

Springer Series in Supply Chain Management

Volume 18

Series Editor

Christopher S. Tang, University of California, Los Angeles, CA, USA

Supply Chain Management (SCM), long an integral part of Operations Management, focuses on all elements of creating a product or service, and delivering that product or service, at the optimal cost and within an optimal timeframe. It spans the movement and storage of raw materials, work-in-process inventory, and finished goods from point of origin to point of consumption. To facilitate physical flows in a time-efficient and cost-effective manner, the scope of SCM includes technology-enabled information flows and financial flows.

The Springer Series in Supply Chain Management, under the guidance of founding Series Editor Christopher S. Tang, covers research of either theoretical or empirical nature, in both authored and edited volumes from leading scholars and practitioners in the field – with a specific focus on topics within the scope of SCM.

This series has been accepted by Scopus.

Springer and the Series Editor welcome book ideas from authors. Potential authors who wish to submit a book proposal should contact Ms. Jialin Yan, Associate Editor, Springer (Germany), e-mail: jialin.yan@springernature.com

Xi Chen • Stefanus Jasin • Cong Shi
Editors

The Elements of Joint Learning and Optimization in Operations Management

 Springer

Editors

Xi Chen
New York University
New York, NY, USA

Stefanus Jasin
University of Michigan–Ann Arbor
Ann Arbor, MI, USA

Cong Shi
University of Michigan–Ann Arbor
Ann Arbor, MI, USA

ISSN 2365-6395 ISSN 2365-6409 (electronic)
Springer Series in Supply Chain Management
ISBN 978-3-031-01925-8 ISBN 978-3-031-01926-5 (eBook)
<https://doi.org/10.1007/978-3-031-01926-5>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2022

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To our parents:

Jianming Chen and Xiaohong Yu

Andi Wirawan Jasin and Sandra Widjaja

Xiping Shi and Qiong Yao

and to our families:

Yingze Wang and Andrew Chen

Yan Huang

Miao Ni and Janie Shi and Anna Shi

Preface

The last decade has seen an explosion of research at the intersection of operations research and machine learning. While the classical operations research has focused largely on optimizing the system under the assumption of known dynamics and known parameters, in reality, the “known” are typically unknown and need to be estimated from the continuously generated data. The later gives rise to the problem of joint learning and optimization, which is one of the core research topics in the machine learning community. However, while the machine learning community has largely focused on solving problems that are directly relevant for computer science applications, the operations research community has its own long list of problems that are not typically considered in the context of joint learning and optimization. This presents a wonderful opportunity for combining operations research and machine learning techniques to solve some of the most fundamental analytic problems.

This book consists of 15 chapters written by some of the world’s leading experts on the subject, covering a wide range of topics such as price optimization, assortment optimization, inventory optimization, and healthcare operations. As noted above, the field has grown very quickly within the last decade, and it is not our intention to provide a comprehensive overview of the field. Rather, we have a more modest aim to introduce interested readers to some fundamental results that have been developed in the field within the last decade. This book is a suitable reading for graduate students (either PhD or advanced master’s) in operations research and/or machine learning. It is also suitable for researchers in other fields who are interested in the topic of joint learning and optimization.

For a better organization, we cluster the 15 chapters into five different parts:

Part I. Generic Tools The first part of the book consists of Chaps. 1–3 and covers standard tools and concepts that are commonly used in the learning literature. Many of the topics discussed in this part are also covered in more details in other more specialized books. Our objective here is to quickly introduce readers to some of the key tools and concepts. Chapter 1 discusses fundamental algorithms for multi-armed bandit; Chap. 2 discusses fundamental algorithms for reinforcement learning;

and Chap. 3 discusses optimal learning from the perspective of statistical design of experiments.

Part II. Price Optimization The second part of the book consists of Chaps. 4–7 and covers a variety of topics on joint learning and price optimization. Chapter 4 discusses state-of-the-art parametric and non-parametric learning algorithms for single-product and multiple-product settings; Chap. 5 discusses learning algorithms in the presence of inventory constraints; Chap. 6 provides literature review on joint learning and pricing in non-stationary environments; and Chap. 7 discusses learning algorithms for high dimensional setting.

Part III. Assortment Optimization The third part of the book consists of Chaps. 8–10 and covers a variety of topics on joint learning and assortment optimization. Chapter 8 discusses recent advances in non-parametric estimation of choice models; Chap. 9 discusses learning algorithms for assortment optimization under the popular multinomial logit (MNL) choice model; and Chap. 10 discusses learning algorithms for assortment optimization under non-MNL choice model.

Part IV. Inventory Optimization The fourth part of the book consists of Chaps. 11–13 and covers a variety of topics on joint learning and inventory optimization. Chapter 11 discusses state-of-the-art algorithms on inventory optimization with censored demand; Chap. 12 discusses learning algorithms for the joint inventory and price optimization problem where both the price and inventory decisions need to be simultaneously optimized; and Chap. 13 discusses optimization in the “small data, large scale” regime.

Part V. Healthcare Operations The fifth part of the book consists of Chaps. 14–15 and covers topics related to healthcare operations. Chapter 14 discusses bandit algorithms/procedures for clinical trials and Chap. 15 provides an in-depth overview of dynamic treatment regime.

This book would not have been possible without the excellent contribution of all authors and the help of the team at Springer, for which we are forever grateful.

New York, NY, USA
Ann Arbor, MI, USA
Ann Arbor, MI, USA

Xi Chen
Stefanus Jasin
Cong Shi

Contents

Part I Generic Tools

- 1 The Stochastic Multi-Armed Bandit Problem** 3
Shipra Agrawal
- 2 Reinforcement Learning** 15
Zheng Wen
- 3 Optimal Learning and Optimal Design** 49
Ilya O. Ryzhov

Part II Price Optimization

- 4 Dynamic Pricing with Demand Learning: Emerging Topics and State of the Art** 79
Arnoud V. den Boer and Nuri Bora Keskin
- 5 Learning and Pricing with Inventory Constraints** 103
Qi (George) Chen, He Wang, and Zizhuo Wang
- 6 Dynamic Pricing and Demand Learning in Nonstationary Environments** 137
Arnoud V. den Boer and Nuri Bora Keskin
- 7 Pricing with High-Dimensional Data** 151
Gah-Yi Ban

Part III Assortment Optimization

- 8 Nonparametric Estimation of Choice Models** 177
Srikanth Jagabathula and Ashwin Venkataraman
- 9 The MNL-Bandit Problem** 211
Shipra Agrawal, Vashist Avadhanula, Vineet Goyal, and Assaf Zeevi

10	Dynamic Assortment Optimization: Beyond MNL Model	241
	Yining Wang and Yuan Zhou	
Part IV Inventory Optimization		
11	Inventory Control with Censored Demand	273
	Xiangyu Gao and Huanan Zhang	
12	Joint Pricing and Inventory Control with Demand Learning	305
	Boxiao Chen	
13	Optimization in the Small-Data, Large-Scale Regime	337
	Vishal Gupta	
Part V Healthcare Operations		
14	Bandit Procedures for Designing Patient-Centric Clinical Trials	365
	Sofia S. Villar and Peter Jacko	
15	Dynamic Treatment Regimes for Optimizing Healthcare	391
	Nina Deliu and Bibhas Chakraborty	

Editors and Contributors

About the Editors

Xi Chen is a professor in the Department of Technology, Operations, and Statistics at Stern School of Business, New York University. He is also Professor of Computer Science at the Center for Data Science at New York University. His research and teaching have been recognized by numerous awards, including The World's Best 40 under 40 MBA Professors by Poets & Quants, NSF CAREER Award, Forbes 30 Under 30, the Inaugural International Chinese Statistical Association Outstanding Young Researcher Award, and Faculty Research Awards, and by a number of leading technology and financial giants, such as Google, Facebook, Adobe, JPMorgan, and Bloomberg. In addition, he is an elected member of the International Statistical Institute (ISI) and an associate editor of Management Science, Operations Research, and Annals of Statistics.

Stefanus Jasin is a professor in the Department of Technology and Operations at the Ross School of Business, University of Michigan, Ann Arbor. His research focuses on algorithmic and/or prescriptive business analytics and has been recognized by numerous awards, including INFORMS Revenue Management and Pricing Section Prize Award, and INFORMS eBusiness Section Best Paper Award. He is a department editor of Production and Operations Management. In addition, he is also an associate editor of Management Science, Operations Research, Manufacturing and Service Operations Management, Production and Operations Management, and Naval Research Logistics.

Cong Shi is a professor in the Department of Industrial and Operations Engineering at the University of Michigan at Ann Arbor. His research and teaching have been recognized by numerous awards, including INFORMS George Nicholson Paper Competition, INFORMS JFIG Paper Competition, Amazon Research Award, UM

IOE Professor of the Year, and UM CoE Vulcans Education Excellence Award. He is an associate editor of *Management Science*, *Production and Operations Management*, *IIE Transactions*, and *Operations Research Letters*.

Contributors

Shipra Agrawal Department of Industrial Engineering and Operations Research, Columbia University, New York, NY, USA

Vashist Avadhanula Facebook, Menlo Park, CA, USA

Gah-Yi Ban Department of Decision, Operations & Information Technologies, Robert H. Smith Business School, University of Maryland, College Park, MD, USA

Bibhas Chakraborty Center for Quantitative Medicine, Duke-NUS Medical School, National University of Singapore, Singapore, Singapore

Boxiao Chen College of Business Administration, University of Illinois Chicago, Chicago, IL, USA

Qi (George) Chen Department of Management Science and Operations, London Business School, London, UK

Nina Deliu MRC Biostatistics Unit, School of Clinical Medicine, University of Cambridge, Cambridge, UK

Arnoud V. den Boer Department of Mathematics, University of Amsterdam, Amsterdam, GE, Netherlands

Xiangyu Gao Department of Decision Sciences and Managerial Economics, The Chinese University of Hong Kong, Hong Kong, China

Vineet Goyal Department of Industrial Engineering and Operations Research, Columbia University, New York, NY, USA

Vishal Gupta Department of Data Science and Operations, Marshall School of Business, University of Southern California, Los Angeles, CA, USA

Peter Jacko Department of Management Science, Lancaster University, Lancaster, UK

Berry Consultants, Abingdon, UK

Srikanth Jagabathula Department of Information, Operations & Management Sciences, Leonard N. Stern School of Business, New York University, New York, NY, USA

Nuri Bora Keskin Department of Operations Management, Fuqua School of Business, Duke University, Durham, NC, USA

Ilya O. Ryzhov Department of Decision, Operations, and Information Technologies, Robert H. Smith School of Business, University of Maryland, College Park, MD, USA

Ashwin Venkataraman Department of Operations Management, Naveen Jindal School of Management, University of Texas at Dallas, Richardson, TX, USA

Sofia S. Villar MRC Biostatistics Unit, School of Clinical Medicine, University of Cambridge, Cambridge, UK

He Wang H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA, USA

Yining Wang Naveen Jindal School of Management, University of Texas at Dallas, Richardson, TX, USA

Zizhuo Wang School of Data Science, The Chinese University of Hong Kong, Shenzhen, China

Zheng Wen Google DeepMind, Mountain View, CA, USA

Assaf Zeevi Department of Decision, Risk, and Operations, Columbia Business School, Columbia University, New York, NY, USA

Huanan Zhang Department of Strategy, Entrepreneurship, and Operations, Leeds School of Business, University of Colorado Boulder, Boulder, CO, USA

Yuan Zhou Mathematical Sciences Center, Tsinghua University, Beijing, China