TUTORIALS ON EMERGING METHODOLOGIES AND APPLICATIONS IN OPERATIONS RESEARCH

Recent titles in the

INTERNATIONAL SERIES IN OPERATIONS RESEARCH & MANAGEMENT SCIENCE

Frederick S. Hillier, Series Editor, *Stanford University*

Zhu, J. / *QUANTITATIVE MODELS FOR PERFORMANCE EVALUATION AND BENCHMARKING*

Ehrgott, M. & Gandibleux, X. */MULTIPLE CRITERIA OPTIMIZATION: State of the Art Annotated Bibliographical Surveys*

Bienstock, D. / *Potential Function Methods for Approx. Solving Linear Programming Problems*

Matsatsinis, N.F. & Siskos, Y. / *INTELLIGENT SUPPORT SYSTEMS FOR MARKETING DECISIONS*

Alpern, S. & Gal, S. */ THE THEORY OF SEARCH GAMES AND RENDEZVOUS*

Hall, R.W. */ HANDBOOK OF TRANSPORTATION SCIENCE - 2nd Ed.*

Glover, F. & Kochenberger, G.A. */HANDBOOK OF METAHEURISTICS*

Graves, S.B. & Ringuest, J.L. / *MODELS AND METHODS FOR PROJECT SELECTION: Concepts from Management Science, Finance and Information Technology*

Hassin, R. & Haviv, M./ *TO QUEUE OR NOT TO QUEUE: Equilibrium Behavior in Queueing Systems*

Gershwin, S.B. et al / *ANALYSIS & MODELING OF MANUFACTURING SYSTEMS*

Maros, I./ *COMPUTATIONAL TECHNIQUES OF THE SIMPLEX METHOD*

Harrison, T., Lee, H. & Neale, J./ *THE PRACTICE OF SUPPLY CHAIN MANAGEMENT: Where Theory And Application Converge*

Shanthikumar, J.G., Yao, D. & Zijm, W.H./ *STOCHASTIC MODELING AND OPTIMIZATION OF MANUFACTURING SYSTEMS AND SUPPLY CHAINS*

Nabrzyski, J., Schopf, J.M., **Węglarz, J./** *GRID RESOURCE MANAGEMENT: State of the Art and Future Trends*

Thissen, W.A.H. & Herder, P.M./ *CRITICAL INFRASTRUCTURES: State of the Art in Research and Application*

Carlsson, C., Fedrizzi, M., & Fullér, R./ *FUZZY LOGIC IN MANAGEMENT*

Soyer, R., Mazzuchi, T.A., & Singpurwalla, N.D./ *MATHEMATICAL RELIABILITY: An Expository Perspective*

Chakravarty, A.K. & Eliashberg, J./ *MANAGING BUSINESS INTERFACES: Marketing, Engineering, and Manufacturing Perspectives*

Talluri, K. & van Ryzin, G./ *THE THEORY AND PRACTICE OF REVENUE MANAGEMENT*

Kavadias, S. & Loch, C.H./*PROJECT SELECTION UNDER UNCERTAINTY: Dynamically Allocating Resources to Maximize Value*

Brandeau, M.L., Sainfort, F., Pierskalla, W.P./ *OPERATIONS RESEARCH AND HEALTH CARE: A Handbook of Methods and Applications*

Cooper, W.W., Seiford, L.M., Zhu, J./ *HANDBOOK OF DATA ENVELOPMENT ANALYSIS: Models and Methods*

Luenberger, D.G./ *LINEAR AND NONLINEAR PROGRAMMING, 2nd Ed.*

Sherbrooke, C.C./ *OPTIMAL INVENTORY MODELING OF SYSTEMS: Multi-Echelon Techniques, Second Edition*

Chu, S.-C., Leung, L.C., Hui, Y. V., Cheung, W./ *4th PARTY CYBER LOGISTICS FOR AIR CARGO*

Simchi-Levi, Wu, Shen/ *HANDBOOK OF QUANTITATIVE SUPPLY CHAIN ANALYSIS: Modeling in the E-Business Era*

Gass, S.I. & Assad, A.A./ *AN ANNOTATED TIMELINE OF OPERATIONS RESEARCH: An Informal History*

**** A list of the early publications in the series is at the end of the book ****

TUTORIALS ON EMERGING METHODOLOGIES AND APPLICATIONS IN OPERATIONS RESEARCH
Presented at INFORMS 2004, Denver, CO

Edited by
HARVEY J. GREENBERG
Mathematics Department
University of Colorado at Denver

Springer

eBook ISBN: 0-387-22827-6
Print ISBN: 0-387-22826-8

Created in the United States of America

Visit Springer's eBookstore at: http://ebooks.springerlink.com
and the Springer Global Website Online at: http://www.springeronline.com

This book is dedicated to the memory of Carl M. Harris, a pioneer in operations research with great vision and perseverance.

Contents

Dedication v

Contributing Authors ix

Preface xiii

Foreword xvii

Acknowledgments xviii

Chapter 1
Heuristic Search for Network Design 1–1
Ioannis Gamvros, Bruce Golden, S. Raghavan, and ***Daliborka Stanojević***

Chapter 2
Polyhedral Combinatorics 2–1
Robert D. Carr and *Goran Konjevod*

Chapter 3
Constraint Languages for Combinatorial Optimization 3–1
Pascal Van Hentenryck and *Laurent Michel*

Chapter 4
Radiation Oncology and Optimization 4–1
Allen Holder and *Bill Salter*

Chapter 5
Parallel Algorithm Design for Branch and Bound 5–1
David A. Bader, William E. Hart, and *Cynthia A. Phillips*

Chapter 6
Computer-Aided Design for Electrical and Computer Engineering 6–1
John W. Chinneck, Michel S. Nakhla, and *Q.J. Zhang*

Chapter 7
Nonlinear Programming and Engineering Applications 7–1
Robert J. Vanderbei

Chapter 8
Connecting MRP, MRP II and ERP — Supply Chain
Production Planning via Optimization Models 8–1
Stefan Voß and *David L. Woodruff*

Contributing Authors

David A. Bader is Associate Professor and Regents' Lecturer of the Departments of Electrical & Computer Engineering and Computer Science, University of New Mexico, since 1996. He received the NSF CAREER award for *High-Performance Algorithms for Scientific Applications,* for 2001–06. He is Chair, IEEE Computer Society Technical Committee on Parallel Processing. David is a member of the Founding Editorial Board of *The International Journal of High Performance Computing and Networking (IJHPCN)* and Associate Editor for *The ACM Journal of Experimental Algorithmics.* dbader@eece.unm.edu

Robert D. Carr is a Senior Member of the Technical Staff in the Algorithms and Discrete Mathematics Department of Sandia National Laboratories, Albuquerque since 1997. After receiving a Ph.D. in Mathematics from Carnegie Mellon in 1995, he held a post-doctoral position at the University of Ottawa and the ACO Post-doctoral fellowship at Carnegie Mellon. As Adjunct Faculty of the Computer Science Department at the University of New Mexico in 2001, he taught a course in polyhedral combinatorics. The notes from that course became part of this book's chapter. bobcarr@cs.sandia.gov

John W. Chinneck is the Associate Dean (Research) for the Faculty of Engineering and Design, and Associate Chair of the Department of Systems and Computer Engineering, at Carleton University. He has developed computer tools that assist in the formulation and analysis of very large and complex optimization models. His algorithms for the analysis of infeasible linear programs have been incorporated in many commercial linear programming solvers, including LINDO, CPLEX, XPRESS-MP, Frontline Systems Excel solvers, and OSL. chinneck@sce.carleton.ca

Ioannis Gamvros is a doctoral student at the University of Maryland. His research interests are in Telecommunications Network Design. Currently, he is working on solving network design and revenue management problems that arise in satellite communication systems. igamvros@rhsmith.umd.edu

Bruce Golden is the France-Merrick Chair in Management Science in the Robert H. Smith School of Business at the University of Maryland. His research interests include heuristic search, combinatorial optimization, and applied OR. He has received numerous awards, including the Thomas L. Saaty Prize (1994), the University of Maryland Distinguished Scholar-Teacher Award (2000), and the INFORMS Award for the Teaching of OR/MS Practice (2003). He is currently Editor-in-Chief of *Networks* and was previously Editor-in-Chief of the *INFORMS Journal on Computing.* bgolden@rhsmith.umd.edu

William E. Hart is Principle Member of the Algorithms and Discrete Mathematics Department, Sandia National Laboratories, Albuquerque. After earning his Ph.D. in Computer Science from the University of California at San Diego in 1994, Bill joined SNL as an AMS Fellow and received their Award for Excellence in 1995, 1999, and 2001. In 1997, Bill received the *Best Paper by a Young Scientist* from RECOMB. He has performed algorithmic research on a variety of global and combinatorial optimization methods, and he has been a primary architect of the SNL Parallel Integer and Combinatorial Optimization system (PICO). wehart@sandia.gov

Pascal Van Hentenryck is Professor of Computer Science at Brown University since 1990. He is the main designer and implementor of the CHIP system (the foundation of all modern constraint programming systems), the OPL optimization programming language for constraint and mathematical programming, and the Numerica system for global optimization. These three systems are all described in books published by the MIT Press. pvh@cs.brown.edu

Allen Holder is Assistant Professor of Mathematics, Trinity University; Adjunct Professor of Radiation Oncology, University of Texas Health Science Center at San Antonio; and, Research Assistant, Hearin Center for Enterprise Science, The University of Mississippi. He received his Ph.D. in Applied Mathematics from The University of Colorado at Denver, 1998. In 2000, Allen received the INFORMS *William Pierskalla Award in Health Applications.* He currently supervises undergraduate research under an NSF REU. aholder@trinity.edu

Goran Konjevod is Assistant Professor of Computer Science and Engineering at Arizona State University since 2000. He is also a consultant for Los Alamos National Laboratory. He has designed and analyzed algorithms for discrete problems in operations research. goran@asu.edu

Laurent Michel is Assistant Professor of Computer Science & Engineering at University of Connecticut since 2002. His research interests focus on the design and implementation of domain-specific languages for combinatorial optimization, but they extend to programming languages, constraint programming, artificial intelligence, non-linear programming, and reasoning under uncertainty. He co-developed Newton, Numerica, The Optimization Programming Language (OPL), the constrained-based library Modeler++, and the local search tools Localizer, Localizer++ and Comet. ldm@engr.uconn.edu

Michel S. Nakhla is Chancellor's Professor in the Department of Electronics at Carleton University. He arrived in 1988 as holder of the Computer-Aided Engineering Senior Industrial Chair, established by Bell-Northern Research

and the Natural Sciences and Engineering Research Council of Canada, and he founded Carleton's high-speed CAD research group. He is Associate Editor of the *IEEE Transactions on Circuits and Systems — Fundamental Theory and Applications* and of the *Circuits, Systems and Signal Processing Journal.* msn@doe.carleton.ca

Cynthia A. Phillips is a Distinguished Member of the Technical Staff in the Algorithms and Discrete Math Department at Sandia National Laboratories. She joined the Labs right after receiving her Ph.D. in computer science from MIT in 1990. She received a Lockheed Martin/Sandia National Laboratories Employee Recognition Award for individual technical excellence in 2000, SNL Awards for Excellence in 1993, 1998, 2002, and 2003, and was the YWCA (Central Rio Grande) *Woman on the Move in Science and Technology* in 2000. Cindy is one of three main developers of the SNL PICO massively-parallel integer programming code. caphill@sandia.gov

S. Raghavan is Assistant Professor of Management Science at the Robert H. Smith School of Business, University of Maryland. In 1996 he received the *George B. Dantzig Dissertation Award* from INFORMS for his thesis, "Formulations and Algorithms for Network Design Problems with Connectivity Requirements." He serves as Associate Editor of *Networks,* and he has recently co-edited a book, *Telecommunications Network Design and Management.* raghavan@umd.edu

Bill Salter is Assistant Professor of Radiation Oncology and Associate Director of Medical Physics at the Cancer Therapy and Research Center (CTRC) at The University of Texas Health Science Center, San Antonio. He is the inventor of technology used to enhance the delivery capabilities of the Nomos Peacock IMRT system for delivery of Intensity Modulated RadioSurgical (IMRS) treatments. bsalter@ctrc.net

Daliborka Stanojević is pursuing a Ph.D. in Management Science at the University of Maryland. Her primary research interests are in Telecommunications Network Design. Most recently she has been working on developing optimization techniques for designing optical communication networks. dstanoje@rhsmith.umd.edu

Robert J. Vanderbei is Professor of Operations Research and Financial Engineering at Princeton University. He is also an Associated Faculty Member, Departments of Mathematics and Computer Science, and the Program in Applied and Computational Mathematics. He is the Director of the Program in Engineering and Management Systems. His 1997 book, *Linear Programming:*

Foundations and Extensions has been used extensively, supplemented by the wealth of materials on his web site. rvdb@princeton.edu

Stefan Voß is Professor and Director of the Institute of Information Systems at the University of Hamburg. Previous positions include Professor and Head of the Department of Business Administration, Information Systems and Information Management at the University of Technology Braunschweig. Stefan is Associate Editor of *INFORMS Journal on Computing* and Area Editor of *Journal of Heuristics.* He is co-author of the 2003 book, *Introduction to Computational Optimization Models for Production Planning in a Supply Chain.* stefan.voss@uni-hamburg.de

David L. Woodruff is Professor of Management at University of California, Davis. He was Chair of the INFORMS Computing Society, and serves on several editorial boards: *INFORMS Journal On Computing, Journal Of Heuristics* (Methodology Area Editor), *Production and Operations Management,* and *International Journal of Production Research.* He is co-author of the 2003 book, *Introduction to Computational Optimization Models for Production Planning in a Supply Chain.* dlwoodruff@ucdavis.edu

QJ. Zhang is a Professor in the Electronics Department, Carleton University. His research interests are neural network and optimization methods for high-speed/high-frequency electronic design, and has over 160 papers in the area. He is co-author of *Neural Networks for RF and Microwave Design,* co-editor of *Modeling and Simulation of High-Speed VLSI Interconnects,* a contributor to *Analog Methods for Computer-Aided Analysis and Diagnosis,* and twice a Guest Editor for the Special Issues on Applications of Artificial neural networks to RF and Microwave Design for the *International Journal of RF and Microwave Computer-Aided Engineering.* qjz@doe.carleton.ca

Preface

This volume reflects the theme of the INFORMS 2004 Meeting in Denver: *Back to OR Roots.* Emerging as a quantitative approach to problem-solving in World War II, our founders were physicists, mathematicians, and engineers who quickly found peace-time uses. It is fair to say that Operations Research (OR) was born in the same incubator as computer science, and it has spawned many new disciplines, such as systems engineering, health care management, and transportation science. Although people from many disciplines routinely use OR methods, many scientific researchers, engineers, and others do not understand basic OR tools and how they can help them.

Disciplines ranging from finance to bioengineering are the beneficiaries of what we do — we take an interdisciplinary approach to problem-solving. Our strengths are modeling, analysis, and algorithm design. We provide a quantitative foundation for a broad spectrum of problems, from economics to medicine, from environmental control to sports, from e-commerce to computational geometry. We are both producers and consumers because the mainstream of OR is in the interfaces.

As part of this effort to recognize and extend OR roots in future problem-solving, we organized a set of tutorials designed for people who heard of the topic and want to decide whether to learn it. The 90 minutes was spent addressing the questions:

- What is this about, in a nutshell?
- Why is it important?
- Where can I learn more?

In total, we had 14 tutorials, and eight of them are published here.

Chapter 1, *Heuristic Search for Network Design,* by Ioannis Gamvros, Bruce Golden, S. Raghavan, and **Daliborka Stanojević,** is a great meeting of OR roots with modern solution techniques. Network design is an early OR problem, but still too complex for exact solution methods, like integer programming. The success of heuristic search, as advanced through many OR applications, makes it a natural approach. This chapter considers simple heuristics first (a piece of good advice to problem solvers), then takes a hard look at local search and a variety of metaheuristics, such as GRASP, simulated annealing, tabu search, and genetic algorithms. They proceed to describe a series of highly effective genetic algorithms, giving insight into how the algorithm controls are developed for various network design problems.

Chapter 2, *Polyhedral Combinatorics,* by Robert D. Carr and Goran Konjevod, draws from some early mathematical foundations, but with a much deeper importance for solving hard combinatorial optimization problems. They care-

fully describe problem formulations and impart an intuition about how to recognize better ones, and why they are better. This chapter also brings together concepts of modeling with a view of algorithm design, such as understanding precisely the separation problem and its relation with duality.

Chapter 3, *Constraint Languages for Combinatorial Optimization,* by Pascal Van Hentenryck and Laurent Michel, brings together OR and AI vantages of combinatorial optimization. Traditionally, OR has focused on methods and hence produced very good algorithms, whereas AI has focused on models and hence produced some languages of immediate value to OR problem-solving. Constraint-based languages comprise a class, and these authors have been major contributors to this marriage. This chapter illustrates how constraint-based languages provide a powerful and natural way to represent traditional OR problems, like scheduling and sequencing.

Chapter 4, *Radiation Oncology and Optimization,* by Allen Holder and Bill Salter, reflects on how directly OR applies to science. This particular problem in radiation therapy was modeled with linear programming in 1968, but this was not extended until 1990. It is now a core problem in medical physics being addressed by modern OR techniques, aimed at giving physicians accurate information and helping to automate radiation therapy. Further, the authors' interdisciplinary collaboration personifies an element of OR roots.

Chapter 5, *Parallel Algorithm Design for Branch and Bound,* by David A. Bader, William E. Hart, and Cynthia A. Phillips, draws from the authors' vast experiences, and includes a section on how to debug an algorithm implemented on a parallel architecture. As computers become more powerful, we expand our scope of problem domains to keep the challenges ongoing. Parallelism is a natural way to meet this challenge. OR has always been at the forefront of computer science, not by coincidence, but by design. In the 1950's, linear programming was used to debug hardware and software of new computers because it challenged every aspect of symbolic and numerical computing. This chapter reflects a modern version of this, with combinatorial optimization posing computational challenges, and the OR/CS interfaces continue to flourish.

Chapter 6, *Computer-Aided Design for Electrical and Computer Engineering,* by John W. Chinneck, Michel S. Nakhla, and Q.J. Zhang, exemplifies the application of OR techniques to an area of engineering whose problems challenge our state-of-the-art due to size and complexity. This chapter achieves the daunting task of addressing the two, disjoint communities, so that not only will OR people learn about these CAD problems, but also the electrical and computer engineering community will learn more about the applicability of OR techniques. After carefully developing a mixed-integer, nonlinear programming model of physical design, this tutorial goes further into circuit optimization and routing.

Chapter 7, *Nonlinear Programming and Engineering Applications,* by Robert J. Vanderbei, is a perfect example of drawing from OR roots to solve engineering problems. After describing LOQO, the author's interior point code for nonlinear programming, this chapter describes its application to Finite Impulse Response (FIR) filter design, telescope design — optics, telescope design — truss structure, and computing stable orbits for the ***n*-body** problem. Many of the early engineering applications used nonlinear programming, and this chapter shows how his interior point algorithm can push that envelope.

Chapter 8, *Connecting mrp, MRP II and ERP Supply Chain Planning via Optimization Models,* by Stefan Voß and David L. Woodruff, is concerned with a problem that is dubbed in modern parlance "supply chain planning." They point out that this stems from the OR roots in *materials requirements planning* and proceed to develop a family of mathematical programming models. This chapter presents the model development step-by-step, moving toward greater flexibility and scope, such as incorporating substitutions at various levels of the supply chain and identifying bottlenecks.

Collectively, these chapters show how OR continues to apply to business, engineering, and science. The techniques are mainstream OR, updated by recent advances.

HARVEY J. GREENBERG

Foreword

To keep a lamp burning we have to keep putting oil in it.
– MOTHER TERESA

The field of operations research has a glorious history, distinguished by impressive foundations steeped in deep theory and modeling and an equally impressive range of successful applications. However, to remain healthy and vigorous, any field must continually renew itself, embracing new methodologies and new applications.

With the Denver meeting, INFORMS is both bringing attention to its OR roots and also looking toward the future. The tutorials on emerging technologies and applications in this collection are a part of that effort, not only in reflecting a wide range of theory and applications, but also in making operations research known to a much broader population who might not know about the profession. As an engineer, I am delighted that this book is designed to bring attention to the profession's roots and to an array of analytic methods and intellectual ideas that have had, and will continue to have, considerable impact on practice. The editor is to be congratulated for assembling a first-rate cast of authors with impressive experience in developing OR methods and applying OR to engineering, science, and technology.

Through the impressive range of topics covered in this volume, readers will learn directly about the breadth of operations research, and also find outstanding guides to the literature. In particular, one cannot help but see the many ties between operations research and engineering.

In fact, I see something of a renewal these days in the application of operations research to engineering and science, with many notable and visible applications in such fields as medicine, communications, supply chain management, and systems design, as reflected in the pages to follow. But I also see less visible, but equally impressive, imbedded applications, a sort of 'OR Inside,' in contexts such as the design of computer compilers, machine learning, and human memory and learning.

I am delighted that this volume is dedicated to Carl Harris. Carl had an unwavering exuberance for operations research and especially the interplay between theory and practice. He would very much have enjoyed both the content and intended objective of these tutorial papers.

The editor, Harvey Greenberg, who himself is noted for the breadth of his experiences in research and applications, is to be congratulated for assembling such a fine volume and for his efforts to keep the lamp of OR burning by highlighting important developments and, hopefully, fueling new fields of inquiry and application within operations research.

Thomas L. Magnanti
Dean, School of Engineering
Massachusetts Institute of Technology
Cambridge, MA - June 2004

Acknowledgments

First, and foremost, I thank the authors, without whom this book could not have been written. Amidst busy schedules, they worked hard to enable this book to be published before the INFORMS 2004 meeting, and the results are evidently outstanding. I also thank Manuel Laguna, our Meeting Chair, who encouraged this to happen and helped with sorting out some of the early details. Gary Folven, from Kluwer Academic Press, also supported this from the beginning, and he helped with the production process. Last, but not least, it is the memory of visionaries like Carl Harris that inspire books like this one to be produced.