Contents

What’s New in the Tenth Edition 23
Acknowledgments 25
About the Author 27
Trademarks 29

Chapter 1 What Is Operations Research? 31
1.1 Introduction 31
1.2 Operations Research Models 31
1.3 Solving the OR Model 34
1.4 Queuing and Simulation Models 35
1.5 Art of Modeling 36
1.6 More than Just Mathematics 37
1.7 Phases of an OR Study 39
1.8 About this Book 41
   Bibliography 41
   Problems 42

Chapter 2 Modeling with Linear Programming 45
2.1 Two-Variable LP Model 45
2.2 Graphical LP Solution 47
   2.2.1 Solution of a Maximization Model 48
   2.2.2 Solution of a Minimization Model 50
2.3 Computer Solution with Solver and AMPL 52
   2.3.1 LP Solution with Excel Solver 52
   2.3.2 LP Solution with AMPL 56
2.4 Linear Programming Applications 59
   2.4.1 Investment 60
   2.4.2 Production Planning and Inventory Control 62
   2.4.3 Workforce Planning 67
   2.4.4 Urban Development Planning 70
   2.4.5 Blending and Refining 73
   2.4.6 Additional LP Applications 76
   Bibliography 76
   Problems 76
4.5 Post-Optimal Analysis 185
  4.5.1 Changes Affecting Feasibility 186
  4.5.2 Changes Affecting Optimality 189

Bibliography 192
Problems 192

Chapter 5  Transportation Model and Its Variants 207
  5.1 Definition of the Transportation Model 207
  5.2 Nontraditional Transportation Models 211
  5.3 The Transportation Algorithm 214
    5.3.1 Determination of the Starting Solution 216
    5.3.2 Iterative Computations of the Transportation Algorithm 220
    5.3.3 Simplex Method Explanation of the Method of Multipliers 226
  5.4 The Assignment Model 227
    5.4.1 The Hungarian Method 227
    5.4.2 Simplex Explanation of the Hungarian Method 230

Bibliography 231

Case Study: Scheduling Appointments at Australian Tourist Commission Trade Events 232
Problems 236

Chapter 6  Network Model 247
  6.1 Scope and Definition of Network Models 247
  6.2 Minimal Spanning Tree Algorithm 250
  6.3 Shortest-Route Problem 251
    6.3.1 Examples of the Shortest-Route Applications 252
    6.3.2 Shortest-Route Algorithms 255
    6.3.3 Linear Programming Formulation of the Shortest-Route Problem 261
  6.4 Maximal Flow Model 265
    6.4.1 Enumeration of Cuts 266
    6.4.2 Maximal Flow Algorithm 267
    6.4.3 Linear Programming Formulation of Maximal Flow Mode 272
  6.5 CPM and PERT 273
    6.5.1 Network Representation 274
    6.5.2 Critical Path Method (CPM) Computations 276
    6.5.3 Construction of the Time Schedule 279
## Contents

6.5.4 Linear Programming Formulation of CPM  282  
6.5.5 PERT Networks  283  

Bibliography  285  

Case Study: Saving Federal Travel Dollars  286  

Problems  289  

### Chapter 7  Advanced Linear Programming  305  

7.1 Simplex Method Fundamentals  305  
7.1.1 From Extreme Points to Basic Solutions  306  
7.1.2 Generalized Simplex Tableau in Matrix Form  309  

7.2 Revised Simplex Method  311  
7.2.1 Development of the Optimality and Feasibility Conditions  311  
7.2.2 Revised Simplex Algorithm  312  
7.2.3 Computational Issues in the Revised Simplex Method  315  

7.3 Bounded-Variables Algorithm  317  

7.4 Duality  322  
7.4.1 Matrix Definition of the Dual Problem  322  
7.4.2 Optimal Dual Solution  322  

7.5 Parametric Linear Programming  325  
7.5.1 Parametric Changes in C  325  
7.5.2 Parametric Changes in b  327  

7.6 More Linear Programming Topics  329  

Bibliography  330  

Problems  330  

### Chapter 8  Goal Programming  341  

8.1 A Goal Programming Formulation  341  

8.2 Goal Programming Algorithms  343  
8.2.1 The Weights Method  343  
8.2.2 The Preemptive Method  345  

Bibliography  350  

Case Study: Allocation of Operating Room Time in Mount Sinai Hospital  350  

Problems  354  

### Chapter 9  Integer Linear Programming  359  

9.1 Illustrative Applications  359  
9.1.1 Capital Budgeting  360  
9.1.2 Set-Covering Problem  361
9.1.3 Fixed-Charge Problem 362
9.1.4 Either-Or and If-Then Constraints 364

9.2 Integer Programming Algorithms 366
9.2.1 Branch-and-Bound (B&B) Algorithm 367
9.2.2 Cutting-Plane Algorithm 373

Bibliography 378
Problems 379

Chapter 10 Heuristic Programming 397
10.1 Introduction 397
10.2 Greedy (Local Search) Heuristics 398
10.2.1 Discrete Variable Heuristic 399
10.2.2 Continuous Variable Heuristic 401
10.3 Metaheuristic 404
10.3.1 Tabu Search Algorithm 404
Summary of Tabu Search Algorithm 408
10.3.2 Simulated Annealing Algorithm 408
Summary of Simulated Annealing Algorithm 410
10.3.3 Genetic Algorithm 411
Summary of Genetic Algorithm 414
10.4 Application of Metaheuristics to Integer Linear Programs 415
10.4.1 ILP Tabu Algorithm 416
10.4.2 ILP Simulated Annealing Algorithm 418
10.4.3 ILP Genetic Algorithm 420
10.5 Introduction to Constraint Programming (CP) 423
Bibliography 425
Problems 425

Chapter 11 Traveling Salesperson Problem (TSP) 435
11.1 Scope of the TSP 435
11.2 TSP Mathematical Model 437
11.3 Exact TSP Algorithms 441
11.3.1 B&B Algorithm 441
11.3.2 Cutting-Plane Algorithm 444
11.4 Local Search Heuristics 445
11.4.1 Nearest-Neighbor Heuristic 445
11.4.2 Reversal Heuristic 446
11.5 Metaheuristics 449
11.5.1 TSP Tabu Algorithm 449
11.5.2 TSP Simulated Annealing Algorithm 452
Chapter 12 Deterministic Dynamic Programming 469

12.1 Recursive Nature of Dynamic Programming (DP) Computations 469
12.2 Forward and Backward Recursion 473
12.3 Selected DP Applications 474
  12.3.1 Knapsack/Fly-Away Kit/Cargo-Loading Model 475
  12.3.2 Workforce Size Model 480
  12.3.3 Equipment Replacement Model 482
  12.3.4 Investment Model 485
  12.3.5 Inventory Models 488
12.4 Problem of Dimensionality 488
Bibliography 490
Case Study: Optimization of Crosscutting and Log Allocation at Weyerhaeuser 491
Problems 494

Chapter 13 Inventory Modeling (with Introduction to Supply Chains) 501

13.1 Inventory Problem: A Supply Chain Perspective 501
  13.1.1 An Inventory Metric in Supply Chains 502
  13.1.2 Elements of the Inventory Optimization Model 504
13.2 Role of Demand in the Development of Inventory Models 505
13.3 Static Economic-Order-Quantity Models 507
  13.3.1 Classical EOQ Model 507
  13.3.2 EOQ with Price Breaks 511
  13.3.3 Multi-Item EOQ with Storage Limitation 514
13.4 Dynamic EOQ Models 517
  13.4.1 No-Setup EOQ Model 518
  13.4.2 Setup EOQ Model 521
13.5 Sticky Issues in Inventory Modeling 530
Bibliography 531
Case Study: Kroger Improves Pharmacy Inventory Management 531
Problems 535
Chapter 14  Review of Basic Probability  543

14.1 Laws of Probability  543
   14.1.1 Addition Law of Probability  544
   14.1.2 Conditional Law of Probability  544

14.2 Random Variables and Probability Distributions  545

14.3 Expectation of a Random Variable  547
   14.3.1 Mean and Variance (Standard Deviation) of a Random Variable  547
   14.3.2 Joint Random Variables  548

14.4 Four Common Probability Distributions  551
   14.4.1 Binomial Distribution  551
   14.4.2 Poisson Distribution  551
   14.4.3 Negative Exponential Distribution  552
   14.4.4 Normal Distribution  553

14.5 Empirical Distributions  555

Bibliography  560
Problems  560

Chapter 15  Decision Analysis and Games  567

15.1 Decision Making Under Certainty—Analytic Hierarchy Process (AHP)  567

15.2 Decision Making Under Risk  574
   15.2.1 Decision Tree–Based Expected Value Criterion  574
   15.2.2 Variants of the Expected Value Criterion  576

15.3 Decision Under Uncertainty  581

15.4 Game Theory  585
   15.4.1 Optimal Solution of Two-Person Zero-Sum Games  585
   15.4.2 Solution of Mixed Strategy Games  587

Bibliography  592
Case Study: Booking Limits in Hotel Reservations  593
Problems  595

Chapter 16  Probabilistic Inventory Models  611

16.1 Continuous Review Models  611
   16.1.1 "Probabilitized" EOQ Model  611
   16.1.2 Probabilistic EOQ Model  613

16.2 Single-Period Models  617
   16.2.1 No-Setup Model (Newsvendor Model)  618
   16.2.2 Setup Model (s-S Policy)  620
16.3 Multiperiod Model 623
Bibliography 625
Problems 625

Chapter 17 Markov Chains 629
17.1 Definition of a Markov Chain 629
17.2 Absolute and n-Step Transition Probabilities 632
17.3 Classification of the States in a Markov Chain 633
17.4 Steady-State Probabilities and Mean Return Times of Ergodic Chains 634
17.5 First Passage Time 636
17.6 Analysis of Absorbing States 639
Bibliography 642
Problems 642

Chapter 18 Queuing Systems 653
18.1 Why Study Queues? 653
18.2 Elements of a Queuing Model 654
18.3 Role of Exponential Distribution 656
18.4 Pure Birth and Death Models (Relationship Between the Exponential and Poisson Distributions) 657
18.4.1 Pure Birth Model 658
18.4.2 Pure Death Model 661
18.5 General Poisson Queuing Model 662
18.6 Specialized Poisson Queues 665
18.6.1 Steady-State Measures of Performance 667
18.6.2 Single-Server Models 670
18.6.3 Multiple-Server Models 674
18.6.4 Machine Servicing Model—(M/M/R): (GD/K/K), R < K 680
18.7 (M/G/1):(GD/∞/∞)—Pollaczek-Khintchine (P-K) Formula 682
18.8 Other Queuing Models 683
18.9 Queuing Decision Models 684
18.9.1 Cost Models 684
18.9.2 Aspiration Level Model 686
Bibliography 688
Case Study: Analysis of an Internal Transport System in a Manufacturing Plant 688
Problems 690

Chapter 19  Simulation Modeling 711
19.1 Monte Carlo Simulation 711
19.2 Types of Simulation 715
19.3 Elements of Discrete Event Simulation 715
  19.3.1 Generic Definition of Events 715
  19.3.2 Sampling from Probability Distributions 716
19.4 Generation of Random Numbers 720
19.5 Mechanics of Discrete Simulation 722
  19.5.1 Manual Simulation of a Single-Server Model 722
  19.5.2 Spreadsheet-Based Simulation of the Single-Server Model 726
19.6 Methods for Gathering Statistical Observations 728
  19.6.1 Subinterval Method 729
  19.6.2 Replication Method 730
19.7 Simulation Languages 731
Bibliography 733
Problems 733

Chapter 20  Classical Optimization Theory 741
20.1 Unconstrained Problems 741
  20.1.1 Necessary and Sufficient Conditions 742
  20.1.2 The Newton-Raphson Method 744
20.2 Constrained Problems 746
  20.2.1 Equality Constraints 747
  20.2.2 Inequality Constraints—Karush–Kuhn–Tucker (KKT) Conditions 754
Bibliography 758
Problems 758

Chapter 21  Nonlinear Programming Algorithms 763
21.1 Unconstrained Algorithms 763
  21.1.1 Direct Search Method 763
  21.1.2 Gradient Method 766
21.2 Constrained Algorithms 769
  21.2.1 Separable Programming 770
  21.2.2 Quadratic Programming 777
21.2.3 Chance-Constrained Programming 781
21.2.4 Linear Combinations Method 785
21.2.5 SUMT Algorithm 787
Bibliography 788
Problems 788

Appendix A Statistical Tables 793

Appendix B Partial Answers to Selected Problems 797

Index 833