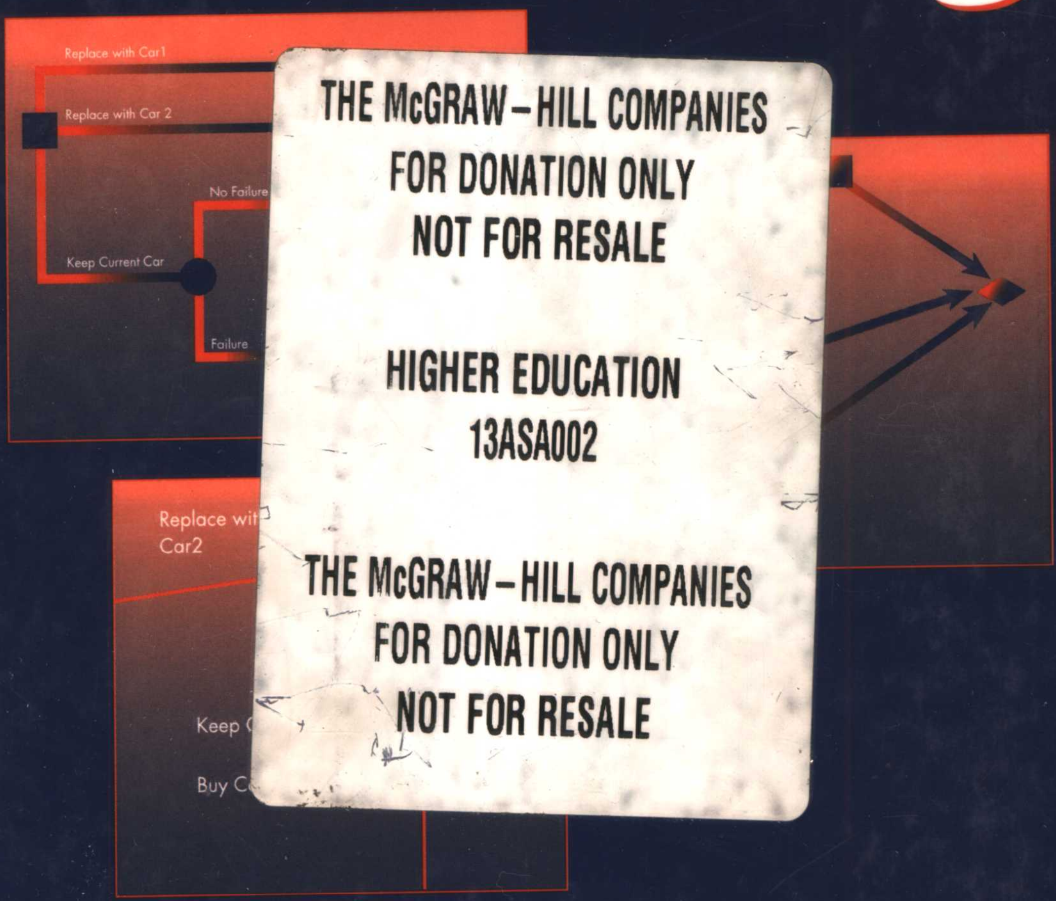
Decision Making and Forecasting



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DECISION MAKING AND FORECASTING

With Emphasis on Model Building and Policy Analysis

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Robert M. Oliver is Professor of Operations Research and Engineering Science at the University of California, Berkeley. He received his doctorate in Physics at the Massachusetts Institute of Technology in 1957 and is a recipient of the Fulbright Scholarship to the University of London and the Lanchester Prize of the Operations Research Society of America for his research in predicting and scheduling U.S. Post Office mail flow and sorting operations. He has held numerous appointments as technical advisor and consultant to corporations and U.S. government agencies and is the author of over 100 papers, journal articles, and books in forecasting, filtering, prediction, and decision-making models of operations research.

To the influence of
Morse and Kimball
and
To Donna and Sophie

PREFACE

The purpose of this book is to bring the scientific method to decision making and forecasting. Our objectives are best summarized from a passage in Morse and Kimball [1951]:

> Operations Research is a scientific method of providing executive departments with a quantitative basis for decisions regarding the operations under their control.

The emphasis throughout this book is to give the reader exposure and experience in the art and science of model-building, to show the close connection between forecasting and decision making, and to illustrate how decision trees and influence diagrams can be used as a common framework for discussion by both the mathematically trained analyst and the client or decision maker who may not have sophisticated quantitative skills.

For more years than we care to admit, both authors have taught courses in Operations Research and Management Science curricula that dealt with applied probability, forecasting, and decision-making models for undergraduate and graduate college students. These courses were taught separately without any attempt to link their common topics and we were always confronted with the inbuilt dilemma of presenting techniques to solve a mathematical problem once the model was clearly laid out before the student rather than explaining how to design models that represent real problems. This natural conflict was reinforced by the apparent lack of rigor in the art of model building when compared with the more formal mathematical foundations of the techniques themselves and by our own frustration in having to teach "standard" operations research and management science courses which seldom focussed on the central theme of making better decisions in real-world environments.

INTEGRATING FORECASTS IN DECISION MODELS

Several important developments have occurred during the past decade which offers all of us not only an opportunity to integrate forecasting and decision making but also to use graphical aids in the formulation and design of mathematical models and the presentation of results to decision makers. The natural language of influence diagrams and decision trees has found substantial application in a small number of industrial consulting companies but is only offered in the curricula of a very few universities. We hope that will change.

The essential ingredients of an integrated forecasting and decision-making formulation are

- development of a clear understanding of how uncertainty is to be handled and a logical framework in which to discuss and analyze rational courses of action.
- clear identification of the sources of uncertainty, identifying the effects of new sources of information and new forecasts and whether the decision maker and forecaster are one and the same or different people or institutions.
- careful and thoughtful problem formulation, including who makes decisions, which factors are known, which ones are uncertain, which ones directly influence decisions, and the timing of information and decisions.
- identification of objectives of the decision maker(s) and the decision-making environment. It is important to understand how objectives have different effects on strategies, and how objectives depend on the client(s).
- recognition of multiple attributes and the understanding of the extent to which there may be tradeoffs among them.
- emphasis on sensitivity analyses, recognizing that models are only crude approximations to real-world problems.
- communication of results and insights to decision makers.

Throughout, we repeatedly make use of four principles: those of coherence of probabilities, consistent units of measurement, optimality in sequential decision making, and parsimony in the construction of models. Perhaps even more important but not explicitly stated is the principle of common sense: if a model gives solutions that do not make sense it is probably the wrong model!

Beginning with single decision problems with only one uncertainty, we study a number of one-stage decision problems for perishable commodities where multiple uncertainties are present. This set of problems includes those known as yield management problems. The extension to sequential decisions, many periods of time, multiple forecasts, several attributes and criteria, and the use of nonlinear utilities are complications which are introduced as one attempts to solve real-world problems.

In this book we see how to design the most important features of realistic decision problems into mathematical models that reveal their structure and give insight. We emphasize model building rather than an axiomatic unifying theory, but references are given where the interested reader can pursue the mathematical theory if he or she chooses.

In this way we hope to bridge the gap between decision theorists and decision makers whose primary interest is to understand their particular problem but who have little time to pursue a unifying theory.

Because we place great emphasis on model formulation we rely on graphical techniques that use influence diagrams and decision trees. The analyses that follow the formulation are themselves often graphical. Such techniques have proved useful both in building models with client input as a prime factor and in analysis to explain results and give insights. We show how forecasting must be integrated with decision making in a coherent manner, recognizing the reality that forecasters and decision makers are almost always different individuals or organizations. We make frequent use of the economic value of forecasts and how these are related to discrimination and calibration of forecasts. The methods and models we describe can be developed on modern personal computer spreadsheet software although there are now several commercial packages linking influence diagrams and decision trees.

Many books on decision theory present a unified and consistent mathematical theory based on a given set of axioms. Emphasis is on the mathematical structure and its properties derived through theorems. The examples are often contrived to illustrate these properties; of necessity there is little regard for realism. Such texts can be thought of as technique oriented. The student studying them becomes well versed in the theory and its properties, but when faced with a real decision problem, often finds it hard to recognize how the theory applies or how one goes about the task of building a mathematical model to explore alternatives and different outcomes. Another approach is to base problem formulation on in-depth and detailed case studies of real problems. Real problems are almost always encumbered with complex details making it hard for the student to understand their structure or the sources of uncertainties. Our goal is to provide a text that lies between abstract theory and detailed case studies.

USE OF THE TEXT IN INSTRUCTION

The level of the text is aimed towards business and economics students entering a quantitative business program or a final year course for science or engineering students. Both of us have taught graduate and undergraduate courses using the material in the book. We have always found that there is more material than can be taught in a one-semester course, particularly with graduate students whose education is primarily mathematical and seem to lack the basic skills of model building.

For undergraduate students Chapter 1 and portions of Chapter 2 can be followed by Chapters 4 and 5 and portions of Chapters 6 and 7. A graduate course could require Chapters 1, 2, and 3 as preliminary reading with emphasis on Chapter 4 and material from 6, 7, 8, and 9 depending on which topics the instructor wanted to emphasize. The prerequisites include a knowledge of calculus, elementary linear algebra, and probability theory; we have found that even the better-prepared graduate students with backgrounds in probability and statistics do not feel comfortable dealing with more than two random variables. Conditional independence and its implications takes substantial time to sink in; working with formulations of real, not toy, problems may be the only way to develop this expertise as common sense can be used to check mathematical results. The text includes a body of core material, followed by more advanced sections that are clearly indicated as such, and which could be used with students possessing a more mature mathematical background. Elementary and advanced problems are included with each chapter. Some are thought to be difficult.

ACKNOWLEDGMENTS

This book had its origins in a seminar at Berkeley during the sabbatical visit of one of the authors and a series of eight lectures given in the fall of 1990 at the Institute of Statistics and Operations Research, Victoria University, New Zealand where the other author was on sabbatical leave. The focus in the lectures was on the application of decision trees and influence diagrams to forecasting and decision analysis. We assembled notes on several problems that either were simplified models of real-world decision problems or which illustrated how forecasting could be integrated with decision making and provide economic value to the endeavor.

We want to thank the faculty, staff, and students of the Institute of Statistics and Operations Research at Victoria University, Wellington, New Zealand for their original interest in the topics and for providing secretarial, computing, and other services for a sabbatical visitor. Corrections to the first set of notes were the result of many helpful suggestions and comments made by G. Anthony Vignaux. We are most appreciative of the support of the chairs of the departments of our host institutions, Professor Peter Purdue of the Operations Research Department at the U.S. Naval Postgraduate School, and Professor Shmuel Oren of the Industrial Engineering and Operations Research Department at the University of California, Berkeley, for affording us the support and encouragement in scheduling the original seminars based on early versions with incomplete notes.

Our many thanks to a large number of students who had to suffer through early offerings of the courses and problems; they are too numerous to name individually except for Zvi Covaliu, a former doctoral student at the University of California, and Teo Weng Lim of the Singapore Air Force, a former masters student at the Naval Postgraduate School. Dr. Covaliu taught an undergraduate version of the course in his final year and unselfishly shared many problem formulations to illustrate new ideas and suggest better ways of teaching them. Both Dr. Covaliu and Captain Lim continually contributed many constructive criticisms that led to correction of errors and greater clarification of our presentation. We are very grateful to both of them. Earlier versions of the book have been used in the classroom by four different teachers. Our reviewers included Zvi Covaliu, George Washington University; Jane Fraser, The Ohio State University; Simon French, University of Leeds; Craig Kirkwood, Arizona State University; Stephen Pollock, University of Michigan; and Robert Winkler, Duke University; all of whom made suggestions that resulted in very substantial changes and, in our opinion, improvements to the manuscript.

We take responsibility for any remaining errors and hope that interested readers who find them, or have suggestions for correcting and improving the text, will share their ideas with us.

Kneale T. Marshall
Robert M. Oliver

CONTENTS

CHAPTER 1

BASIC CONCEPTS

1.1 INTRODUCTION

The purpose of this book is to present an approach to modeling, analyzing, and integrating forecasts into decision making in insightful ways. The reader might ask, "Why another book on decision making or forecasting?" Many books are available on these topics, a number of which we have drawn on and from which we quote. But most of them emphasize analysis of models rather than model building and treat decision making, information gathering, and forecasting as separate topics. We stress model building, the linkages between decision making and forecasting, graphical methods, and sensitivity analyses that examine the decisions and policy spaces. Throughout the book we are keenly interested in the economic value of information and forecasts derived from relevant data rather than the examination of forecasting techniques isolated from decision making. We have drawn on our own experiences in making decisions in management positions and in teaching the material in graduate and undergraduate courses.

The term *decision making* is very broad, encompassing a wide range of possible topics, from a simple choice between two alternatives, each with known certain outcomes, to an axiomatic mathematical logic found in texts on statistical decision theory. *In this book the most important common characteristic of the problems we consider is* that decisions must be made when one does not know with certainty their effect because of the randomness of future events. Some of our examples involve using past and current data to forecast and so reduce uncertainty about the future. Others depend heavily on individual subjective judgments about the future, and still others use forecasts that combine expert opinion with historical data. Some have simple outcome measures that are directly quantifiable, and others have conflicting outcome measures not all of which are directly quantifiable. Some involve making sequential decisions over time, so that in making today's decision we must consider what decisions we should make in the future.

It is usual to treat the subject of forecasting uncertain futures separately from decision making. Most of the literature in forecasting makes no more than passing reference to how it might be applied in making decisions. In this book, one of our aims is to demonstrate how forecasting and decision making are necessarily intertwined. Emphasis is always on demonstrating how various factors can be modeled in ways useful to a decision *maker*.

The word *maker* is emphasized to stress that our models are not ones that simply present an "optimal" solution. It may seem redundant to state that decision makers make decisions! But all too often the analyst, who has the technical expertise to develop and analyze models to assist such a person, forgets this fact and is disappointed when the decision maker does not accept his or her "optimal" solution. In fact, the decision maker is often more interested in obtaining insights and understanding how decisions change with varying conditions or assumptions and much less in a particular numerical value that may be a solution under a restrictive set of assumptions. A decision maker at top levels of management is more concerned with the appropriateness of the model than with the mathematical techniques used to solve a given model. That is why in this book we emphasize model building and analysis rather than the mathematical techniques themselves.

We emphasize graphical representations of results as these are often more easily understood than algebraic formulations. They are also useful in showing which decisions are best over ranges of possible parameter values rather than only offering point solutions. Using a word the reader will see repeatedly in this book, our models and the techniques we use to solve them are designed to give insight to the decision maker who has the ultimate responsibility for making the decision. Although we discuss numerical algorithms for making forecasts and solving decision problems, our primary interests are in developing concepts, formulating, and designing good models, rather than in numerically efficient computations.

The remainder of this chapter describes the essentials of the type of decision problems discussed in this book, sets up the mathematical notation used, reviews the material the reader will need in the area of probability theory, introduces the reader to the elements of influence diagrams and decision trees, and illustrates their use in model building and analysis through a number of examples. This chapter concludes with an overview of the remaining chapters in the book.

1.2 THE IMPORTANCE OF MODELS IN DECISION MAKING

A significant portion of this book deals with what is conventionally called *Decision Analysis*, including the use of influence diagrams and decision trees, suitable methods for measuring outcomes, and preferences among choices. Decision analysis has proved extremely useful for "executive" or "strategic" decision making. An article by Corner and Kirkwood in 1991 lists over eighty applications published in the open literature from 1970 through 1989. The rate of growth in applications is very great, and the fields where they have been applied include environmental, medical, management, legal, accounting, transportation, finance, and governance, to name only a few. To quote from their paper,

> *Decision analysis provides tools for quantitatively analyzing decisions with uncertainty and/or multiple conflicting objectives. These tools are especially useful when there is limited directly relevant data so that expert judgment plays a significant role in the decision making process. Such situations include government policy making and regulation, strategic business decisions, and such risky personal decisions as selecting a treatment for a serious medical problem.* (p. 206)

The importance of making quantitative formulations of decision problems cannot be overemphasized, even though they have not always been used by decision makers to solve problems. The increasing complexity of decision making and the availability of computers and large data bases in industry and government make it imperative that we understand the costs and benefits of the timely use of relevant information and how decisions taken at one point in time depend on the decisions that follow.

Insufficient attention has been given in the classroom to the formulation and study of decision-making models. We hope that modeling in decision making will become more important in the undergraduate and graduate education of students in business, science, and engineering. We know of only a few institutions of higher education where a serious effort is made to teach this important subject—even in the operations research and management science fields the primary focus is on the mathematical techniques rather than problem formulation and the derivation of useful insights.

1.3 THE NATURE OF A DECISION PROBLEM

There are basic common threads to the problems discussed in this book. In every problem a decision maker has a number of alternate choices of actions from which one or more must be chosen to achieve some desired objective. Often, the set of alternative actions consists of two elements, either do something or do nothing. At other times the set of alternatives consists of a small number of alternate choices. In some examples in Chapter 2 the reader will see that the decision maker can have infinitely many choices. We denote the set of decision alternatives by $\mathcal{D}$; it is usually obvious in our examples what this set of possible decisions is.

In multistage problems where decisions are made in sequence over time from different sets, we denote by $\mathcal{D}_i$ the set of decision alternatives at stage i. A generic decision is denoted d, an element of $\mathcal{D}$, or $d \in \mathcal{D}$ for short. It is important that lowercase d not be confused with upper case D, which we use to denote a generic decision before it is made. For example, a decision maker may have to decide whether or not to proceed with a certain course of action (e.g., submit a proposal, develop a product, repair a facility). In this case $\mathcal{D}$ would contain two elements, "take the action" and "do not take the action"; thus d must be one of these decisions. But before the decision maker has decided on a specific decision, the decision is referred to by D.