APPLIED SYSTEMS ANALYSIS

Engineering Planning and Technology Management

Richard de Neufville
Massachusetts Institute of Technology

McGraw-Hill Publishing Company
New York St. Louis San Francisco Auckland Bogotá Caracas Hamburg
Lisbon London Madrid Mexico Milan Montreal New Delhi Oklahoma City
Paris San Juan São Paulo Singapore Sydney Tokyo Toronto

This book was set in Times Roman by Publication Services.
The editors were B. J. Clark and John M. Morriss;
the production supervisor was Janelle S. Travers.
The cover was designed by John Hite.
Project supervision was done by Publication Services.
R. R. Donnelley & Sons Company was printer and binder.

APPLIED SYSTEMS ANALYSIS
Engineering Planning and Technology Management

3 4 5 6 7 8 9 0 DOC DOC 9 5 4 3 2

ISBN 0-07-016372-3

Library of Congress Cataloging-in-Publication Data

de Neufville, Richard, (date).
Applied systems analysis: Engineering planning and technology management / Richard de Neufville.
p. cm.
Includes index.
ISBN 0-07-016372-3
1. Engineering economy. 2. Systems analysis. 3. Operations research. I. Title.
TA177.4.D45 1990
658.4'032—dc20 89-12094

ABOUT THE AUTHOR

Professor Richard de Neufville is Founding Chairman of the Technology and Policy Program at the Massachusetts Institute of Technology (MIT). This innovative curriculum in systems planning and management received the Sizer Award for the Most Significant Contribution to MIT Education.

Professor de Neufville received his bachelor of science, master of science, and doctorate in civil engineering from MIT.

He has taught Applied Systems Analysis at MIT since 1968, in both the School of Engineering and the School of Management. He has also held visiting appointments in Engineering at the University of California, Berkeley, and the Ecole Centrale de Paris, and in Management at the London Graduate School of Business and the Master's in International Business Program in France. His previous book for McGraw-Hill, *Systems Analysis for Engineers and Managers,* was awarded a NATO Systems Science Prize.

His work in decision analysis and strategic planning is widely recognized for its impact on professional practice. His experimental research won the Alpha Kappa Psi and the Risk and Insurance Awards. Most recently, the Australian Institution of Engineers cited his work on the Second Sydney Airport for Engineering Excellence.

The author of two other textbooks, *Airport Systems Planning* (MIT Press and MacMillan in England) and *Systems Planning and Design* (Prentice-Hall), Professor de Neufville was named as a U.S.-Japan Leadership Fellow in 1989. Previously he was a Guggenheim Fellow and served as a first White House Fellow for President Johnson.

CONTENTS

PREFACE

THE TOPIC

Applied Systems Analysis is the use of rigorous methods to help determine preferred plans and designs for complex, often large-scale systems. It combines knowledge of the available analytic tools, understanding of when each is more appropriate, and skill in applying them to practical problems. It is both mathematical and intuitive, as is all planning and design.

Systems Analysis is a relatively new field. Its development parallels that of the computer, the computational power of which enables us to analyze complex relationships, involving many variables, at reasonable cost. Most of its techniques depend on the use of the computer for practical applications. Applied Systems Analysis may be thought of as the set of computer-based methods essential for the planning of major projects. It is thus central to a modern engineering or business curriculum.

Applied Systems Analysis covers much of the same material as operations research, in particular linear and dynamic programming and decision analysis. The two fields differ substantially in direction, however. Operations research tends to be interested in specific techniques and their mathematical properties. Applied Systems Analysis focuses on the use of the methods.

Systems Analysis includes the topics of engineering economy, but goes far beyond them in depth of concept and scope of coverage. Now that both personal computers and efficient financial calculators are available, there is little need for professionals to spend much time on detailed calculations. It is more appropriate to understand the concepts and their relationship to the range of techniques available to deal with complex problems.

Applied Systems Analysis emphasizes the kinds of real problems to be solved; considers the relevant range of useful techniques, including many besides those of operations research; and concentrates on the guidance they can provide toward improving plans and designs.

Use of Systems Analysis instead of the more traditional set of tools generally leads to substantial improvements in design and reductions in cost. Gains of 30% are not uncommon. These translate into an enormous advantage when one is considering projects worth tens and hundreds of millions of dollars.

SCOPE OF TEXT

The object of this book is to help the student and practitioner learn to apply Systems Analysis successfully and productively. It is addressed to the user, who has to know how to select the techniques appropriate in any situation, to apply them to real problems, and to interpret their results intelligently. It is also addressed to the customer, the person responsible for large projects, who has to know how to evaluate the results and proposals generated by systems analysts. To meet their needs, the text presents the techniques and concepts that have been found to be most important in practice.

The text presents the fundamental topics of optimization and evaluation. Each is treated differently, according to the state of analytical and conceptual progress in the area.

Optimization focuses on linear and dynamic programming as the central methods of interest in practice. Insofar as standard computer programs are available to execute these methods, the emphasis here is on how to formulate problems correctly and efficiently, and on how to translate the mathematical results into improved designs. Procedures that are not used in practice, such as the simplex method, are bypassed so that time can be spent productively on important considerations. The presentation is integrated with the classical techniques of engineering and economics so that students can learn to exploit the range of methods according to their needs.

Evaluation features decision analysis as the principal means to identify optimal strategies in the risky environment that is necessarily part of complex, long-term projects. Indeed, use of this approach is leading to fundamental improvements in the way we plan such developments. The presentation here is unique in the way it integrates decision analysis into the hierarchy of evaluation techniques. Each of these, particularly including engineering economy and cost-benefit analysis, is described in sufficient detail.

The text does not cover two topics sometimes included in systems analysis: dynamic systems and statistics. Dynamic systems are not treated because their applicability to problems of management and design, as distinct from mechanical systems, is minimal. Research into the possibility that large-scale physical systems and organizations can be described with feedback loops and the like is suggestive but still too speculative for actual practice. Classroom experience, on the other hand, indicates that statistical procedures are extremely difficult to integrate effectively with optimization and evaluation: A careful treatment of the methods and issues requires more understanding of probability and causal mechanisms than is generally available.

A major strength of the text, as emphasized by reviewers, is the way it effectively integrates the broad range of methods available to the user. The idea throughout has been to help the user understand the relative strengths and weaknesses of alternative methods, to indicate when they are best used, and to provide guidelines for application.

PRESENTATION

The presentation of the techniques differs substantially from that of competitive texts. It particularly features

Application to real problems, drawn from an extensive range of practical work over the last 20 years.

Synthesis of the methods, ordinarily treated quite distinctly in separate texts, into an integrated framework.

Consideration of multiple objectives, as a realistic feature of the actual nature of planning and management.

The text is easy to use for teaching and learning because it does not require extensive mathematical skills. Because people who need to apply Systems Analysis come from a wide range of backgrounds, every effort has been made to avoid unnecessary mathematical complexity. The idea is to teach, not to impress. Readers should, however, be familiar with

Elementary Calculus, so that they can deal with the classical techniques of optimization.

Vectors and Matrices, the basic means of describing problems to computers.

Elementary Probability, to work with expected values.

They should also have some acquaintance with real-world problems, so that they can appreciate when and why some techniques are better than others.

Making the material easy to learn and to teach has been a leading consideration. Great care has been devoted to defining concepts clearly and consistently, to giving and explaining examples, and to making the text completely self-contained. The language and sentences are also kept as simple and as direct as possible, in recognition that a text may be used as much at one in the morning as at one in the afternoon!

The format uses three special devices to make learning easier. These are

Boxes, self-contained blocks of material inserted in the text, that highlight examples.

Semantic Cautions, indented sections drawing attention to potential ambiguities caused by conflicting definitions used in different disciplines.

Italicizing of definitions where they first appear, to help readers locate and refer to important concepts.

Additionally, references to detailed case studies easily available in the literature are provided where appropriate.

Both conceptually and pedagogically, *Applied Systems Analysis* is a complete rewrite of my previous textbook (*Systems Analysis for Engineers and Managers,* coauthored with Joseph Stafford). It includes many case studies, drawn from a second text (*Systems Planning and Design: Case Studies in Modeling Optimization and Evaluation,* coauthored with David Marks) and two decades of worldwide professional experience. It incorporates recent developments while dropping topics that have proven to be of little use in practice. It offers a wider, more instructive range of problem sets. Finally, it is written to be clear, even on the most difficult points.

The text reflects the current pervasive use of personal computers throughout, in its choice of topics and their use. The material on sensitivity analysis, multiobjective optimization, and system optimization procedure can only be applied to realistic problems when computers are available. Likewise, topics such as the evaluation of cash flows are best done in practice by spreadsheet programs. As a practical matter, however, specific programs have not been incorporated into the text, because of the enormous, ever-changing variety of software available. Experience suggests that instructors will find it easiest to use the programs with which they and the students are familiar. Alternatively, if there is not enough time to go into the mechanics of specific software, the material may be covered completely without computers.

SUGGESTED USE

The material works well for the wide range of users who need a comprehensive introduction to Applied Systems Analysis. It provides in one text the material ordinarily found only in several specialized subjects. Years of classroom experience indicate that introducing students to Systems Analysis in this way, with many examples of real applications, is highly motivational: It encourages students to select the more advanced topics that will be most useful to them.

Juniors and seniors in engineering follow the mathematics easily and are challenged by the references to practice. Entering graduate students who have not previously had Systems Analysis appreciate the way the applications motivate the study of the techniques.

The text is also appropriate for first-year students in management, provided they have had a reasonable grounding in mathematics. It is routinely used in this context both at the Massachusetts Institute of Technology and in the Master's in International Business Program in France.

Experienced professionals appreciate the way the material applies to real problems. Although some may have to brush up analytic skills, many have used the material for self-study and reference. The predecessor text, *Systems Analysis for Engineers and Managers,* was adopted by the Open University in Britain for nationwide educational television. It was also awarded the NATO Systems Science Prize.

At the Massachusetts Institute of Technology we now present the material in two kinds of subjects. In the fall, it is given as a schoolwide elective taken by seniors and graduate students in all fields of engineering. During the spring and summer it is given to professionals entering business school programs.

McGraw-Hill and I would like to thank the following reviewers for their many helpful comments and suggestions: William O'Neill, University of Illinois; Elizabeth Paté-Cornell, Stanford University; Robert Stark, University of Delaware; E. Earl Whitlatch, Ohio State University; and Jeff Wright, Purdue University.

Richard de Neufville

PART 1

SYSTEM OPTIMIZATION

CHAPTER 1

INTRODUCTION

The design of a system represents a decision about how resources should be transformed to achieve some objectives. The final design is a choice of a particular combination of resources and a way to use them; it is selected from other combinations that would accomplish the same objectives. For example, the design of a building to provide 100 apartments represents a selection of the number of floors, the spacing of the columns, the type of materials used, and so on; the same result could be achieved in many different ways.

A design must satisfy a number of technical considerations. It must conform to the laws of the natural sciences; only some things are possible. To continue with the example of the building, there are limits to the available strength of either steel or concrete, and this constrains what can be built. The creation of a good design for a system thus requires solid technical competence in the matter at hand. Engineers may take this fact to be self-evident, but it often needs to be stressed to industrial or political leaders motivated by their hopes for what a proposed system might accomplish.

Economics and values must also be taken into account in the choice of design; the best design cannot be determined by technical considerations alone. Moreover, these issues tend to dominate the final choice of a design for a system. As a general rule, the designer must choose between many possible designs, each of which appears equally effective technically. The selection of a design is then determined by the costs and relative values associated with the different possibilities. The choice between constructing a building of steel or concrete is generally a question of cost, as both can be essentially equivalent technically. For more complex systems, political or other values may be more important than costs. In planning an airport for a city for instance, it is usually the case that several sites can be made to perform technically; the final choice hinges on societal decisions about the relative importance of ease of access and the environmental impacts of the airport, in addition to its cost.

The centrality of economic considerations in the design of engineering systems needs to be stressed. The recognition that economic theory is essential to engineering practice is relatively new, and thus relatively limited. This new relevance results from the evolution in engineering from the detailed design of devices to the design of systems.

As engineering more explicitly deals with the design of systems, we must deal with new issues and incorporate suitable new means of analysis. Traditionally, engineering education and practice have been concerned with detailed designs. At that level technical problems dominate and economics are often secondary. In designing an engine for example, the immediate task—and the trademark of the engineer—is to make the device work properly. In systems designs however, economic considerations can become most important. Thus the design of a transportation system generally assumes that engines to power vehicles will be available, and focuses attention on such issues as whether service can be provided at a price low enough to generate sufficient traffic to make the system worthwhile.

Applied systems analysis thus differs from traditional engineering in that it explicitly includes a great deal of economics. The importance of this discipline to systems analysis is particularly strong because one of the economists' main concerns has been with what they call "resource allocation." This is the problem of determining how to apply different resources to achieve any given objective at least cost. From the theoretical point of view, this problem is exactly that faced by the systems designer. Economists have therefore developed a body of theory and means of analysis particularly suited for applied systems analysis.

Systems optimization, the topic treated in the first part of the text, is the prime instance of how economic theory has been incorporated into engineering systems analysis. Many of the key concepts have been adapted with little modification. In particular, the basic model of the way we can transform resources to achieve objectives, the production function, comes directly from economics. So does marginal analysis, which is the basic method for solving the resource allocation—or design—problem.

The treatment of systems optimization starts in Chapter 2 with the description of the production function as the underlying model of any system. Chapter 3 then briefly covers the mathematical theory of optimization with constraints. This section forms the basis for all that follows. Chapter 4 covers marginal analysis, a simple method that is not only useful in many complex situations but that provides substantial perspective on the nature of optimal solutions. Chapters 5 to 7 then cover the most important methods of modern, computer-based systems analysis.

Chapter 5 covers linear programming, the most widely used and effective means of optimization. Chapter 6 describes sensitivity analysis, an essential ingredient to any practical optimization since our mathematical descriptions of reality are inherently inexact. Chapter 7 covers dynamic programming as the most important example of the enumerative class of optimization techniques that complements linear programming. Chapter 8 introduces the essential elements of multiobjective analysis, an activity that is still very much in the process of development. Finally, Chapter 9 integrates the preceding material into a coherent procedure for optimizing the design of systems, and provides an extended example.

REFERENCE

Miser, H. J., and Quade, E. S., eds., (1985). *Handbook of Systems Analysis*, Elsevier Science Publishers, New York.