

## Contents

<i>List of Figures</i>	<i>page</i> xvii
<i>List of Tables</i>	xix
<i>Preface</i>	xxi
<i>Acknowledgments</i>	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

viii	<b>Contents</b>	
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 <i>Price</i> Indexes	102
4.4	Economic <i>Quantity</i> Indexes	106
4.5	Economic <i>Productivity</i> 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

<b>Contents</b>	ix	
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

x	<b>Contents</b>	
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

<b>Contents</b>	xi
9.3.1 Bootstrap for Individual Efficiency Estimates	307
9.4 Concluding Remarks	314
9.5 Exercises	315
<b>10 Statistical Analysis for DEA and FDH: Part 2</b>	<b>316</b>
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
<b>11 Cross-Sectional Stochastic Frontiers: An Introduction</b>	<b>352</b>
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

xii	<b>Contents</b>	
	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

<b>Contents</b>	xiii
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

xiv	<b>Contents</b>	
	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 Approach 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



<b>Contents</b>	xv
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

xvi	<b>Contents</b>	
	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
	<i>Afterword</i>	539
	<i>Bibliography</i>	541
	<i>Subject Index</i>	588
	<i>Author Index</i>	594