CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Measurement of Productivity and Efficiency

Methods and perspectives to model and measure productivity and efficiency have made a number of important advances in the last decade. Using the standard and innovative formulations of the theory and practice of efficiency and productivity measurement, Robin C. Sickles and Valentin Zelenyuk provide a comprehensive approach to productivity and efficiency analysis, covering its theoretical underpinnings and its empirical implementation, paying particular attention to the implications of neoclassical economic theory. A distinct feature of the book is that it presents a wide array of theoretical and empirical methods utilized by researchers and practitioners who study productivity issues. An accompanying website includes methods, programming codes that can be used with widely available software like Matlab and R, and test data for many of the productivity and efficiency estimators discussed in the book. It will be valuable to upper-level undergraduates, graduate students, and professionals.

Robin C. Sickles is the Reginald Henry Hargrove Professor of Economics and Professor of Statistics at Rice University. He served as Editor-in-Chief of the Journal of Productivity Analysis as well as an Associate Editor for a number of other economics and econometrics journals. He is currently an Associate Editor of the Journal of Econometrics.

Valentin Zelenyuk is the Australian Research Council Future Fellow at the School of Economics at the University of Queensland, where he was an Associate Professor of Econometrics and also served as Research Director and Director of the Centre for Efficiency and Productivity Analysis (CEPA). He is currently an Associate Editor of the Journal of Productivity Analysis and the Data Envelopment Analysis Journal and an elected member in the Conference on Research in Income and Wealth (CRIW) of the National Bureau of Economic Research (NBER).

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Measurement of Productivity and Efficiency

Theory and Practice

Robin C. Sickles
Rice University, Texas

Valentin Zelenyuk
The University of Queensland, Australia

CAMBRIDGE
UNIVERSITY PRESS

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre,
New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107036161
DOI: 10.1017/9781139565981

© Robin C. Sickles and Valentin Zelenyuk 2019

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2019

Printed and bound in Great Britain by Clays Ltd, Elcograf S.p.A.

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data
Names: Sickles, Robin, author. | Zelenyuk, Valentin, author.
Title: Measurement of productivity and efficiency theory and practice / Robin C. Sickles, Rice University, Texas. Valentin Zelenyuk, University of Queensland, Australia.
Description: New York : Cambridge University Press, [2019]
Identifiers: LCCN 2018035971 | ISBN 9781107036161
Subjects: LCSH: Labor productivity – Measurement. | Industrial efficiency – Measurement – Mathematical models. | Performance – Management.
Classification: LCC HD57 .S4977 2019 | DDC 658.5/15–dc23
LC record available at https://lccn.loc.gov/2018035971

ISBN 978-1-107-03616-1 Hardback
ISBN 978-1-107-68765-3 Paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

To my family: Janet, Danielle, and David

—Robin Sickles

To my family: Natalya, Angelina, Kristina, Mary;
my parents: Hrystyna Myhaylivna and Petro Ivanovych;
my brother Oleksiy and sister Elena

—Valentin Zelenyuk

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Contents

List of Figures *page* xvii
List of Tables xix
Preface xxi
Acknowledgments xxiv

Introduction 1

1 Production Theory: Primal Approach 9
1.1 Set Characterization of Technology 9
1.2 Axioms for Technology Characterization 13
1.3 Functional Characterization of Technology: The Primal Approach 19
1.4 Modeling Returns to Scale in Production 26
1.5 Measuring Returns to Scale in Production: The Scale Elasticity Approach 31
1.6 Directional Distance Function 34
1.7 Concluding Remarks on the Literature 36
1.8 Exercises 37

2 Production Theory: Dual Approach 39
2.1 Cost Minimizing Behavior and Cost Function 39
2.2 The Duality Nature of Cost Function 42
2.3 Some Examples of Using the Cost Function 45
2.4 Sufficient Conditions for Cost and Input Demand Functions 47
2.5 Benefits Coming from the Duality Theory for the Cost Function: A Summary 49
2.6 Revenue Maximization Behavior and the Revenue Function 49
2.7 Profit-Maximizing Behavior 54
2.8 Exercises 57
2.9 Appendix 57

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

3 Efficiency Measurement 59
3.1 Various Measures of Technical Efficiency 59
3.2 Relationships Among Efficiency Measures 65
3.2.1 Shephard vs. Directional Distance Functions 66
3.2.2 Farrell vs. Russell Measures 68
3.2.3 Directional Distance Function vs. Additive Measure 70
3.2.4 Hyperbolic vs. Others 72
3.3 Properties of Technical Efficiency Measures 74
3.4 Cost and Revenue Efficiency 80
3.5 Profit Efficiency 82
3.6 Slack-Based Measures of Efficiency 84
3.7 Unifying Different Approaches 89
3.8 Remarks on the Literature 90
3.9 Exercises 91
3.10 Appendix 92

4 Productivity Indexes: Part 1 96
4.1 Productivity vs. Efficiency 96
4.2 Growth Accounting Approach 99
4.3 Economic *Price* Indexes 102
4.4 Economic *Quantity* Indexes 106
4.5 Economic *Productivity* Indexes 110
4.6 Decomposition of Productivity Indexes 114
4.7 Directional Productivity Indexes 117
4.8 Directional Productivity Change Indicators 119
4.9 Relationships among Productivity Indexes 120
4.10 Indexes vs. Growth Accounting 128
4.11 Multilateral Comparisons, Transitivity, and Circularity 129
4.11.1 General Remarks on Transitivity 129
4.11.2 Transitivity and Productivity Indexes 130
4.11.3 Dealing with Non-Transitivity 137
4.11.4 What to Do in Practice? 140
4.12 Concluding Remarks 141
4.13 Exercises 141

5 Aggregation 143
5.1 The Aggregation Problem 143
5.2 Aggregation in Output-Oriented Framework 145
5.2.1 Individual Revenue and Farrell-Type Efficiency 145
5.2.2 Group Farrell-Type Efficiency 146
5.2.3 Aggregation over Groups 150
5.3 Price-Independent Weights 152

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

5.4 Group-Scale Elasticity Measures 153
5.5 Aggregation of Productivity Indexes 158
5.5.1 Individual Malmquist Productivity Indexes 158
5.5.2 Group Productivity Measures 159
5.5.3 Aggregation of the MPI 160
5.5.4 Geometric vs. Harmonic Averaging of MPI 162
5.5.5 Decomposition into Aggregate Changes 163
5.6 Concluding Remarks 164
5.7 Exercises 165

6 Functional Forms: Primal and Dual Functions 166
6.1 Functional Forms for Primal Production Analysis 167
6.1.1 The Elasticity of Substitution: A Review of the Allen, Hicks, Morishima, and Uzawa Characterizations of Substitution Possibilities 168
6.1.2 Linear, Leontief, Cobb–Douglas, CES, and CRESH Production Functions 171
6.1.3 Flexible-Functional Forms and Second-Order Series Approximations of the Production Function 175
6.1.4 Choice of Functional Form Based on Solutions to Functional Equations 182
6.2 Functional Forms for Distance Function Analysis 185
6.3 Functional Forms for Cost Analysis 187
6.3.1 Generalized Leontief 189
6.3.2 Generalized Cobb–Douglas 190
6.3.3 Translog 190
6.3.4 CES-Translog and CES-Generalized Leontief 192
6.3.5 The Symmetric Generalized McFadden 193
6.4 Technical Change, Production Dynamics, and Quasi-Fixed Factors 195
6.5 Functional Forms for Revenue Analysis 199
6.6 Functional Forms for Profit Analysis 201
6.7 Nonparametric Econometric Approaches to Model the Distance, Cost, Revenue, and Profit Functions 203
6.8 Concluding Remarks 204
6.9 Exercises 205

7 Productivity Indexes: Part 2 207
7.1 Decomposition of the Value Change Index 207
7.2 The Statistical Approach to Price Indexes 208
7.3 Quantity Indexes: The Direct Approach 210
7.4 Quantity Indexes: The Indirect Approach 211

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

7.5 Productivity Indexes: Statistical Approach 213
7.6 Properties of Index Numbers 214
7.7 Some Key Results in the Statistical Approach to Index Numbers 221
7.8 Relationship between Economic and Statistical Approaches to Index Numbers 225
7.8.1 Flexible Functional Forms 225
7.8.2 Relationships for the Price Indexes 227
7.8.3 Relationships for the Quantity Indexes 229
7.8.4 Relationships for the Productivity Indexes 234
7.9 Concluding Remarks on the Literature 238
7.10 Exercises 239
7.11 Appendix 240

8 Envelopment-Type Estimators 243
8.1 Introduction to Activity Analysis Modeling 243
8.2 Non-CRS Activity Analysis Models 251
8.3 Measuring Scale 256
8.4 Estimation of Cost, Revenue, and Profit Functions and Related Efficiency Measures 261
8.5 Estimation of Slack-Based Efficiency 267
8.6 Technologies with Weak Disposability 269
8.7 Modeling Non-Convex Technologies 273
8.8 Intertemporal Context 277
8.9 Relationship between CCR and Farrell 278
8.10 Concluding Remarks 283
8.11 Exercises 285

9 Statistical Analysis for DEA and FDH: Part 1 286
9.1 Statistical Properties of DEA and FDH 286
9.1.1 Assumptions on the Data Generating Process 287
9.1.2 Convergence Rates of DEA and FDH 289
9.1.3 The Dimensionality Problem 290
9.2 Introduction to Bootstrap 292
9.2.1 Bootstrap and the Plug-In Principle 292
9.2.2 Bootstrap and the Analogy Principle 294
9.2.3 Practical Implementation of Bootstrap 296
9.2.4 Bootstrap for Standard Errors of an Estimator 297
9.2.5 Bootstrapping for Bias and Mean Squared Error 299
9.2.6 Bootstrap Estimation of Confidence Intervals 301
9.2.7 Consistency of Bootstrap 303
9.3 Bootstrap for DEA and FDH 307

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

9.3.1 Bootstrap for Individual Efficiency Estimates 307
9.4 Concluding Remarks 314
9.5 Exercises 315

10 Statistical Analysis for DEA and FDH: Part 2 316
10.1 Inference on Aggregate or Group Efficiency 316
10.2 Estimation and Comparison of Densities of Efficiency Scores 321
10.2.1 Density Estimation 321
10.2.2 Statistical Tests about Distributions of Efficiency 325
10.3 Regression of Efficiency on Covariates 334
10.3.1 Algorithm 1 of SW2007 335
10.3.2 Algorithm 2 of SW2007 336
10.3.3 Inference in SW2007 Framework 338
10.3.4 Extension to Panel Data Context 340
10.3.5 Caveats of the Two-Stage DEA 342
10.4 Central Limit Theorems for DEA and FDH 348
10.4.1 Bias vs. Variance 348
10.5 Concluding Remarks 350
10.6 Exercises 350

11 Cross-Sectional Stochastic Frontiers: An Introduction 352
11.1 The Stochastic Frontier Paradigm 355
11.2 Corrected OLS 357
11.3 Parametric Statistical Approaches to Determine the Boundary of the Level Sets: The "Full Frontier" 359
11.3.1 Aigner–Chu Methodology 360
11.3.2 Afriat–Richmond Methodology 362
11.4 Parametric Statistical Approaches to Determine the Stochastic Boundary of the Level Sets: The "Stochastic Frontier" 365
11.4.1 Olson, Schmidt, and Waldman (1980) Methodology 371
11.4.2 Estimation of Individual Inefficiencies 372
11.4.3 Hypothesis Tests and Confidence Intervals 374
11.4.4 The Zero Inefficiency Model 378
11.4.5 The Stochastic Frontier Model as a Special Case of the Bounded Inefficiency Model 380
11.5 Concluding Remarks 387
11.6 Exercises 388
11.7 Appendix 389
11.7.1 Derivation of $E(\varepsilon_i)$ 389
11.7.2 Derivation of the Moments of a Half-Normal Random Variable 389

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

11.7.3 Derivation of the Distribution of the Stochastic Frontier Normal–Half-Normal Composed Error 391

12 Panel Data and Parametric and Semiparametric Stochastic Frontier Models: First-Generation Approaches 394
12.1 Productivity Growth and its Measurement 394
12.1.1 Residual-Based Productivity Measurement 394
12.2 International and US Economic Growth and Development 395
12.2.1 The Neoclassical Production Function and Economic Growth 396
12.2.2 Modifications of the Neoclassical Production Function and Economic Growth Model: Endogenous Growth 396
12.3 The Panel Stochastic Frontier Model: Measurement of Technical and Efficiency Change 398
12.4 Index Number Decompositions of Economic Growth-Innovation and Efficiency Change 400
12.4.1 Index Number Procedures 401
12.5 Regression-Based Decompositions of Economic Growth-Innovation and Efficiency Change 401
12.6 Environmental Factors in Production and Interpretation of Productive Efficiency 403
12.7 The Stochastic Panel Frontier 404
12.7.1 Cornwell, Schmidt, and Sickles (1990) Model 407
12.7.2 Alternative Specifications of Time-Varying Inefficiency: The Kumbhakar (1990) and Battese and Coelli (1992) Models 411
12.7.3 The Lee and Schmidt (1993) Model 412
12.7.4 Panel Stochastic Frontier Technical Efficiency Confidence Intervals 415
12.7.5 Fixed versus Random Effects: A Prelude to More General Panel Treatments 416
12.8 Concluding Remarks 417
12.9 Exercises 417

13 Panel Data and Parametric and Semiparametric Stochastic Frontier Models: Second-Generation Approaches 419
13.1 The Park, Sickles, and Simar (1998, 2003, 2007) Models 419
13.1.1 Implementation 420
13.2 The Latent Class Models 423
13.2.1 Implementation 425
13.3 The Ahn, Lee, and Schmidt (2007) Model 426

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

13.3.1 Implementation 426
13.4 Bounded Inefficiency Model 428
13.5 The Kneip, Sickles, and Song (2012) Model 428
13.5.1 Implementation 430
13.6 The Ahn, Lee, and Schmidt (2013) Model 432
13.6.1 Implementation 433
13.7 The Liu, Sickles, and Tsionas (2017) Model 435
13.7.1 Implementation 436
13.8 The True Fixed Effects Model 437
13.8.1 Implementation 438
13.9 True Random Effects Models 440
13.9.1 The Tsionas and Kumbhakar Extension of the Colombi, Kumbhakar, Martini, and Vittadini (2014) Four Error Component Model 440
13.9.2 Extensions on the Four Error Component Model 442
13.10 Spatial Panel Frontiers 442
13.10.1 The Han and Sickles (2019) Model 445
13.11 Concluding Remarks 448
13.12 Exercises 448

14 Endogeneity in Structural and Non-Structural Models of Productivity 450
14.1 The Endogeneity Problem 450
14.2 Simultaneity 451
14.3 Selection Bias 452
14.4 Traditional Solutions to the Endogeneity Problem Caused by Input Choices and Selectivity 453
14.5 Structural Estimation 454
14.6 Endogeneity in Nonstructural Models of Productivity: The Stochastic Frontier Model 458
14.7 Endogeneity and True Fixed Effects Models 463
14.8 Endogeneity in Environmental Production and in Directional Distance Functions 464
14.9 Endogeneity, Copulas, and Stochastic Metafrontiers 465
14.10 Other Types of Orthogonality Conditions to Deal with Endogeneity 466
14.11 Concluding Remarks 467
14.12 Exercises 467

15 Dynamic Models of Productivity and Efficiency 469
15.1 Nonparametric Panel Data Models of Productivity Dynamics 469

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

15.1.1 Revisiting the Dynamic Output Distance Function and the Intertemporal Malmquist Productivity Index: Cointegration and Convergence of Efficiency Scores in Productivity Panels 470
15.2 Parametric Panel Data Models of Productivity Dynamics 476
15.2.1 The Ahn, Good, and Sickles (2000) Dynamic Stochastic Frontier 477
15.3 Extensions of the Ahn, Good, and Sickles (2000) Model 480
15.4 Concluding Remarks 481
15.5 Exercises 482

16 Semiparametric Estimation, Shape Restrictions, and Model Averaging 483
16.1 Semiparametric Estimation of Production Frontiers 484
16.1.1 Kernel-Based Estimators 484
16.1.2 Local Likelihood Approach 487
16.1.3 Local Profile Likelihood Approach 489
16.1.4 Local Least-Squares Approache 490
16.2 Semiparametric Estimation of an Average Production Function with Monotonicity and Concavity 493
16.2.1 The Use of Transformations to Impose Constraints 494
16.2.2 Statistical Modeling 495
16.2.3 Empirical Example using the Coelli Data 497
16.2.4 Nonparametric SFA Methods with Monotonicity and Shape Constraints 497
16.3 Model Averaging 499
16.3.1 Insights from Economics and Statistics 499
16.3.2 Insights from Time-Series Forecasting 501
16.3.3 Frequentist Model Averaging 501
16.3.4 The Hansen (2007) and Hansen and Racine (2012) Model Averaging Estimators 502
16.3.5 Other Model Averaging Approaches to Develop Consensus Productivity Estimates 506
16.4 Concluding Remarks 506
16.5 Exercises 507

17 Data Measurement Issues, the KLEMS Project, Other Data Sets for Productivity Analysis, and Productivity and Efficiency Software 509
17.1 Data Measurement Issues 509

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

17.2 Special Issue of the International Productivity Monitor from the Madrid Fourth World KLEMS Conference: Non-Frontier Perspectives on Productivity Measurement 511
17.2.1 Productivity and Economic Growth in the World Economy: An Introduction 512
17.2.2 Recent Trends in Europe's Output and Productivity Growth Performance at the Sector Level, 2002–2015 513
17.2.3 The Role of Capital Accumulation in the Evolution of Total Factor Productivity in Spain 514
17.2.4 Sources of Productivity and Economic Growth in Latin America and the Caribbean, 1990–2013 516
17.2.5 Argentina Was Not the Productivity and Economic Growth Champion of Latin America 517
17.2.6 How Does the Productivity and Economic Growth Performance of China and India Compare in the Post-Reform Era, 1981–2011? 518
17.2.7 Can Intangible Investments Ease Declining Rates of Return on Capital in Japan? 520
17.2.8 Net Investment and Stocks of Human Capital in the United States, 1975–2013 522
17.2.9 ICT Services and Their Prices: What Do They Tell Us About Productivity and Technology? 523
17.2.10 Productivity Measurement in Global Value Chains 525
17.2.11 These Studies Speak of Efficiency but Measure it with Non-Frontier Methods 527
17.3 Datasets for Illustrations 527
17.4 Publicly Available Data Sets Useful for Productivity Analysis 528
17.4.1 Amadeus 528
17.4.2 Bureau of Economic Analysis 528
17.4.3 Bureau of Labor Statistics 528
17.4.4 Business Dynamics Statistics 528
17.4.5 Center for Economic Studies 529
17.4.6 CompNet 529
17.4.7 DIW Berlin 529
17.4.8 Longitudinal Business Database 529
17.4.9 National Bureau of Economic Research 529
17.4.10 OECD 530
17.4.11 OECD STAN 530
17.4.12 Penn World Table 530
17.4.13 Statistics Canada 530

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

17.4.14 UK Fame 530
17.4.15 UK Office of National Statistics 531
17.4.16 UNIDO 531
17.4.17 USDA-ERS 531
17.4.18 World Bank 531
17.4.19 World Input–Output Database 531
17.4.20 World KLEMS Database 532
17.5 Productivity and Efficiency Software 532
17.6 Global Options 533
17.6.1 Model Setup 533
17.6.2 Weighted Averages of Efficiencies 533
17.6.3 Truncation 534
17.6.4 Figures and Tables 534
17.7 Models 535
17.7.1 Schmidt and Sickles (1984) Models 535
17.7.2 Hausman and Taylor (1981) Model 535
17.7.3 Park, Sickles, and Simar (1998, 2003, 2007) Models 535
17.7.4 Cornwell, Schmidt, and Sickles (1990) Model 535
17.7.5 Kneip, Sickles, and Song (2012) Model 536
17.7.6 Battese and Coelli (1992) Model 536
17.7.7 Almanidis, Qian, and Sickles (2014) Model 536
17.7.8 Jeon and Sickles (2004) Model 536
17.7.9 Simar and Zelenyuk (2006) Model 536
17.7.10 Simar and Zelenyuk (2007) Model 537
17.8 Concluding Remarks 538

Afterword 539

Bibliography 541

Subject Index 588

Author Index 594

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Figures

1.1	A typical production process.	*page* 10
1.2	Examples of a technology set.	11
1.3	Examples of an output set.	11
1.4	Examples of an input requirement set.	12
1.5	Example of the output set as a "slice" of the technology set.	13
1.6	Illustrations for the Axiom A5.	16
1.7	Illustrations for the Axiom A5AW.	16
1.8	Illustrations for the Axiom A6.	18
1.9	Illustrations for the Axiom A6AW.	18
1.10	Geometric intuition of the output distance function for a one-input–one-output example of T.	21
1.11	Geometric intuition of output distance function for a one-input–two-output example of T.	22
1.12	A CRS technology.	27
1.13	An NIRS technology.	27
1.14	An NDRS technology.	29
1.15	A VRS technology.	30
1.16	An example of technology where $D_i(y, x) = 1 \Leftrightarrow D_o(x, y) = 1$ is not always true.	33
1.17	Geometric intuition of the directional distance function.	35
2.1	Geometric intuition of the cost minimization problem.	41
2.2	Geometric intuition of the revenue maximization problem.	51
2.3	Geometric intuition of the profit maximization problem.	55
3.1	An example of the failure of the Farrell measure to identify the efficient subset of the isoquant.	61
3.2	Geometric intuition of the directional distance function.	65
3.3	Technical, allocative, and cost efficiency measures.	80
3.4	Technical, allocative, and revenue efficiency measures.	82
3.5	Geometric intuition of profit-based efficiency measures.	84

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

3.6	Illustration of the advantage of slack-based measures.	88
4.1	Geometric intuition of Konüs-type input price indexes.	104
4.2	Geometric intuition of Konüs-type output price indexes.	105
4.3	Geometric intuition of Malmquist output quantity indexes.	107
4.4	Geometric intuition of Malmquist input quantity indexes.	108
4.5	Geometric intuition of Malmquist output productivity indexes.	112
5.1	Aggregation over output sets and revenue functions.	149
8.1	One-input–one-output example of constructing AAM under CRS.	247
8.2	One-input–one-output example of constructing AAM under NIRS.	252
8.3	One-input–one-output example of constructing AAM under VRS.	255
8.4	Intuition of the output-oriented scale efficiency measure.	258
8.5	Output- vs. input-oriented scale efficiency measures.	260
8.6	An example of AAM for T that only imposes Free Disposability.	274
8.7	An example of AAM for $L(y)$ that only imposes Free Disposability.	274
8.8	An example of AAM for $P(x)$ that only imposes Free Disposability.	275
10.1	True and estimated densities ($n = 100$).	323
10.2	True and estimated densities ($n = 1000$).	323
10.3	True and estimated densities ($n = 100$).	325
10.4	True and estimated densities ($n = 1000$).	325
10.5	Power for the adapted Li-test, with Alg. II ($n_A = n_Z = 20$).	333
10.6	Power for the adapted Li-test, with Alg. II ($n_A = n_Z = 100$).	333
11.1	Input requirement set and boundary for a CRS technology.	354
11.2	Production isoquant and the isocost line.	357
11.3	Average and frontier production function for a linear technology.	358
13.1	Industry linkages.	444
13.2	Multiplier product matrix heat map.	447
13.3	Decaying function profiles for different values of η.	448
16.1	Surface and contour plots of capital and labor: Coelli data using the Wu–Sickles Estimator.	498

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Tables

5.1 A hypothetical example of the aggregation problem. *page* 144
10.1 Bootstrapping aggregate efficiency results for a simulated example. 320
11.1 Key results. 383
17.1 Models included in the software. 532

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Preface

Cambridge University Press has published a number of successful books that focus on topics related to ours: Chambers (1988), Färe et al. (1994b), Chambers and Quiggin (2000), Kumbhakar and Lovell (2000), Ray (2004), Balk (2008), and Grifell-Tatjé and Lovell (2015). These books – and an increasing number of articles related to production analysis, published in top international journals in economics, econometrics, and operations research – suggest a growing interest in the academic and business audience on the subject.[1]

Our book is meant to complement and expand selected topics covered in the above-mentioned books, as well as the volume edited by Fried et al. (2008) and the edited volume by Grifell-Tatjé et al. (2018), and addresses issues germane to productivity analysis that would be of interest to a broad audience. Our book provides something genuinely unique to the literature: a comprehensive textbook on the measurement of productivity and efficiency, with deep coverage of both its theoretical underpinnings as well as its empirical implementation and a coverage of recent developments in the area. A distinctive feature of our book is that it presents a wide array of theoretical and empirical methods utilized by researchers and practitioners who study productivity issues. Our book is intended to be a relatively self-contained textbook that can be used in any graduate course devoted to econometrics and production analysis, of use also to upper-level undergraduate students in economics and in production analysis, and to analysts in government and in private business whose research or business decisions require reasoned analytical foundations and reliable and feasible empirical approaches to assessing the productivity and efficiency of their organizations and enterprises. We provide an integrated and synthesized treatment of the topics we cover. We have covered some topics in greater depth, some at a broader scope, but at all times with the same theme of motivating the material with an applied orientation.

[1] For a remarkable treatment of the history of the US economic growth experience and the sustainability of innovation-induced productivity growth see Gordon (2016).

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE
Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Our book is structured in such a way that it can be used as a textbook for (instructed or self-oriented) academics and business consultants in the area of quantitative analysis of productivity of economic systems (firms, industries, regions, countries, etc.). In addition, some parts of this book can be used for short, intensive courses or supplements to longer courses on productivity and other topics, such as empirical industrial organization. Another example of the book's application would be to use the first section on production theory as a supplement in a course on advanced microeconomics. We have tried to structure the textbook in such a way as to broaden the audience for the topics we cover, and – just as important – help readers to have a self-contained source for gaining knowledge on the topics we cover with key references for further details.

It is important to note that the many methods we detail in our textbook are meant to be viewed as relative measures to some benchmark. We provide several different benchmarks in our early chapters, based on technical considerations as well as on excess costs, diminished revenues, and lower profits than could be generated were the firm or decision-making unit optimizing with respect to standard neoclassical assumptions. However, we are purposeful in our silence about the type of market mechanism that is adopted by firms or industries that are being analyzed. Reality shows that any country, or industry within any country, or firm within any industry – whether centrally planned or market oriented, or a hybrid of the two – can have inefficiency and low levels of productivity and therefore can be analyzed using the methods we detail in our book. As Thaler and Sunstein (2009, p. 6) have pointed out:

> Individuals make pretty bad decisions in many cases because they do not pay full attention in their decision-making (they make intuitive choices based on heuristics), they don't have self-control, they are lacking in full information, and they suffer from limited cognitive abilities.

Our book speaks to firms or agencies that are privately or state-owned, capitalist or centrally planned economies, developed, developing, or transitional countries – anywhere where the goal is to measure productivity and identify and explain possible inefficiencies. An aim of our textbook is to help a productive entity improve and move to higher levels of efficiency and productivity and a more efficient utilization of valuable and costly resources.

Our textbook also can be viewed as a comprehensive and integrated treatment of both neoclassical production theory and of the broader contextual theoretical and empirical treatment that renders it a special case. Such a treatment of production theory and productivity that explicitly allows and accounts for inefficiency has the advantage of providing researchers with the tools to pursue the production side of theories developed by Robert Thaler, the winner of the 49th Sveriges Riksbank prize in economic sciences (2017 Nobel Memorial Prize in Economic Science). According to the Nobel committee, Thaler provided a "more realistic analysis of how people think and behave

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE
Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

when making economic decisions." We feel that allowing for similar realistic possibilities that producers, just like consumers, make decisions that may not reflect optimizing behaviors is warranted on both empirical and theoretical grounds.

Another important distinctive feature of our book is the availability of software. Much of the applied work in productivity and efficiency analysis that we discuss can be implemented using the packages of code for the MATLAB software that can be accessed at https://sites.google.com/site/productivityefficiency/ and is maintained by Dr. Wonho Song of the School of Economics, Chung-Ang University, Seoul, South Korea. The different packages for the MATLAB software were programmed by various scholars – Pavlos Almanidis, Robin Sickles, Léopold Simar, Wonho Song, Valentin Zelenyuk – and then checked, integrated and synthesized by Dr. Song to go along with this book. This MATLAB code is free and can also be integrated into R, Julia, and C++ programming environments. Details on how to access and implement the various estimators we discuss in our book, as well as data sources available to productivity researchers, are in Chapter 17. We anticipate that the availability of such freeware will allow a broad audience of interested scholars and practitioners to implement the methods outlined in our book as well as promote empirical research on the subject of efficiency and productivity modeling. The website has data sets for efficiency analysis, an inventory of the public use data available to researchers worldwide, and various instructional aids for teachers as well as students, including answer keys for selected exercises from the book. Software to estimate several of the Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) models that we have considered using cross-section, time series, and panel data can also be found in LIMDEP, R, STATA, and SAS, to mention a few.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

Acknowledgments

For both of us, this book is a culmination of professional careers in economics dating back over several decades. It would make sense that there are numerous people we wish to thank for making this book possible. They are our families, our mentors, our collaborators, our students, and our many colleagues who contributed by providing substantive comments and contributions to the book's narrative and technical details. Below we give individual and more specific acknowledgments.

From Robin Sickles I was quite fortunate to have remarkable mentors in my life. My brother Rick, who has given me advice throughout my entire life; my first economics teacher, Carl Biven, whose course in the History of Economic Thought at Georgia Tech inspired my transition from a major and co-op job in aerospace engineering to economics; and Mike Benoit, whose friendship and support was instrumental in my making the career choice to pursue graduate studies. In some cases, an individual or individuals may take on the role of both a mentor and a collaborator. C. A. Knox Lovell and Peter Schmidt are two such people. It is remarkably fortunate that I would be in graduate school at the University of North Carolina at Chapel Hill in the early 1970s at a time when these remarkable scholars' careers were defined by their collaborative efforts that led to the iconic Aigner, Lovell, and Schmidt stochastic frontier paper and many other seminal works, often with each other, with other colleagues at UNC, or with other students at UNC. I have expressed my appreciation and gratitude and have acknowledged my debt to Knox and Peter in many venues – edited special journal issues, volumes, and special awards that I have been honored to present. It is rare indeed for a collaborative enterprise to have lasted such a long time, but we continue to work together on many projects and to attend many of the same professional conferences. Not only have the collaborative efforts among us been long lasting as a professional enterprise, but so has our friendship. That is a rare gift, and I will always know how lucky I have been to have had such mentors, collaborators, and friends.

My career in productivity and efficiency would not have had the longevity it has had were I also not in the right place at the right time in 1976 when

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

I began my appointment as an assistant professor at the George Washington University. John Kendrick (who received his PhD at UNC) asked me to assist him in developing methods to attribute specific factor productivity growth to particular factors of production in the US airline industry. That work with the Air Transport Association was my first formal endeavor in the field of productivity, and I thank my late colleague and mentor John Kendrick for giving me that opportunity. Lovell and Sickles (2010) have a brief memorial article on John and his seminal contributions to productivity. Later, after I had moved to the University of Pennsylvania, I was lucky enough to have an appointment as a Faculty Research Fellow at the National Bureau of Economic Research. I am indebted to Ernst Berndt and to Zvi Griliches for making that possible, and to Ned Nadiri, Erwin Diewert, and my many other colleagues in the Productivity Program during my time in that position. While at Penn, Jere Behrman, Robert Pollak, Paul Taubman and I worked on a number of productivity-related issues, some of which are referenced in this book. I am indebted to them for their kind support and their most appreciated mentorship.

I have been particularly lucky to have had exceptional graduate students with whom I have worked and who have helped teach me so much. By far and away my best student in productivity has been David H. Good, who was a PhD student of mine while I was at Penn and who is the Director of the Transportation Research Center at Indiana University at Bloomington, as well as a faculty member of the School of Public and Environmental Affairs there. David and I wrote many, many papers together on productivity and efficiency, and our joint research has been some of my very best. Another student of mine at Penn whom I must also thank is Lars-Hendrik Röeller, who stepped down as the founding President of the ESMT Berlin European School of Management and Technology in 2011 to become the Chief Economic Advisor to the Chancellor, Federal Chancellery, Germany.

PhD students at Rice who have taught me much, and with whom I have been engaged in productivity and efficiency work, much of which is detailed in this textbook, include Byeong-Ho Gong, Mary Streitwieser, Purvez Captain, Ila Semenick Alam, Robert Adams, Patrik Hultberg, Byeong Jeon, Lullit Getachew, Wonho Song, Timothy Gunning, Junhui Qian, Pavlos Almanidis, Hulushi Inanoglu, David Blazek, Levent Kutlu, Jiaqi Hao, Junrong Liu, Pavlo Demchuk, Chenjun Shang, Jaepil Han, Deockhyun Ryu, and Binlei Gong.

I have benefited from the assistance of a number of people in preparing the draft materials for the book and for providing technical expertise to make possible the editing of the final manuscript. Among these are Aditi Bhattacharyya, John Paul Peng, Wajiha Noor, my former Rice PhD students and collaborators Jaepil Han, Binlei Gong, and Wonho Song, my current PhD students Shasha Liu and Kevin Bitner, and former Rice PhD students Nigel Soria and Nick Copeland. Rice Economics PhD student Peter Volkmar and Rice Statistics Masters student Jiacheng Liang provided programming expertise

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE
Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

to translate the MATLAB code for estimating the various productivity and efficiency estimators discussed in Chapter 17 into compatible R code.

My contribution to this book would not have been possible were it not for these many wonderful students I have learned from over my 32 years at Rice University, and I thank the University and the Department of Economics for the good fortune I have had in working with our remarkable students and with my distinguished Rice colleagues.

I would like to thank Léopold Simar at the Center for Operations Research and Econometrics (CORE) and the Institut de Statistique at the Université Catholique de Louvain for my many summer visits that he sponsored there, that led directly to this book project. In addition to my many research works with Léopold Alois Kneip, and visiting faculty Byeong Park while in Louvain-la-Neuve, I also first discussed this book project with Valentin Zelenyuk while we were both visiting Léopold's Institute of Statistics.

I would like to thank Christopher O'Donnell, Valentin, and the Center for Efficiency and Productivity Analysis at the University of Queensland for providing me the funding during my sabbatical leave at the University in 2014 to work on portions of this manuscript. Seminars at UQ and substantial interactions with leading scholars there made a difference in my approach to writing this book.

I would like to thank Loughborough University's School of Business and Economics, and its former Dean Angus Laing and current Dean Stewart Robinson, who have supported my efforts during visits there that began in 2014. During those times I have been engaged with my co-authors Anthony Glass and Karligash Kenjegalieva in our work on spatial productivity measurement and efficiency spillovers, and also with them and my colleagues David Saal and Victor Podinovski in developing Loughborough's Centre for Productivity and Performance.

Particular thanks are also due to Aditi Bhattacharyya, Will Grimme, Hiro Fukuyama, Levent Kutlu, Young C. Joo, Hideyuki Mizobuchi, Alecos Papadopoulos, Jaemin Ryu, Kien C. Tran, Kerda Varaku, and Yi Yang, who have provided extensive edits and helpful additions and comments on many of the chapters.

From Valentin Zelenyuk Besides thanking my dear family and parents, all my teachers through life, co-authors and students, friends and opponents, I would like to express my sincerest thanks to the two greatest researchers and mentors I had the enormous honor to work with: Rolf Färe and Léopold Simar. Most of the research I have done (and probably will do in the future) is directly or indirectly related to what I learned from them, and has been inspired in a large part by them.

Indeed, my start in this area was largely due to Rolf Färe, and to some extent Shawna Grosskopf, when I set out as their first MSc student in 1998, and then as their PhD student in 1999–2002, at Oregon State University (here I thank the Edmund Muskie program of the US government for sending me

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE
Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

there on a fellowship). After giving me a great foundation in production theory and in the theory of DEA and its applications, and helping with developing and publishing several works that were exciting for me, Rolf and Shawna strongly recommended me (at my public PhD defense) to find ways to work with and learn from Léopold Simar. A few weeks later I attended NAPW-2002, where I first met and talked to Léopold and another research era started for me at that point, filled with many other exciting research projects.

The collaboration with Léopold was particularly vital for me in keeping up with research despite the heavy teaching load – eight courses per year – at the EERC program of Kyiv-Mohyla Academy in Ukraine, later renamed as the Kyiv School of Economics (KSE), as well as at IAMO (Germany). Fortunately, three of those courses were related to advanced production theory and productivity and efficiency analysis, and this is where the writing of this book was originated for me. Here, it is worth noting that, being sponsored by various donors (Eurasia Foundation in USA, the World Bank, Soros Foundation, Swedish government, etc.), the EERC/KSE was gathering many of the best students from Ukraine and nearby countries, creating the best motivation for me to prepare hard for my lectures and so I am thankful to this school and its donors, and Ukraine in general, for this opportunity. I especially thank the students who kept me working above my normal pace and in particular those with whom I worked and who gave valuable feedback to my lecture notes: Mykhaylo Salnykov, Vladimir Nesterenko, Oleg Badunenko, Pavlo Demchuk, Bogdan Klishchuk, Alexandr Romanov, Oleg Nivyevskiy, to mention just a few.

I also thank the Center for Russian and Eurasian Studies at Harvard University: the great academic spirit and atmosphere of Harvard fueled my enthusiasm to write the first draft of about quarter of this book during my two months, sabbatical visit there in the winter of 2004. That was a great start to what turned out to be a very turbulent period both in my life and in Ukraine. Indeed, at that time Ukraine was on the verge of either sliding into a dictatorship or having a revolution. As we now know, the latter happened – the Orange Revolution of 2004 – and like many patriotically minded activists, feeling euphoric, I almost made a fatal error – going into politics – and it was the exciting work with and learning from Léopold that literally saved me from it: the Postdoc Fellowship at the Institute of Statistics of the Université Catholique de Louvain (UCL) in Belgium in 2004/2005 was one of the most productive times for me, and I am very thankful to Léopold and the Institute in general for that period and for many fruitful visits I made there afterward, which kept me engaged in the area despite other temptations from businesses or politics, and despite the GFC-related turbulence.

Interestingly, it was also there at UCL that I met Robin Sickles in 2004, and I am very happy we decided to combine our efforts on this book, and I thank Robin for his valuable feedback on my writings. It was also there at UCL, in 2009, that I incidentally learned of, applied to, and eventually got a position at the School of Economics at the University of Queensland (UQ), which for me

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-03616-1 — Measurement of Productivity and Efficiency
Robin C. Sickles , Valentin Zelenyuk
Frontmatter
More Information

was (and still is) associated with one of the greatest focal points of research in the area: the Centre for Efficiency and Productivity Analysis (CEPA). It is mainly because of this Centre, or more precisely the people that form and visit it, that I made what at that time seemed to many of my friends a fairly radical decision: to move to Australia. In hindsight, I see it as one of the best decisions I have ever made; it helped me substantially progress in my research endeavors in general and in writing this book in particular. So, I would like to express sincere thanks to Australia in general and the UQ School of Economics and CEPA in particular, and especially my CEPA colleagues: Knox Lovell, Chris O'Donnell, Antonio Peyrache, Alicia Rambaldi, and Prasada Rao, as well as Tim Coelli who was at CEPA's origin: together they created the greatest environment for productivity and efficiency analysis in the world, and I am honored to have joined their efforts, trying to make my own contribution. I also thank Hideyuki Mizobuchi, Hirofumi Fukuyama and Sung-Ko Li, as well as his students (especially Xinju He), for valuable comments on this book and for our joint research that helped in shaping it.

I also thank Per Agrell, Bert Balk, Rajiv Banker, Peter Bogetoft, Robert Chambers, Laurens Cherchye, Erwin Diewert, Finn Førsund, Paul Frijters, Jiti Gao, William Greene, William Horrace, Jeffrey Kline, Dale Jorgenson, Subal Kumbhakar, Flavio Menezes, Byeong Uk Park, Chris Parmeter, Victor Podinovski, John Quiggin, Subhash Ray, John Ruggiero, Robert Russell, David Saal, Peter Schmidt, Rabee Tourky, Ingrid Van Keilegom, Hung-Jen Wang, Paul Wilson, Joe Zhu, among many others who I had great opportunity to interact with and learn from on many occasions and from their works, which directly or indirectly helped me in gaining or synthesizing the knowledge for this book.

Last, yet not least, I also would like to thank the students at UQ who gave valuable feedback and technical assistance on various versions of this book, especially Bao Hoang Nguyen, Duc Manh Pham, Andreas Mayer, and Yan Meng, as well as David Du, Kelly Trinh, and Alexander Cameron. Finally, besides support from the universities that employed me or hosted me for research visits, I also would like to acknowledge the support of my research from ARC DP130101022 and ARC FT170100401, as some of this research directly or indirectly influenced the content of this book.

Both authors would like to thank a number of scholars who have provided needed criticism and suggested additions to earlier drafts that have broadened and enhanced the topics and technical material we develop in our book. These include Robert Chambers, Erwin Diewert, Rolf Färe, William Greene, Shawna Grosskopf, Kris Kerstens, Subal Kumbhakar, Young Hoon Lee, C. A. Knox Lovell, Chris Parmeter, Victor Podinovski, Robert Russell, Peter Schmidt, William Schworm and Léopold Simar.

Finally, we thank our Cambridge University Press editor Karen Maloney and the Cambridge University Press editorial team for their patience, support, and professionalism.

© in this web service Cambridge University Press www.cambridge.org