FUNDAMENTALS OF NETWORK ANALYSIS

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To *Donnie* and *Ronnie*—
they never understood
why Daddy worked so hard,
and to *Candy* and *Kathy*—
who also suffered without complaint.

PREFACE

This book is a comprehensive treatment of the theories, algorithms, and computational nature of deterministic network flows. The book was developed from 10 years of classroom lecture notes compiled by ourselves, numerous technical articles, and contributions from leading experts in the field. The fundamental contribution of this textbook is a simple, practical approach to the design and implementation of network-flow algorithms. At the risk of criticism from fellow colleagues, we have sometimes sacrificed theoretical development and mathematical proofs for explanation by way of computational presentations. When appropriate, each technique is first presented as a mathematical programming problem, and then followed by an algorithmic procedure that guarantees problem resolution through faster and more efficient computational techniques as compared to direct use of mathematical models. Every algorithm is used to solve one or more real-world examples. A practical feature of the book is the documentation and listing of a FORTRAN IV network optimization computer program that can be used either for teaching or research purposes, on small- to medium-sized problems.

This book is intended to be an introductory treatment of network flows, and should prove useful as a textbook in a first couse in network analysis at either the undergraduate or graduate level. The treatment is self contained, and no particular degree of mathematical sophistication is necessary to understand the material developed in this book. Limited exposure to linear programming notation and FORTRAN programming would enhance the learning experience, but are not necessary to understand the algorithms as presented.

It has been our pleasure during the last 10 years to note a major explosion in the interest and application of network-flow algorithms. There does not seem to be an educational area that does not embrace network analysis; its applications are continuously surfacing in business administration, all fields of engineering, transportation analysis, project planning and control, sequencing and scheduling, and other areas too numerous to mention. The basic appeal is the great flexibility of network representation and the visual/graphical interpretation of network models. In addition, network solution procedures have recently been developed that are significantly more efficient than conventional linear programming.

The major barrier to widespread acceptance and use of network analysis is undoubtedly technical communication. With only a few exceptions, prior publications in the field and major developments have been presented through a mathematical programming or graph theoretic base. These results have usually surfaced in technical articles or sophisticated reports. This book attempts to avoid some of the theoretical and mathematical sophistication and present the fundamental aspects of network-flow analysis in a nontechnical fashion.

The book is divided into five basic chapters and one appendix. Chapter 1 presents the notation and symbolism used throughout the text, and establishes definitions that pertain to developments in latter chapters. Chapter 2 is a comprehensive treatment of deterministic network flows, and begins with a presentation of several examples illustrating network formulations of practical problems. Chapter 2 utilizes a wide range of examples and introduces FORTRAN IV computer programs to aid practical solution of larger problems. Chapter 3 presents a unified and comprehensive treatment of the elegant out-of-kilter algorithm, and contains a detailed development of the theoretical and computational aspects of this powerful technique. Numerous applications are suggested in this chapter, and several example problems are used to illustrate modeling procedures. Chapter 4 is a complete treatment of project management and control procedures based upon PERT and CPM. Computational procedures, resource balancing/leveling, and computerized procedures are thoroughly discussed in this chapter. Chapter 5 is a treatment of more advanced topics, including networks with gains and losses, GERT procedures for special forms of stochastic networks, and multicommodity network flows. The Appendix provides a complete listing and operating instructions for the network optimization program.

We have attempted to draw upon the knowledge and expertise of many individuals in this field. Indeed, several have contributed directly to

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the material contained in this text. Portions of Chapter 2, particularly many of the applied examples, were contributed by Dr. G. E. Bennington. Portions of Chapter 3, dealing with the out-of-kilter algorithm, were taken from original lecture notes by Dr. Paul A. Jensen, and several examples were contributed by Dr. R. E. D. Woolsey and Dr. Hunter Swanson. Dr. Warren Thomas contributed most of the material on the computational aspects of PERT/CPM in Part I of Chapter 4. The entire section dealing with resource control in Chapter 4 was contributed by Dr. Edward Davis, and the computer software survey in Chapter 4 was taken from an article by Dr. Larry A. Smith and Mr. Peter Mahler. Material in Chapter 5 dealing with the theory of generalized networks was adopted from original research by Drs. Gora Bhaumik and Paul Jensen, with several examples cited from works of Dr. Darwin Klingman and Dr. Fred Glover. Theories and computational aspects of GERT are attributed to Dr. A. Alan B. Pritsker. Finally, the material on multicommodity network flows was contributed totally by Dr. James Evans.

In addition to direct individual contributions in Chapters 3 and 4, this book obviously depends upon and draws from technical material developed by many of our fellow colleagues, too numerous to acknowledge. They will recognize their individual contributions. We are grateful to have benefited from their work. In conclusion, we would like to specifically acknowledge the individual contributions of Dr. Paul A. Jensen and Dr. R. E. D. Woolsey. They will understand and accept our special recognition for their unique support in writing this book. The one individual who deserves grateful allocades for his comprehensive criticisms and contributions to this book is Dr. James Evans. Dr. Evans reviewed our first draft and supplied many important suggestions, for which we are very grateful. We would also be remiss if we didn't thank Mrs. Jan Bertch and Mrs. Candy Phillips for typing preliminary drafts of this manuscript, and suffering through dozens of angry outbursts as the material was composed. Last but not least, we are indebted to the American Institute of Industrial Engineers for permission to reproduce printed material.

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INTRODUCTION

"Cheshire-Puss", she began, rather timidly,
"Would you tell me, please, which way I
ought to go from here" ?
"That depends a great deal on where you
want to get to", said the cat.
"I don't much care where—," said Alice.
"Then it doesn't matter which way you go,"
said the cat.
"—so long as I get somewhere," Alice added.

From *Alice in Wonderland*
Lewis Carroll

As the Cheshire Cat so astutely observed in Wonderland, progress can often be made if one wanders around long enough. However, there are often better ways to search for an optimal solution than the aimless wandering of Alice. Network modeling techniques often provide the framework and computational structure to greatly improve many traditional approaches to systems analysis. The purpose of this chapter is to present the necessary machinery to both understand and apply the fundamental algorithms pre-

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sented in this text. Of course, the application of network analysis techniques often requires not only "where you want to get to" but also "which way you ought to go." Hopefully, this chapter will aid in defining both strategies.

A modern society can be viewed, in part, as a system of networks for transportation, communication, and distribution of energy, goods, and services. The complex structure and cost of these subsystems demand that existing facilities be efficiently used and that new facilities be rationally designed. Network analysis techniques can be of great value in the design, improvement, and rationalization of complex large-scale systems.

Network-flow models and solution techniques provide a rich and powerful framework from which many engineering problems can be formulated and solved. The visual and logical structure of network-flow analysis often provides a fresh and natural approach from which further engineering analysis can proceed. Once only a small segment in the field of operations research, network analysis techniques have recently emerged as a viable and computationally tractable approach to solving significant problems faced by modern engineering analysts.

The origins of network analysis are old and diverse. Network analysis relies heavily on graph theory, a branch of mathematics that evolved with Leonhard Euler's formulation and solution of the famous Konigsberg bridge problem in 1736 [7]. More than a century later, James Clerk Maxwell and

Gustav Robert Kirchhoff discovered certain basic principles of network analysis in the course of their studies of electric circuits. Since then, network analysis has become an important tool in the investigation of electrical systems. Early in the twentieth century, telephone engineers in Europe and the United States devised network methods to determine the best capacity of telephone trunk lines and switching centers in order to guarantee specified levels of customer serviceability. In the 1940s, during the period of World War II, the development of operations research yielded a number of techniques for the mathematical study of large-scale systems. Pioneering work in modern network analysis was conducted by Hitchcock [11] in 1941 and Koopmans [15] in 1947. Since then, network analysis has been a very active and productive research area with well over 1000 published papers. The emphasis of research in the 1950s and early 1960s was on formulation of new models and development of new algorithms. Later, emphasis shifted to the extension, computer implementation, and analysis of previously developed models and algorithms. Survey papers have been written by Fulkerson [10], Elmaghraby [6], Bradley [2], and Magnanti and Golden [16], among others. As the field of network analysis has developed over the years, the need has arisen for updated books providing different orientations at various levels of discussion. Books with extensive treatment of networks have been contributed by Ford and Fulkerson [8], Charnes and Cooper [4], Dantzig [5], Busacker and Saaty [3], Hu [12], Frank and Frisch [9], Whitehouse [21], and, more recently, Jensen and Barnes [14], Bazarra and Jarvis [1], and Minieka [17].

Network models and analysis are widely used in operations research for diverse applications, such as the analysis and design of large-scale irrigation systems, computer networks, cable television networks, transportation systems, and ground and satellite communication networks. Efficient network methodologies have been implemented to solve industrial problems, such as the warehousing and distribution of goods, project scheduling, equipment replacement, cost control, traffic studies, queueing analysis, assembly-line balancing, inventory control, and manpower allocation, to name a few.

Pritsker [20] provides some insight as to the recent surge in the application of network analysis techniques:

> Networks and network analyses are playing an increasingly important role in the description and improvement of operational systems primarily because of the ease with which systems can be modeled in network form. This growth in the use of networks can be attributed to:
>
> 1. The ability to model complex systems by compounding simple systems.
> 2. The mechanistic procedure for obtaining system figure-of-merits from networks.

3. The need for a communication mechanism to discuss the operational system in terms of its significant features.
4. A means for specifying the data requirements for analysis of the system.
5. A starting point for analysis and scheduling of the operational system.

Item 5 was the original reason for network construction and use. The advantages that accrued outside of the analysis procedure soon justified the network approach. Considerable work is motivated by the need for extending present analysis procedures to keep pace with applications of networks.

Network analysis is not a discipline confined to only one branch of academia or industry. Indeed, the real strength of the network approach lies in the fact that it can be successfully applied to almost any problem when the modeler has enough knowledge and insight to construct the proper network representation. The advantages of using network models can be stated as follows:

1. Network models accurately represent many real-world systems.

2. Network models seem to be more readily accepted by nonanalysts than perhaps any other type of models used in operations research. This phenomenon appears to stem from the notion that "a picture is worth a thousand words." Managers seem to accept a network diagram more easily than they do abstract symbols. Additionally, since network models are often related to physical problems, they can be easily explained to people with little quantitative background.

3. Network algorithms facilitate extremely efficient solutions to some large-scale models.

4. Network algorithms can often solve problems with significantly more variables and constraints than can be solved by other optimization techniques. This phenomenon is due to the fact that a network approach often allows the exploitation of particular structures in a model.

1.1 Definitions, Notation, and Symbolism

A *network* consists of a set of *nodes* and a set of *arcs* connecting the nodes. The nodes are also referred to as vertices or points. The arcs are also called edges, links, lines, or branches. A network can be represented by the notation $G = (\mathbf{N}, \mathbf{A})$, where **N** is the set of nodes and **A** the set of arcs of the network G.

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