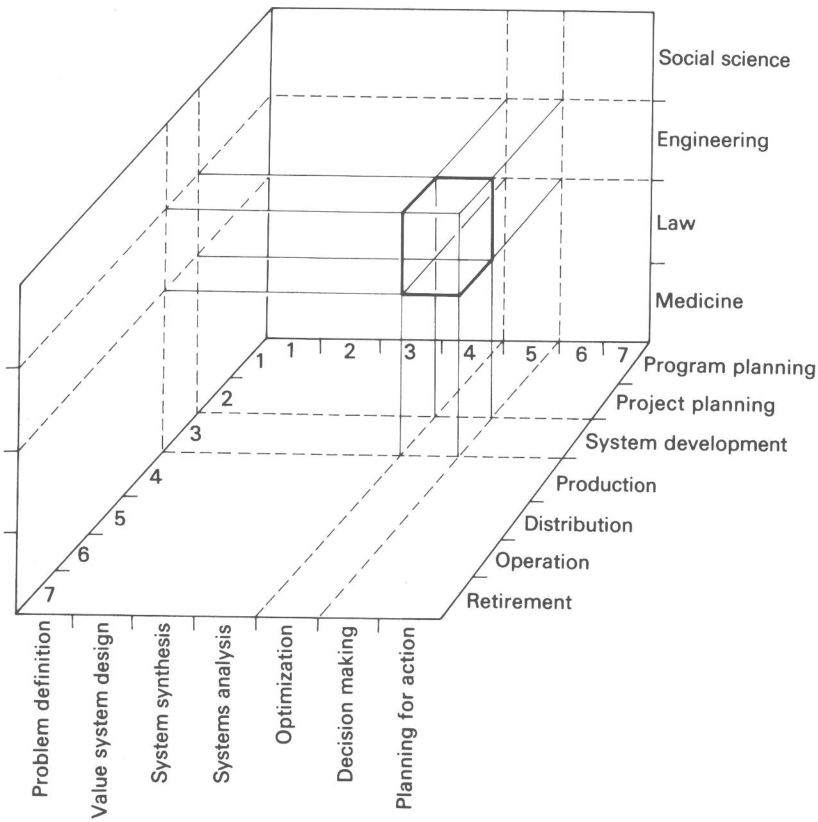

Figure 1.3-2 Morphological box for systems engineering.

Table 1.3-1 Seven phases for systems engineering

1	Program planning
2	Project planning
3	System development
4	Production
5	Installation
6	Operation
7	Retirement

Table 1.3-2 Seven steps of systems engineering

1	Problem definition
2	Value system design
3	Systems synthesis
4	Systems analysis
5	Optimization of alternatives
6	Decision making
7	Planning for action (to implement the next phase)

refine and improve the results of any lower-numbered step as a consequence of the results of any higher-numbered step. In each of the seven phases of systems engineering it is necessary to conduct each of the seven steps. Each of the steps of systems engineering is very important. All of Chap. 3 will be devoted to a discussion of how they combine to form one of the phases of systems engineering.

Table 1.3-3 Hall activity matrix for systems engineering

Steps of the fine structure / Logic → ; Phases of the coarse structure / Time ↓	Problem definition	Value system design	System synthesis	Systems analysis	Rank (optimize) alternatives	Decision making	Planning for action
Program planning							
Project planning							
System development							
Production							
Distribution							
Operations							
Retirement							

Hall's (1969) morphological box for systems engineering is illustrated in Fig. 1.3-2. In this box are the three dimensions of systems engineering with their seven steps and seven phases. In this figure is indicated the specific engineering-optimization-system development activity. Of much concern will be the *activity plane* or *activity matrix*, consisting of the phases and steps of systems engineering. The activity matrix for systems engineering is illustrated in Table 1.3-3, and, as indicated before, Chap. 3 will be devoted to further development of the many important ideas represented by this activity matrix.

1.4 TOOLS AND METHODOLOGY OF SYSTEMS ENGINEERING

In the following discussion, the Hall morphological box, or more specifically the Hall activity matrix, will be used to provide structure to systems engineering. This structure is, in turn, applied to a particular problem in order to incorporate the elements of a methodology of systems engineering for the specific problem.

By *methodology* we mean an open set of procedures which provides the means for solving problems. The "tools" of systems engineering are the elements of a methodology necessary for accomplishing the steps and phases of the Hall activity matrix, Table 1.3-3. We select as the tools of systems engineering *words*, *mathematics*, and *graphics*. It is interesting to note that these are also the elements of communication. When we combine a set of tools, a set of proposed activities, and a set of relations among the tools and the activities, we have a methodology. We have proposed the set of activities in the form of the Hall activity matrix. Many of the tools of systems engineering will be developed in succeeding chapters. Several case studies will be used to illustrate the kinds of relations that may exist between the activities and the tools.

1.5 OUTLINE OF SUCCEEDING CHAPTERS

A conventional policy formulation process is shown in Fig. 1.5-1. Policy determination is based upon a value system, often nonarticulated, and a conceptual model of the world. There is considerable evidence that societies' value systems, or at least perceptions of societies' value systems, are changing in time, and this, coupled with shorter response times to policy changes as a result of advanced technology, leads to a most difficult problem of policy determination—and leads to the phenomenon of "future shock," on an individual as well as a group level. The conceptual model of the real world is often a mental model determined by individuals, often based on many years of observation. Obviously, this model

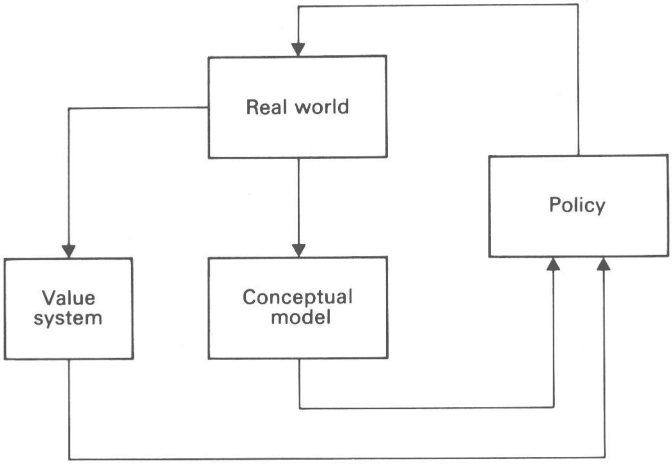

Figure 1.5-1 Conventional policy formulation model.

may differ from individual to individual. Value systems will often not be articulated and may contain hidden intents, and may be nontransitive.[1] With these types of models of reality and these forms of value systems, policy is determined by appropriate bodies.

The material presented in his text can be used to develop a *structural* basis for improving the policy formulation process. Figure 1.5-2 presents a sketch of the potential systems-based policy formulation process. It differs from Fig. 1.5-1 in that systems engineering methodology is used to structure models of societal problems and the program and project planning phases are used to assist policy determination.

The graphic tools for a systems engineering methodology are presented and explained in Chap. 2, along with a rationale for the need for their use. An important point of Chap. 2 is that the graphical displays which result from the application of these methodologies to technical, urban, or societal situations are in fact a transformation of an essay or mental model of a situation to a graphical model of the same situation. The graphic tools are combined with program planning concepts in Chap. 3 to develop an important part of our systems engineering methodology.

In Chap. 3, concepts for identifying needs, alterables, and constraints are presented and applied to example problems. It is shown how to develop these elements in self-interaction matrices. The problem definition linkages of a methodology of unified program planning result. There is a need for value

[1] A transitive preference structure is one where if a is preferred to b ($a\mathscr{P}b$) and b is preferred to c ($b\mathscr{P}c$), then a is preferred to c ($a\mathscr{P}c$). See Chap. 4 for a more complete discussion of transitivity.