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# FUNDAMENTALS OF SUPPLY CHAIN THEORY

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Second Edition

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 **WILEY-  
INTERSCIENCE**

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Published simultaneously in Canada.

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***Library of Congress Cataloging-in-Publication Data:***

Fundamentals of Supply Chain Theory / Lawrence V. Snyder and Zuo-Jun Max Shen.  
p. cm.—(Wiley series in XXX)  
“Wiley-Interscience.”  
Includes bibliographical references and index.  
ISBN XXX (pbk.)  
1. Supply Chain Management. 2. Operations Research sciences—Research—Supply Chain Management.

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

# PREFACE

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## Goals of This Book

In the past few decades, the study of supply chain management has evolved into a cohesive body of knowledge—not merely a haphazard collection of models, algorithms, and theorems, but a rich theory whose components intersect and inform each other. We wrote this book to help codify the foundations of this emerging supply chain theory and to demonstrate how recent developments build upon the classical models. Our focus is primarily on the seminal models and algorithms of supply chain theory—the building blocks that underlie much of the supply chain literature. We believe that an understanding of these models provides researchers with a sort of guidebook to the literature, as well as a toolbox to draw from when developing new models. We also discuss some more recent models that demonstrate how the classical models can be extended and applied in richer settings. These models provide graduate students and other new researchers in the field with some examples of the trajectory of research on supply chain theory—how the building blocks can be assembled to create something more complex, interesting, or useful.

Studying supply chain theory as a whole allows us the luxury of gaining some perspective on the field, a perspective that is not always evident when we immerse ourselves deeply in the literature on a particular topic. To that end, wherever possible, we have attempted to highlight the connections among supply chain models—for example, the conceptual similarities among different supply chain pooling models, the ways that inventory and location models can be combined, or the ways that inventory theory interacts with game theory to produce supply chain coordination models.

## Who Should Read This Book

This book was written for anyone who is interested in quantitative approaches for studying supply chains. This includes people from a wide range of disciplines, such as industrial engineering/operations research, mathematics, management, economics, computer science, and finance. This also includes students (primarily graduate students), faculty, researchers, and practitioners of supply chain theory. And it includes scholars who are new to supply chain theory and want a gentle but rigorous introduction to it, or scholars who are well versed in the field and want a refresher or a reference for the seminal models. Finally, since you are holding this book, it most likely includes you.

One of the hallmarks—and, in our opinion, the great pleasures—of supply chain theory is that it makes use of a wide variety of the tools of operations research, mathematics, and computer science. In this book, you will find mathematical programming models (linear, integer, nonlinear, conic, stochastic, robust), duality theory, optimization techniques (Lagrangian relaxation, column generation, dynamic programming, line search, plus optimization by calculus and finite differences), heuristics and approximations, probability, stochastic processes, game theory, combinatorics, simulation, and complexity theory.

To make use of this book, you need not be an expert in all of these. (We are not.) We assume that you are familiar with basic optimization theory—that you know how to formulate a linear program and its dual, that you know how branch-and-bound works, and that you can perform a simple line search method such as bisection search. We also assume that you understand probability distributions and know how to compute expectations of random variables and functions thereof. We assume that your calculus is in good working order, that you can compute derivatives and integrals, including ones that involve multiple variables or other derivatives or integrals. We assume you have met Markov chains before, but we don't require you to remember much about them. For just about everything else, we will start from the ground up and tell you (or remind you of) what you need to know in order to understand the topic at hand. For some topics, you will find a useful reference in Appendix C, which lists formulas for calculating expectations, loss functions, geometric series, and some tricky derivatives and integrals. Because Lagrangian relaxation and column generation play a role in several chapters of this book, we have included a brief primer on those topics in Appendix D.

Probably the single most important prerequisite for this book is a high level of general mathematical maturity. We discuss a lot of mathematical proofs, and ask you to write your own in the homework problems. If you do not have much experience in this area, you may find the proofs to be the most challenging aspect of this book. To help you out, we have included in Appendix B a short guide to proof-writing. We hope this appendix will familiarize you with some of the basic principles of proof-writing, as well as some of the finer points of proof style and syntax. But, proof-writing is perhaps more art than science, and the appendix will only get you so far. You will learn to be a good proof-writer mainly by practicing the craft.

## Organization of This Book

Our intention in writing this book was to cover a broad range of topics in supply chain theory, even if that meant that we could not cover some topics as deeply as we might have

liked. Most of the material in this book is derived from earlier papers, and of course we have cited those papers carefully so that readers can delve deeper into any topics they wish. We have also cited important related references, and review articles where possible, so that readers can find more information about topics that interest them.

Most of this book (Chapters 2–12) deals with *centralized* supply chain models, in which all of the decision variables are under the control of a single decision-maker. Most classical supply chain models, such as those for optimizing inventories and facility locations, are centralized models. In contrast, the *decentralized* models of Chapters 13–15 involve multiple parties with independent, conflicting objectives and the autonomy to choose their decision variables to optimize those objectives. The bullwhip effect (Chapter 13) is an example of a result of this decentralization, while the models of Chapters 14 and 15 discuss strategies for mitigating the negative financial effects of decentralization.

This chapters of this book are as follows:

- Chapter 1 (“Introduction”) gives an overview of supply chain management and defines terms that we will use throughout the book.
- Chapter 2 (“Forecasting and Demand Modeling”) discusses classical and machine-learning-based forecasting methods, as well as three approaches—the Bass diffusion model, leading indicators, and choice models—that have been used more recently to predict demand. We refer to these latter approaches as “demand modeling” to differentiate them from classical forecasting techniques and to emphasize the fact that they aim to provide a model of the demand itself and not merely of its statistical properties.
- We discuss classical single-location inventory models in Chapters 3 (“Deterministic Inventory Models”), 4 (“Stochastic Inventory Models: Periodic Review”), and 5 (“Stochastic Inventory Models: Continuous Review”). For most of these models, we discuss how to formulate the objective function as well as how to optimize it—exactly or heuristically, in closed form or using algorithms—by our choice of inventory parameters. We also explore the theoretical properties of some of these models, including the optimality of inventory policies and the worst-case performance of heuristics.
- In Chapter 6 (“Multiechelon Inventory Models”), we discuss multiechelon inventory models, including both stochastic-service models (including the Clark–Scarf model for serial systems and the Shang and Song approximation) and guaranteed-service models (also known as strategic safety stock placement problems).
- Chapter 7 (“Pooling and Flexibility”) discusses risk pooling, as well as other techniques, such as postponement, transshipments, and process flexibility, that can provide similar pooling benefits.
- In Chapter 8 (“Facility Location Models”), we turn our attention to facility location models. We present the classical uncapacitated fixed-charge location problem (UFLP) in some detail, including its formulation as an integer programming problem and its solution by Lagrangian relaxation. We then discuss other classical location models such as the  $p$ -median problem and covering models, as well as stochastic versions of the UFLP. Finally, we cover network design problems, including both

problems in which we make yes/no decisions on the nodes and those in which we do the same for the arcs.

- In Chapter 9 (“Supply Uncertainty”), we consider randomness in the availability or quantity of supply and develop models for coping with this uncertainty in inventory and facility location models.
- Chapter 10 (“The Traveling Salesman Problem”) discusses perhaps the most famous supply chain problem, the traveling salesman problem (TSP). We discuss both exact and heuristic solution methods for the TSP, as well as theoretical properties of the model and the algorithms. We conclude with a digression on TSP “world records.”
- In Chapter 11 (“The Vehicle Routing Problem”), we extend the TSP to consider the more practical problem of routing multiple vehicles simultaneously to deliver to many customers, a problem known as the vehicle routing problem (VRP). We present algorithms, focusing mainly on heuristics for this very difficult computational problem. We discuss theoretical properties of the problem, as well as some of the many extensions that have been proposed to add more practical features to the classical model.
- Chapter 12 (“Integrated Supply Chain Models”) discusses models that combine multiple types of models discussed earlier in the book. In particular, we include location–inventory, location–routing, and inventory–routing models.
- In Chapter 13 (“The Bullwhip Effect”), we discuss a phenomenon of demand variability amplification known as the bullwhip effect. The bullwhip effect can occur because of irrational or suboptimal behavior on the part of supply chain managers, but it can also occur as the result of rational, optimizing behavior. We cover mathematical models for proving that the bullwhip effect occurs as a result of the latter type.
- When supply chain partners each optimize their own objective functions, they typically arrive at solutions that are suboptimal from the point of view of the total supply chain. In Chapter 14 (“Supply Chain Contracts”), we discuss contracts that achieve coordination within a supply chain made up of individual players with differing objectives.
- Chapter 15 (“Auctions”) introduces mathematical models for auctions, which are frequently used to set prices within supply chains. Auctions can be thought of as another way to mitigate the effects of decentralized decision-making and to bring supply chains into closer coordination.
- Chapter 16 (“Applications of Supply Chain Theory”) explores three non-supply-chain fields in which supply chain theory has been widely applied: electricity systems, health care, and public sector operations. In each of these topics, we cover a few (typically more recent) models that directly apply the tools you will have learned earlier in the book. Our aim is to demonstrate the application of supply chain theory, now that you have mastered its methodologies.
- The book concludes with four appendices. Appendix A contains homework problems whose solutions use material from multiple chapters. Appendix B provides a short

primer on how to write mathematical proofs. Appendix C lists helpful formulas that are used throughout the book. Appendix D gives a brief overview of Lagrangian relaxation and column generation.

The material in this book can accommodate a good deal of reordering and omission by the instructor. The only real exception is the inventory-theoretic material (Chapters 3–6), which is at the core of much of the subsequent material in the book and therefore should be covered early on. However, not all of the material in the inventory chapters is used elsewhere, and much of it can be skipped if desired. A bare-bones treatment of the essential inventory topics would include Section 3.2 on the EOQ model, Section 4.3.2 on the newsvendor problem, and Section 5.1 on  $(r, Q)$  policies—and even this material could be omitted for students who are already familiar with it. In addition, the material in Section 9.6 and Chapter 12 relies on the facility location chapter (Chapter 8), primarily Section 8.2. And of course, Chapter 16, on applications of supply chain theory, draws on material from throughout the book. Other than these, there are no precedence constraints regarding the sequence of material covered, and the instructor is free to rearrange the topics according to his or her preferences, interests, and expertise, as well as those of the students.

The final section of each chapter (except Chapter 1) contains a case study, a new feature in the second edition. The case studies are drawn from the journal *Interfaces* (now called the *INFORMS Journal on Applied Analytics*). Each case study illustrates an application by a real company or organization of the ideas discussed in the chapter. The case studies show the reader how supply chain theory can be applied, sometimes as-is and sometimes with substantial modifications, to solve real-world problems with significant impact.

We have adapted the original notation for the models discussed in the case studies, in order to be consistent with the rest of the book. In some cases we have also simplified or made other minor modifications to the models, while striving to maintain the main ideas of the original models. Each case study gives some basic facts about the company involved—for example, its ranking within its industry. We have attempted to update these facts where possible, but in general the reader should assume the facts were correct at the time that the original *Interfaces* article was published, if not still true today, even if we use the present tense in stating them.

Each of the chapters (again, except Chapter 1) is followed by a set of homework problems, and Appendix A presents problems that use material from multiple chapters. The problems challenge readers to understand, interpret, and extend the models and algorithms discussed in the text. Some of them involve simply applying the models and algorithms presented in the book as-is. Most of them, however, ask the reader to prove theorems, develop models, or somehow explore the material more deeply than it is covered in the chapters. Some of the problems require data sets that are too large to include in the text itself. These data sets are posted on the web site for this book. Where relevant, citations to the original sources for homework problems are given in the solutions, rather than in the problems themselves.

The book's web site also contains a list of errata. If you find errors not contained on this list, please e-mail the authors, whose contact information can also be found on the site.

### **New in the Second Edition**

The second edition of *Fundamentals of Supply Chain Theory* is nearly twice as long as the first. The book has been revised from beginning to end. We have added three entirely

new chapters, on the TSP, the VRP, and applications of supply chain theory. The inventory chapters have been reorganized and significantly expanded, as has the facility location chapter. We have rearranged the material on risk pooling and supply uncertainty into (we feel) more logical groupings. Other new topics include machine learning models for forecasting (Section 2.4), a multisupplier inventory model with supply uncertainty (Section 9.4), a conic optimization approach for the LMRP (Section 12.2.8), location–routing and inventory–routing models (Sections 12.3 and 12.4), a game-theoretic analysis of the VCG auction (Section 15.4.3), and a primer on column generation (Section D.2).

The end-of-chapter case studies are a new feature for the second edition. We have added nearly 200 new homework problems and over 60 new worked examples. We redesigned all of the figures for improved clarity and have added 140 new ones. The algorithm pseudocode has been updated to a more modern format, and the index is now more comprehensive.

### Resources for Instructors

We have developed the following resources to assist instructors:

- An instructor’s manual containing full solutions to the homework problems
- PowerPoint slides for in-class presentation of the book material
- In-depth MATLAB coding assignments so that students can implement the models and algorithms discussed in the book

These resources are available to verified instructors via links on the book’s web site.

### Acknowledgments

We owe a debt of gratitude to many people for many reasons. First, we wish to thank Mindy Okura-Marszycki, Susanne Steitz-Filler, Vini Premkumar, Kathleen Pagliaro, Nithya Sechin, Melissa Yanuzzi, Jackie Palmieri, and the rest of the editorial team at Wiley, for championing the book and bringing it to fruition.

We would like to thank our professors at Northwestern University who taught us while we were graduate students there. Special thanks go to Mark Daskin and David Simchi-Levi, who served as our advisors and mentors. The models in Sections 9.6 and 12.2, in particular, are the results of our collaborations with Mark. Both Mark and David are outstanding researchers, excellent teachers, and generous, supportive advisors—not to mention accomplished textbook authors—and we would not be the professors we are without them.

We thank our colleagues at Lehigh and Berkeley, as well as our current and former Ph.D. students, especially Zümbül Atan, Gang Chen, Leon Chu, Tingting Cui, Tianhu Deng, Lin He, Çağrı Latifoğlu, Shan Li, Yinan Liu, Ho-Yin Mak, Mohsen Moarefdoost, Lian Qi, Ying Rong, Amanda Schmitt, Ye Xu, and Lezhou Zhan, for contributing to this book through their research collaborations (some of which are reflected in the material in this book) and the many productive discussions we have had with them about research and teaching.

This book emerged from lecture notes we developed for our graduate-level supply chain courses at Lehigh and Berkeley. Many students suffered through the early versions of these



notes. Their questions, suggestions, and confused faces helped us find and correct errors and improve the exposition throughout the book. Tingting Cui, Tao Li, Ho-Yin Mak, Scott DeNegre, Kewen Liang, Gokhan Metan, Cory Minglegreen, Jack Oh, Jim Ostrowski, Ye Xu, Mertcan Yetkin, and Hua Zhong, among others, made insightful comments that resulted in a better explanation, an interesting new homework problem, or an elegant solution to a problem.

Tolga Seyhan provided invaluable assistance with the preparation of the first edition of this book, crafting many of the figures, writing the index, assembling references, and lending us his impeccable attention to detail. We also thank Pete Ferrari for helping us build  $\text{BIB}\TeX$  databases, Amy Hendrickson of  $\text{TeX}$ nology, Inc. for sharing her expertise in all things  $\text{L}\TeX$ , and Andrew Ross for his patient answers to questions about stochastic processes. Karen Smilowitz contributed suggestions, feedback, and the occasional homework problem.

Reza Nazari and Afshin Oroojlooy contributed greatly to the second edition of the book through their careful reading of the manuscript, catching many mistakes and offering valuable feedback. Wancheng Feng, Sheng Liu, and Yuli Zhang also offered great help with the preparation of the second edition. Bill Cook of the University of Waterloo generously provided us with TSP data sets and insights. And many people wrote to us to point out errors in the first edition; we thank especially Gil Souza, as well as Onur Babat, Mark Bai, Ory Ball, Ali Diabat, Bisheng Du, Mohammad Ghuloum, Jian Luo, Josh Margolis, Kwami Senam Sedzro, Jieli Tian, Siyu Yang, Zhu Yang, Rui Yu, Dell Zhang, and others too numerous to mention.

Finally, and most importantly, we thank our families—Suzanne, Irene, Matilda, Michelle, Coralie, and Jeffrey—and our extended families for their support, love, encouragement, and guidance as we wrote, and revised, this book.