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## GENERAL DESCRIPTION

### 1.1 INTRODUCTION

It is important to keep in mind that the purpose and interest of this book are not a conventional use of data envelopment analysis (DEA) for efficiency measurement and performance analysis. Rather, this book will direct our research attention and concerns toward a new use of DEA on environment assessment and sustainability development. This chapter<sup>1</sup> is designed to discuss a new research direction for DEA.

This book consists of two sections (I and II). As an initial step, this chapter starts by reviewing fundamental research concepts for a conventional use of DEA. Such a conventional use will be discussed in all chapters of Section I. Then, Section II will extend it from the perspective of policy and business implications concerning environmental assessment and sustainability development. The methodology used for the newly proposed research is referred to as “DEA environmental assessment.” In addition to the environmental assessment, this book focuses upon energy sectors in the world because they are closely associated with various types of industrial pollution. An important environmental issue to be discussed in this book is how to challenge global warming and climate change in the world.

<sup>1</sup>This chapter is partly based upon the article: Ijiri, Y. and Sueyoshi, T. (2010) Accounting essays by Professor William W. Cooper: revisiting in commemoration of his 95th birthday. *ABACUS: A Journal of Accounting, Finance and Business Studies*, 46, 464–505.

Of course, we clearly understand that it is not easy to solve these climate issues by using only the proposed DEA environmental assessment and its applications to energy sectors. Rather, this book will attempt to investigate the global difficulty from the perspectives of business, policy and economics, so that we can assist technology development to avoid serious consequences such as heat waves, droughts, floods and food crisis, as well as other damage to human, social and economic systems. Thus, we will challenge various issues due to the climate change by utilizing the analytical capabilities of DEA environmental assessment, newly proposed in this book. This book will also attempt to change the profit-driven business logic used in a conventional use of DEA in such a manner that it can fit within the global trend for developing a sustainable society.

This chapter is organized in the following manner: Section 1.2 describes the structure of this book. Section 1.3 summarizes contributions on Sections I and II. Section 1.4 specifies abbreviations and nomenclature used in this book. Finally, Section 1.5 summarizes this chapter.

## 1.2 STRUCTURE

First of all, we need to mention that DEA is not a perfect methodology, rather it is an approximation approach for the performance assessment of many organizations in the public and private sectors. See Chapter 6 for methodical comparisons between conventional DEA models. However, it is true that DEA can provide corporate leaders and policy makers with an empirical guideline to assist their decision makings. Such a guideline is very important in assessing environmental issues and sustainability developments. To attain the research direction discussed here, the two sections of this book (Sections I and II) contain the following chapters:

### Section I: Conventional DEA

*Chapter 1 (General Description):* This chapter provides a general description on the structure of this book.

*Chapter 2 (Overview):* This chapter conveys the message that DEA can serve as a very useful methodology in terms of not only conventional performance assessment but also practical and academic purposes in guiding organizations in public and private sectors. However, it is true that DEA is not a perfect methodology, rather being an approximation approach for performance assessment. The review in this chapter provides us with an intuitive description, or rationale, concerning why various DEA applications can be used for examining performance assessment.

*Chapter 3 (History):* This chapter returns to the eighteenth century to describe the origin of L1 regression and its analytical linkage to DEA. It is possible for us to consider that various DEA models are methodologies for multi-objective

optimization which have been originated from the development of goal programming (GP). The history of GP started from the development of L1 regression. Thus, this chapter describes an analytical linkage among L1 regression, GP and DEA.

*Chapter 4 (Radial Measurement):* This chapter discusses two radial models that are used to measure a level of operational efficiency based on the Debreu–Farrell criterion. These models are classified into two categories under variable or constant returns to scale (RTS).

*Chapter 5 (Non-radial Measurement):* This chapter discusses non-radial models and their variations, as methodological alternatives to the two radial models, based on the Pareto–Koopmans criterion.

*Chapter 6 (Desirable Properties):* This chapter discusses nine desirable properties for the measurement of operational efficiency. It is better for each DEA model to satisfy such desirable properties from the perspective of production economics and optimization. Seven radial and non-radial models are theoretically compared from the perspective of nine criteria.

*Chapter 7 (Strong Complementary Slackness Conditions):* It is widely known that DEA has four difficulties in the applications. First, multiple projections occur in DEA. Second, multiple references occur in DEA, as well. Third, DEA cannot handle zero and/or negative values in a data set. Finally, an occurrence of zero may be usually found in dual variables. The occurrence of the fourth problem indicates that production factors, corresponding to dual variables with zero, are not fully utilized in DEA assessment. This chapter discusses the new use of strong complementary slackness conditions (SCSCs) to deal with the first, second and fourth difficulties related to DEA. The third difficulty will be discussed in Chapters 26 and 27, later.

*Chapter 8 (Returns to Scale):* This chapter discusses the concept and type of RTS in a unified framework of DEA production and cost analyses under the assumption of a unique optimal solution (e.g., a unique projection and a unique reference set). Dual relationships between production-based and cost-based RTS measures are discussed in this chapter.

*Chapter 9 (Congestion):* A possible occurrence of congestion serves as a very important concept for environmental assessment. Therefore, this chapter reviews the implication of the occurrence within a conventional framework of DEA. The occurrence of congestion indicates a capacity limit on part or all of a whole production facility. This chapter reassesses previous discussions on a possible occurrence of congestion. The concept discussed in this chapter will be later extended into a new development on eco-technology innovation in Chapter 21.

*Chapter 10 (Network Computing):* To deal with a large data set on various DEA assessments, this chapter highlights the architecture of network computing that is designed to coordinate a simultaneous use of multiple personal computers and other types of computing devices. This chapter provides a

DEA-based computational structure and algorithmic uniqueness. The proposed network computing can fit with modern computer technology, or a super computer, that has multi-processors for parallel computation.

*Chapter 11 (DEA-Discriminant Analysis):* Discriminant analysis (DA) is a classification method that can predict the group membership of a newly sampled observation. This chapter discusses a new type of non-parametric DA approach to provide a set of weights for a discriminant function, consequently yielding an evaluation score for group memberships. The non-parametric DA is referred to as data envelopment analysis–discriminant analysis (DEA-DA) because it maintains a discriminant capability by incorporating the non-parametric feature of DEA into DA. DEA-DA is very useful in assessing financial performance in the private sector.

*Chapter 12 (Literature Study on DEA):* This chapter lists previous research efforts on DEA, along with a link to environmental assessment. This chapter also summarizes software sources that can be used for the computation of DEA.

## **Section II: DEA Environmental Assessment**

*Chapter 13 (World Energy):* This chapter describes a recent world-wide energy trend. Energy is separated into primary and secondary categories. Primary energy is classified into fossil and non-fossil fuels. The fossil fuels include oil, natural gas and coal, while the non-fossil ones include nuclear and renewable energies (e.g., solar, wind, biomass, water and others). In this chapter, electricity is considered as a representative of secondary energy.

*Chapter 14 (Environmental Protection):* This chapter discusses a historical review of various policy efforts to prevent industrial pollution in the four regions: the European Union, Japan, China and the United States. This review of environmental issues is important in understanding a historical reason concerning why we are now facing different types of industrial pollution (e.g., air, water, soil and others) and serious pollution issues (e.g., the global warming and climate change) along with their industrial development and economic growth in the world.

*Chapter 15 (Concepts):* This chapter describes conceptual frameworks that serve as an analytical basis for developing DEA environmental assessment. The chapter incorporates desirable and undesirable outputs in addition to inputs in the proposed computational framework. It is necessary for us to attain economic prosperity in all nations to support the development of social welfare for people and to improve their living standards. Simultaneously, we are now facing various pollution risks on the Earth (e.g., heat waves, droughts, floods and food crises, as well as damages to human, social and economic systems). To handle the global difficulties in the world, this chapter introduces natural and managerial disposability concepts and then links them to other economic and strategic concepts used for sustainability development. Our research effort will be explored by using the new conceptual framework concerning DEA.

*Chapter 16 (Non-Radial Approach for Unified Efficiency Measures):* This chapter extends economic and corporate strategies for sustainability development by presenting mathematical formulations for a non-radial DEA approach. This chapter starts with a description on non-radial models because desirable and undesirable outputs are more easily unified for the proposed environmental assessment than a radial approach. This chapter applies the proposed non-radial approach to evaluate the performance of national and international petroleum firms in the world.

*Chapter 17 (Radial Approach for Unified Efficiency Measures):* This chapter shifts our methodological description from non-radial to radial measurement for environmental assessment. The natural and managerial disposability concepts discussed in Chapter 16 are incorporated into the proposed radial approach. This chapter applies the proposed radial approach to compare the performance of coal-fired power plants under an independent system operator (ISO) and a regional transmission organization (RTO) with that of the other power plants not belonging to ISO and RTO in the United States.

*Chapter 18 (Scale Efficiency):* This chapter describes how to measure scale efficiency under natural or managerial disposability. The scale efficiency indicates the level of a managerial capability regarding how each organization can control its operational size in terms of enhancing a level of unified (operational and environmental) efficiency. This chapter discusses how to measure a degree of scale efficiency within both radial and non-radial measurements. This chapter applies the proposed approach to measure the performance of coal-fired power plants in the north-east region of the United States.

*Chapter 19 (Measurement in Time Horizon):* This chapter discusses the use of DEA environmental assessment in a time horizon because most data sets on energy and environment are often structured by time series. In applying the proposed assessment to such time-series data, this chapter needs to classify production factors in a time horizon. A unique feature of the proposed assessment is that it incorporates the Malmquist index and its subcomponents in order to examine the occurrence of a frontier shift among multiple periods. This chapter utilizes the proposed approach to examine the relationship between a fuel mix for electricity generation and CO<sub>2</sub> emission in ten industrial nations.

*Chapter 20 (Returns to Scale and Damages to Scale):* As an extension of scale efficiency discussed in Chapter 18, this chapter describes how to measure RTS under natural disposability and damages to scale (DTS) under managerial disposability. In this chapter, we extend the concept of RTS, discussed in Chapter 8, by additionally incorporating undesirable outputs into a computational framework of DEA under natural disposability. The concept of DTS extends RTS to an analytical framework for measuring scale-related relationship between inputs and undesirable outputs under managerial disposability.

Business implications from RTS and DTS are discussed for an application to the Japanese chemical industry.

*Chapter 21 (Desirable and Undesirable Congestions):* This chapter classifies a possible occurrence of congestion into two categories: undesirable congestion (UC) under natural disposability and desirable congestion (DC) under managerial disposability. An occurrence of UC implies a capacity limit on part or all of a whole production facility. The phenomenon of UC can be found in all business sectors, including energy industries. Therefore, the identification of UC is important for energy sectors. Meanwhile, an occurrence of DC implies eco-technology innovation. It is easily imagined that DC is more important than UC in terms of environment protection. This chapter discusses policy implications obtained from such a possible occurrence of UC and DC for coal-fired power plants in the United States.

*Chapter 22 (Marginal Rate of Transformation and Rate of Substitution):* This chapter discusses how to measure marginal rate of transformation (MRT) and rate of substitution (RSU) among three production factors. This chapter examines the two measures along with the occurrence of DC, or eco-technology innovation, under managerial disposability. This chapter discusses “explorative analysis,” along with a data adjustment, as a new multiplier restriction method in measuring a degree of MRT and that of RSU. This chapter compares the performance of countries in European Union and North America based upon the measurement of MRT and RSU.

*Chapter 23 (Returns to Damage and Damages to Return):* This chapter discusses a possible occurrence of UC under natural disposability and that of DC under managerial disposability. Then, considering the two disposability concepts, this chapter compares between returns to damage (RTD) under UC and damages to return (DTR) under DC. This chapter applies the proposed approach to examine Chinese energy policy and regional planning. In the application, the occurrence of UC can be considered as an economic difficulty that has been recently observed in the world economy. UC has such an important implication in economics, different from the capacity limit on a production facility discussed in a context of production economics. Meanwhile, DC implies the potential of eco-technology capability in each region. Both RTD and DTR are new economic concepts extended from RTS and DTS.

*Chapter 24 (Disposability Unification):* This chapter discusses how to unify natural and managerial disposability concepts in radial and non-radial measurements. An important assumption, which is incorporated in the unification, is that “undesirable outputs are considered as byproducts of desirable outputs.” As a result of such an assumption, the desirable and undesirable outputs have a functional similarity (i.e., convex functions) between them. This chapter unifies the two disposability concepts and then extends them to

identify a possible occurrence of DC, or eco-technology innovation, under managerial disposability. The proposed approach is used for examining the performance of independent and integrated petroleum companies in the United States.

*Chapter 25 (Common Multipliers):* This chapter discusses the combined use of DEA with SCSCs, proposed in Chapter 7, and DEA-DA from Chapter 11 in order to conduct an “efficiency-based rank analysis” of energy firms. The proposed approach is useful in preparing performance assessment where a single organization is efficient and the remaining others have some level of inefficiency. The proposed approach, equipped with SCSCs, first classifies firms into efficient or inefficient group based upon their efficiency scores. Then, the proposed approach utilizes DEA-DA to obtain common multipliers. The second stage measures an adjusted efficiency score for each organization. This chapter applies the proposed approach to examine the performance of Japanese electric power firms.

*Chapter 26 (Translation Invariance to Handle Zero and Negative Values):* This chapter discusses the property of “translation invariance” in non-radial measurement. The property indicates that an efficiency measure should be not influenced even if inputs, desirable and undesirable outputs are shifted toward a same direction by adding or subtracting a specific real number. The property makes it possible that we can evaluate the performance of organizations, whose production factors contain many zeros and/or negative values in a data set. The proposed approach is used for relatively comparing the energy structures among 33 industrial nations in the world.

*Chapter 27 (Handling Zero and/or Negative Values in Radial Measurement):* This chapter discusses a new use of radial measurement by incorporating the analytical capability to handle zero and/or negative values in a data set. The approach can handle the data set within a framework of radial and non-radial measurements. The proposed approach provides us with not only new quantitative assessment on unified performance but also information regarding how to invest for eco-technology innovation for abating industrial pollutions. This chapter applies the proposed approach to United States industrial sectors by paying attention to both successful companies with positive net incomes and unsuccessful companies with negative net incomes, so being able to measure all aspects of their performance components in a short-term horizon.

*Chapter 28 (Literature Study on DEA Environmental Assessment):* This chapter summarizes previous research efforts on DEA applied to energy and environment. This chapter also examines a recent research trend on applications from the 1980s to the 2010s. The applications contain 693 articles in total, most of which are published in well-known international journals, listed in Science Citation Index or Social Science Citation Index.

### 1.3 CONTRIBUTIONS IN SECTIONS I AND II

First, it is necessary to clearly describe that DEA was first proposed by Professor William Wager Cooper<sup>2</sup> (23 July 1914 to 29 June 2012) and his associates. He was

<sup>2</sup>According to Ijiri and Sueyoshi (2010), Professor William W. Cooper was born in Birmingham, Alabama, in 1914. His father was a bookkeeper and later a distributor for Anheuser–Busch. When William was three years old, the family moved to Chicago where his father owned a chain of gasoline stations that he lost in the Great Depression. Professor Cooper continued in high school only until the end of his sophomore year. With his father in ill health and no family revenue, he had to work at whatever he could find. This included everything from professional boxing to spotting pins in bowling alleys and caddying at golf courses. While hitchhiking to a golf course one day, he met Hall of Fame member in accounting, Eric Kohler, who thereafter became his life-long mentor. This included a loan of funds which enabled him to start a non-degree track at the University of Chicago. He quickly grew to like the academic atmosphere and soon took the college entrance examinations, intending to become a physical chemist because that seemed to offer the best chance of a job. At about this time, Kohler, then a principal with Arthur Andersen, asked him to look over the mathematics used in a patent infringement suit in which Andersen had been retained by the defendant. He found errors in the mathematics used by the plaintiff’s engineers and Andersen hired him full-time in the summer and part-time during the school year. This awakened his interest in accounting so that he changed his major at the University of Chicago from chemistry to economics, and Kohler helped him to learn accounting. He graduated Phi Beta Kappa in economics in 1938. Kohler had by then left Anderson and assumed the position of Controller for the Tennessee Valley Authority (TVA). Kohler brought him to the TVA to head up work on “procedural auditing” (what would now be called “performance auditing”) and to advise Kohler on the mathematics of cost allocation and other disputed matters in which the TVA was involved. This included helping Kohler to prepare testimony on these and other matters to be investigated by a Joint House–Senate Investigation Committee. Most of the work was completed by mid-1940 so that he left to become a PhD candidate at Columbia University where he had been awarded a doctoral fellowship in the School of Business. After passing his “prelims” in 1942, he again left academia to join the Division of Statistical Standards at the United States Bureau of Budget (now the OMB) where, as part of the United States war effort, he was placed in charge of coordinating all of the Federal Government’s accounting and accounting-related statistics program. By late 1944, with the war coming to an end, he left to teach at the University of Chicago. In 1946, he returned to Washington to chair a committee to decide the fate of various war-time programs in financial statistics. He then transferred to Carnegie Institute of Technology (now Carnegie Mellon University, CMU) where he helped found, first, the Graduate School of Industrial Administration and, later, the School of Urban and Public Affairs. There was time out, however, to develop “end-use” audits that Kohler wanted to institute as Comptroller of the Marshal Plan. In 1976, after 30 years at CMU, Professor Cooper went to the Harvard Business School to help reorient their doctoral programs while holding the chair in accounting named for Hall of Fame member Arthur Lowes Dickinson. This task was completed in 1980, when he went to the University of Texas at Austin where he was initially appointed Professor of Management, Accounting and Management Science, and Information Systems, and was the Foster Parker Professor of Finance and Management (Emeritus) and the Nadya Kozmetsky Scott Centennial Fellow in the IC Institute. In 1945, he received an award for the most valuable article on accounting, the first ever awarded by the American Institute of Accountants (now the American Institute of Certified Professional Accountants, AICPA). A fellow of the Econometric Society, he was founding president of the Institute of Management Sciences, and he was also president of the Accounting Researchers International Association. He was the Director of Publications for the American Accounting Association. In 1990, he was named an Outstanding Accounting Educator by the same organization. He was Visiting International Lecturer for the American Accounting Association (AAA), traveling abroad in 1986 to lecture on accounting topics and visit with scholars in Latin America. In 1982, he was co-recipient of the John Von Neumann Theory Medal, jointly awarded by

the father of DEA. Since the original development, his research direction and concerns have been long influencing many proceeding works on DEA until now. Therefore, this chapter briefly reviews his contributions. Then, we specify the proposed research rationale concerning why and how DEA is important for environmental assessment in energy sectors.

According to Ijiri and Sueyoshi (2010), the first published article of Professor Cooper was an economic analysis entitled “*The yardstick of public utility regulation*” that appeared in June 1943 in *The Journal of Political Economy*, vol. **51**, part 3, pp. 258–262. In fact, still earlier in 1938, he published a proceedings paper for the Committee on Capital Gains Taxation of the National Tax Association under which he coauthored with E.L. Kohler. He coauthored an article with E.L. Kohler entitled “*Costs, prices and profits – accounting in the war program,*” and published it in July 1945, in *The Accounting Review*, vol. **20**, part 3, pp. 267–308. On 31 August 1945, the American Institute of Accountants (currently the American Institute of CPAs) established a new award and chose his article as the most significant contribution to accounting in the year of its publication.

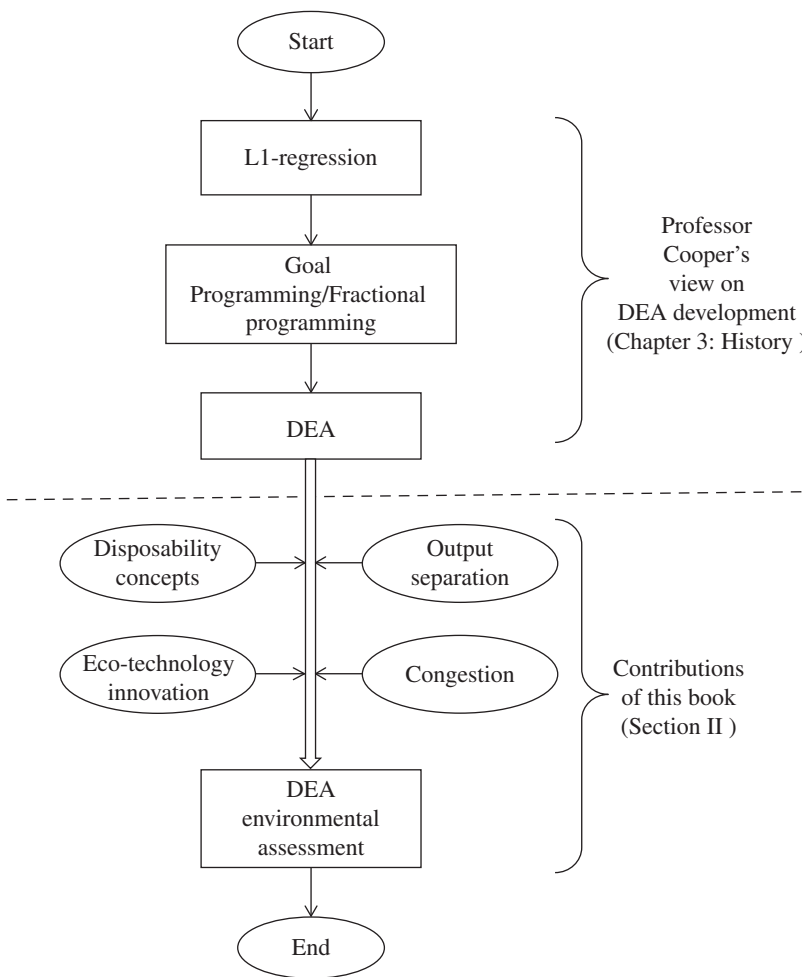
He had been a catalyst of change on a world-wide basis for more than five decades. His research inspired teaching, he was an editor for many periodicals and was a consultant to private, governmental and public institutions. As a prodigious author, his writings often focused on quantitative and creative approaches to management. With his long-time collaborator, a mathematician called A. Charnes, Professor Cooper was known everywhere as “Mr. Linear Programming,” partly because they developed whole new areas such as GP, DEA and chance constrained programming, all of which originate from linear programming.

In reviewing his contributions, this chapter finds two important concerns related to DEA applications to energy and environment. The first concern is that the contribution of Professor Cooper could be summarized in short as “public accounting” and “public economics.” His research interests included research on public sectors. Therefore, the first DEA article by Charnes, *et al.* (1978) was related to performance assessment on education units, so belonging to a public sector application on education. The other concern was that Professor Cooper was very proud of his development on GP. The rationale was because GP could solve L1 regression which none had solved from the eighteenth century. See Chapter 3 for a detailed description on the fact. It is possible for us to consider that various DEA models are methodologies for multi-objective optimization which have been originated from the development of GP. The history of GP has started from the development of L1 regression originated from science in the eighteenth century. Figure 1.1 depicts such a historical view on L1 regression, GP and DEA.

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the Operations Research Society of America and the Institute of Management Sciences. In 1988, he received the Distinguished Service to Auditing Award from the Auditing Section of the AAA as well as an award for serving as the founding editor of Auditing, *A Journal of Practice and Theory*. He has received three McKinsey Foundation Awards for the most valuable article of the year on a management topic, and he has been a consultant to more than 200 institutions including the Marshall Plan, the United States General Accounting Office and others.



**FIGURE 1.1** Developments and contributions.

Figure 1.1 displays an influence from the development of “fractional programming” that has changed the ratio model (i.e., the sum of weighted outputs divided by the sum of weighted inputs), which is non-linear programming, to its linear programming equivalent. As a result of such a structural change, we can now solve the ratio model by linear programming. The original formulation was often referred to “DEA ratio form” because of the analytical reason. In this book, we consider that such a series of DEA developments have been greatly guided by the contribution of Professor Cooper and his associates.

A problem of conventional DEA is that there is a difficulty in applying it to environmental assessment because undesirable outputs are not incorporated in the original formulation and its variations. Therefore, this book needs to shift the

structure of conventional DEA to environmental assessment by adding undesirable outputs. The restructuring process needs to consider four important research changes, including (a) output separation into desirable and undesirable categories, (b) concepts on natural or managerial disposability that are linked to different treatments on inputs, (c) a possible occurrence of congestion and (d) a conceptual implication of eco-technology to reduce various pollutions. All of these have not been explored in previous DEA studies. This book will introduce all such new aspects and will explore them through DEA environmental assessment for energy and other industrial sectors.

## 1.4 ABBREVIATIONS AND NOMENCLATURE

### 1.4.1 Abbreviations Used in This Book

AAA	American Accounting Association
AEc	allocative and scale efficiency
AEv	allocative efficiency
AFD	acquisition, funding and development
AI	aggregation index
AICPA	American Institute of Certified Professional Accountant
AM	additive model
AR	assurance region
AZ	Altman's Z
BACT	best available control technology
BIT	bituminous coal
BOE	barrel of oil equivalent
BP	British Petroleum
CAA	Clean Air Act
CARB	California's Air Resources Board
CDP	Carbon Disclosure Project
CDTR	constant damages to return
CEc	cost and scale efficiency
CEv	cost efficiency
CEQ	Council on Environmental Quality
CEQA	California Environmental Quality Act
CHP	combined heat and power
CH <sub>4</sub>	methane
CMU	Carnegie Mellon University
COI	classification and overlap identification
CO <sub>2</sub>	carbon dioxide
CPB	Central Planning Bureau
CPC	Communist Party of China
CPU	central processing unit

CPUC	California Public Utilities Commission
CR	cone ratio
CRTD	constant returns to damage
CRTS	constant returns to scale
CSAPR	Cross State Air Pollution Rule
CSCs	complementary slackness conditions
CSE	cost-based scale efficiency
CWA	Clean Water Act
DA	discriminant analysis
DAM	day ahead market
DC	desirable congestion
DDTR	decreasing damages to return
DEA	data envelopment analysis
DEA-DA	data envelopment analysis–discriminant analysis
DG	director general
DgRTD	degree of returns to damage
DgDTR	degree of damages to return
DME	di-methyl ether
DMU	decision making unit
DOC	diesel oxidation catalyst
DRTD	decreasing returns to damage
DRTS	decreasing returns to scale
DTR	damages to return
DTS	damages to scale
EAP	environmental action program
EC	European Community
EF	efficiency frontier
EG	efficiency growth
EGUs	electric generating units
EIA	energy information administration
EIS	environmental impact statement
EP	equilibrium point
EPA	Environmental Protection Agency
ERGM	enhanced Russell graph measure
ES	elasticity of substitution
ESA	Endangered Species Act
EU	European Union
FERC	Federal Energy Regulatory Commission
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FIT	feed-in tariff
FWCA	Fish and Wildlife Coordination Act
GDP	gross domestic product
GGTR	greenhouse gas tailoring rule
GHG	greenhouse gas

GP	goal programming
GRP	gross regional product
GTL	gas to liquids
GW	gigawatt
GWe	gigawatt-electrical
GWh	gigawatt hour
HAPs	hazardous air pollutants
HD	hierarchical decomposition
HEW	health, education and welfare
HO	handling overlap
IC	input-oriented congestion
IDTR	increasing damages to return
IEA	International Energy Agency
IEEA	International Electricity Association
IM	Malmquist index under managerial disposability
IMC	IM with crossover
IN	Malmquist index under natural disposability
INC	IN with crossover
IOCs	international oil companies
IPCC	Intergovernmental Panel on Climate Change
IRTD	increasing returns to damage
IRTS	increasing returns to scale
ISO	independent system operator
IUEM	inter-temporal unified efficiency under managerial disposability
IUEN	inter-temporal unified efficiency under natural disposability
IUIM	inter-temporal unified index under managerial disposability
IUIN	inter-temporal unified index under natural disposability
JCC	Japan crude cocktail
KW	kilowatt
KWh	kilowatt hour
LAV	least absolute value
Lb	pound
LNG	liquefied natural gas
LMPs	locational marginal prices
LOO	leave one out
M&A	mergers and acquisitions
MACT	maximum achievable control technology
MATS	mercury and air toxics standards rule
MCF	magnitude control factor
MCP	market clearing price
MEP	Ministry of Environmental Protection
MIP	mixed integer programming
mmBtu	million British thermal units
MMT	methylcyclopentadienyl manganese tricarbonyl

MPSS	most productive scale size
MRT	marginal rate of transformation
MS	milli-second
MW	megawatt
NAPCA	National Air Pollution Control Administration
N <sub>2</sub> O	nitrous oxide
NEPA	National Environmental Policy Act
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NGO	non-governmental organization
NO <sub>2</sub>	nitrogen dioxide
NOCs	national oil companies
NR	non-radial
NYSE	New York Stock Exchange
OC	output-oriented congestion
OE	operational efficiency
OE <sub>c</sub>	operational and scale efficiency
OECD	Organization for Economic Co-operation and Development
OE <sub>v</sub>	operational efficiency under variable RTS
OLS	ordinary least squares
O&M	operating and maintenance
OR and MS	operations research and management science
ORSA	Operations Research Society of America
PB	period block
PC	personal computer
PM	particulate matter
PoPS	pollution possibility set
Pr&PoPS	production and pollution possibility set
PrPS	production possibility set
PSE	production-based scale efficiency
PV	photovoltaic
PVPS	photovoltaic power systems
Q.E.D.	<i>quod erat demonstrandum</i>
R	radial
RAM	range-adjusted measure
RCRA	Resource Conservation and Recovery Act
R&D	research and development
RGGI	Regional Greenhouse Gas Initiative
Rh	right-hand side
RICE NESHAP	Reciprocating Internal Combustion Engines and National Emission Standards for Hazardous Air Pollutants
RM	radial model
RM(c)	radial model under constant RTS
RM(v)	radial model under variable RTS
RP	reserve-production

RS	reference set
RSU	rate of substitution
RTM	real time market
RTD	returns to damage
RTO	regional transmission organization
RTS	returns to scale
SARM	slack-adjusted radial measure
SBM	slack-based measure
SCSCs	strong complementary slackness conditions
SCI	Science Citation Index
SDA	scale damages
SDWA	Safe Drinking Water Act
SE	scale efficiency
SEA	Single European Act
SEC	scale economies
SEM	scale efficiency under managerial disposability
SEN	scale efficiency under natural disposability
SEPA	state environmental protection administration
SFA	stochastic frontier analysis
SMR	super ministry reform
SO	sulfur oxide
SOCP	second-order cone programming
SSCI	Social Science Citation Index
<i>s.t.</i>	subject to
SUB	subbituminous coal
TA	total average
TCP/IP	transmission control protocol/Internet protocol
TD	treatment for dominance
TFP	total factor productivity
TIMS	The Institute of Management Science
TSCA	Toxic Substance Control Act
TVA	Tennessee Valley Authority
TVEs	township and village enterprises
TWh	terawatt hour
UC	undesirable congestion
UE	unified efficiency
UEM	unified efficiency under managerial disposability
UEN	unified efficiency under natural disposability
UENM	unified efficiency under natural and managerial disposability
UK	United Kingdom
UN	United Nations
URS	unrestricted
US	United States
U3O8	triuranium octoxide

VOCs	volatile organic compounds
VRTS	variable returns to scale
W	window
WTI	West Texas Intermediate

### 1.4.2 Nomenclature Used in This Book

$A$	a matrix of observed inputs and desirable outputs of all DMUs
$A_j = (a_{1j}, a_{2j}, \dots, a_{mj})^{Tr}$	a column vector for restriction on inputs
$B = (B_1, B_2, \dots, B_n)$	a $h \times n$ matrix of observed undesirable outputs of all DMUs
$b_{fj}$	an observed value of the $f$ -th undesirable output on the $j$ -th DMU
$\bar{b}_{fj} = b_{fj} + \delta_f$	an adjusted value of the $f$ -th undesirable output
$b_{fjt}$	an observed value of the $f$ -th undesirable output on the $j$ -th DMU in the $t$ th period
$B_j = (b_{1j}, b_{2j}, \dots, b_{hj})^{Tr}$	a column vector of observed $h$ undesirable outputs of the $j$ -th DMU
$B_k = (b_{1k}, b_{2k}, \dots, b_{hk})^{Tr}$	a column vector of observed $h$ undesirable outputs of the $k$ -th DMU
$c$	a value of cost
$c$ (sub or superscript)	this expresses constant RTS or DTS
$cf$	a discriminant score for cutting-off between groups
$C_j = (c_{1j}, c_{2j}, \dots, c_{sj})^{Tr}$	a column vector for restriction on desirable outputs
$c_z$ (network)	the number of the $z$ -th client
$C_1$	a partial group of $G_1$ which are clearly above an estimated discriminant function in Stage 1
$C_2$	a partial group of $G_2$ which are clearly below an estimated discriminant function in Stage 1
$d^b = (d_1^b, d_2^b, \dots, d_h^b)^{Tr}$	a column vector of slacks related to $h$ undesirable outputs
$d_f^b$	a slack related to the $f$ -th undesirable output
$d^s = (d_1^s, d_2^s, \dots, d_s^s)^{Tr}$	a column vector of slacks related to $s$ desirable outputs
$d_r^s$	a slack related to the $r$ -th desirable output
$d_r^{s-}$	a part of $d_r^s$ under natural disposability ( $r = 1, \dots, s$ )
$d_r^{s+}$	a part of $d_r^s$ under managerial disposability ( $r = 1, \dots, s$ )
$D^g$	a positive diagonal desirable output matrix
$D^x$	a positive diagonal input matrix
$d^x = (d_1^x, d_2^x, \dots, d_m^x)^{Tr}$	a column vector of $m$ slacks related to inputs
$d_i^x$	a slack related to the $i$ -th input
$d_i^{x-}$	a part of $d_i^x$ under natural disposability ( $i = 1, \dots, m$ )

$d_q^{x-}$	a part of $d_i^x$ under unified (natural and managerial) disposability ( $q = 1, \dots, m^-$ )
$d_q^{x+}$	a part of $d_i^x$ under unified (natural and managerial) disposability ( $q = 1, \dots, m^+$ )
$d_i^{x+}$	a part of $d_i^x$ under managerial disposability ( $i = 1, \dots, m$ )
$D_1$	a partial group of $G_1$ which are above an estimated discriminant function in Stage 2
$D_2$	a partial group of $G_2$ which are below an estimated discriminant function in Stage 2
$e$	a row vector whose components are all 1
$e_b$	an undesirable output-based scale elasticity
$e_c$	a cost-based scale elasticity
$e_g$	a desirable output-based scale elasticity
$e_1$	a unit vector whose first component is 1
$E$	an efficient DMU group in $J_n$ whose members have unity in their efficiency measures and zero in all slacks and unique optimal solution
$E'$	an efficient DMU group in $J_n$ whose members have unity in their efficiency measures and have zero in all slacks and multiple optimal solutions
$ECD$	a group of DMUs which may become efficiency-candidates implying that they may belong to $E \cup E'$
$f$	a subscript of the $f$ -th undesirable output ( $f = 1, \dots, h$ )
$G = (G_1, G_2, \dots, G_n)$	a $s \times n$ matrix of observed desirable outputs of all DMUs
$G_j = (g_{1j}, g_{2j}, \dots, g_{sj})^{Tr}$	a column vector of observed $s$ desirable outputs of the $j$ -th DMU
$G_k = (g_{1k}, g_{2k}, \dots, g_{sk})^{Tr}$	a column vector of observed $s$ desirable outputs of the $k$ -th DMU
$\bar{g}_{rj} = g_{rj} + \beta_r$	an adjusted value of the $r$ -th desirable output
$g_{rj}^+ = \max(g_{rj}, \varepsilon_s)$	an adjusted value of the $r$ -th desirable output to express a positive part
$g_{rj}^- = \max(g_{rj}, \varepsilon_s) - g_{rj} + \varepsilon_s$	an adjusted value of of the $r$ -th desirable output to express a negative part
$g_{rj}$	an observed value of the $r$ -th desirable output on the $j$ -th DMU
$g_{rjt}$	an observed value of the $r$ -th desirable output on the $j$ -th DMU in the $t$ -th period
$g_{rj}^+$	a positive part of $g_{rj}$ after disaggregation
$g_{rj}^-$	a negative part of $g_{rj}$ after disaggregation
$G_1$	a set of observations in the first group above an estimated discriminant function
$G_2$	a set of observations in the second group below an estimated discriminant function

$G_\zeta$	a set of observations in the $\zeta$ -th group (for $\zeta = 2, \dots, q-1$ )
$i$	a subscript of the $i$ -th input ( $i = 1, \dots, m$ )
$IE$	an inefficient DMU group in $J_d$ whose efficiency measures are less than unity and some intensity variable(s) in $E$ is positive on optimality
$IE'$	an inefficient DMU group in $J_n$ whose members have efficiency measures that are less than unity and some intensity variable(s) in $E$ is positive on optimality
$IF$	an inefficient DMU group in $J_d$ whose members have unity in their efficiency measures but they have at least one positive slack on optimality
$IF'$	an inefficient DMU group in $J_n$ whose members have unity in their efficiency measures but at least one positive slack and multiple optimal solutions
$j$	a subscript of the $j$ -th DMU ( $j = 1, \dots, n$ )
$J$	a whole DMU set
$J_d$	a dominated DMU group
$J_n$	a non-dominated DMU group
$J_t$	all DMUs in the $t$ -th period
$k$	a subscript of the specific $k$ -th DMU ( $k = 1, \dots, n$ ) whose performance is measured by DEA
$lb$	a lower bound
$\underline{lu}_r$	a lower bound of $u_r/u_1$
$\underline{lv}_i$	a lower bound of $v_i/v_1$
$M$	a prescribed large number
$M$ (superscript)	managerial disposability
$N$ (superscript)	natural disposability
$NR$ (superscript)	non-radial measurement
$NY$	a group of DMUs which are not yet examined at the current stage
$ob_j$	the $j$ -th goal (or objective) in GP
$p_j$	a dual variable for the $j$ -th observation ( $\mu_j = np_j - 1$ ) in regression and GP
$q$	a subscript of the $q$ -th input ( $q = 1, \dots, m^+$ ) under managerial disposability
$r$	a subscript of the $r$ -th desirable output ( $r = 1, \dots, s$ )
$R$ (superscript)	radial measurement
$R_f^b$	a data range related to the $f$ -th undesirable output
$R_r^g$	a data range related to the $r$ -th desirable output
$R_h$	a column vector of the right hand side of a formulation
$R_i^x$	a data range related to the $i$ -th input
$RS_k$	a reference set of the $k$ -th DMU
$Tr$	a vector transpose
$t$	the $t$ -th period

$U = (u_1, u_2, \dots, u_s)$	a raw vector of $s$ dual variables for desirable outputs
$ub$	an upper bound
$u_r$	a dual variable related to the $r$ -th desirable output
$\overline{uu}_r$	an upper bound of $u_r/u_1$
$\overline{uv}_r$	an upper bound of $v_i/v_1$
$v$ (subscript)	this expresses variable RTS or DTS
$V = (v_1, v_2, \dots, v_m)$	a raw vector of $m$ dual variables for inputs
$v_i^-$	a dual variable related to the $i$ -th input
$v_i^-$ (natural and managerial disposability)	a dual variable related to the $i$ -th input
$v_q^+$ (natural and managerial disposability)	a dual variable related to the $q$ -th input
$W = (w_1, w_2, \dots, w_h)$	a raw vector of $h$ dual variables for undesirable outputs
$w_f$	a dual variable related to the $f$ -th undesirable output
$w_r^g$	a weight assigned to the $r$ -th desirable output-based slack
$w_i^x$	a weight assigned to the $i$ -th input-based slack
$X = (X_1, X_2, \dots, X_n)$	a $m \times n$ matrix of observed inputs of all DMUs
$x_i$	an unknown variable for the $i$ -th input quantity to be used to find cost minimum
$x_{ij}$	an observed value of the $i$ -th input on the $j$ -th DMU
$\bar{x}_{ij} = x_{ij} + \alpha_i$	an adjusted value of the $i$ -th input
$x_{ijt}$	an observed value of the $i$ -th input on the $j$ -th DMU in the $t$ th period
$X_j = (1, x_{1j}, \dots, x_{mj})$	the $j$ -th observation on the $m$ -th independent variable in regression
$X_j = (x_{1j}, x_{2j}, \dots, x_{mj})^{Tr}$	a column vector of observed $m$ inputs on the $j$ -th DMU
$X_k = (x_{1k}, x_{2k}, \dots, x_{mk})^{Tr}$	a column vector of observed $m$ inputs of the $k$ -th DMU
$y_j$	the $j$ -th observation on a dependent variable in regression
$z_{ij}$	the $j$ -th observation on the $i$ -th independent factor
$z_{ik}$	the newly sampled $k$ -th observation on the $i$ -th independent factor
$\alpha$	$\theta$ under a possible occurrence of congestion in DEA
$\beta$	$\tau$ under a possible occurrence of congestion in DEA
$\beta = (\beta_0, \beta_1, \dots, \beta_m)^{Tr}$	a column vector of parameters on unknown independent variables in regression
$\gamma_i^+$	an unknown binary variable related the $i$ -th positive slack
$\gamma_i^-$	an unknown binary variable related the $i$ -th negative slack
$\delta_j^+$ and $\delta_j^-$	positive and negative deviations (errors) of the $j$ -th observation from an estimated regression hyperplane in regression and GP

$\Delta_x$	an increased column vector of $m$ inputs of the $k$ -th DMU
$\Delta_g$	an increased column vector of $s$ desirable outputs of the $k$ -th DMU
$\varepsilon$	a small number (e.g., 0.1 and 1) for MCF that is prescribed by a DEA user
$\varepsilon_s$	a very small number (e.g., 0.00001) to be prescribed by a DEA user
$\varepsilon_n$	a non-Archimedean small number
$\eta$	an unknown decision variable to be used for satisfying SCSCs
$\theta$	an efficiency score measured by an input-oriented radial model
$\theta_i$	an efficiency score measured by the $i$ -th input (Russell measure)
$\underline{\vartheta}^*$ and $\overline{\vartheta}^*$	upper and lower bounds on an adjusted intercept for determining the type of RTS
$\zeta_i$	a binary variable regarding the $i$ -th parameter
$\zeta_r$	a binary variable regarding the $r$ -th parameter
$\kappa$	a functional form for a supporting hyperplane
$\lambda = (\lambda_1, \lambda_2, \dots, \lambda_n)^{Tr}$	a column vector of intensity (or structural) variables for all DMUs
$\lambda_i$ (discrimination)	an unknown weight estimate on the $i$ -th factor
$\lambda_j$	an intensity or structural variable related to the $j$ -th DMU
$\lambda_{jt}$	an intensity or structural variable related to the $j$ -th DMU in the $t$ th period
$\mu$	an arbitrary positive number
$\mu_j$	a binary variable of the $j$ -th observation to express correct or incorrect classification
$\pi = [\pi_1, \dots, \pi_m]^{Tr}$	an $m$ -dimensional non-negative column vector
$\Pi = [\pi, \pi, \dots, \pi]$	a non-negative matrix
$\rho$	a variable to express an absolute distance between the discriminant score and a discriminant function
$\rho_j$	an adjusted efficiency of the $j$ -th DMU
$\sigma$	a dual variable regarding the constraint (i.e. the sum of all $\lambda_j$ is unity)
$\tau$	an efficiency score measured by a desirable output-oriented radial model
$\tau_r$	an efficiency score measured by the $r$ -th desirable output (Russell measure)
$v_i^+$ and $v_i^-$	binary variables regarding the $i$ -th parameter
$\underline{v}^*$ and $\overline{v}^*$	upper and lower bounds on an adjusted intercept for determining the type of DTS
$\phi$	an empty set
$\varphi_j$	an intensity or structural variable to substitute for $\lambda_j$
$\xi$	an inefficiency score measured by DEA environmental assessment

$\psi = [\psi_1, \dots, \psi_s]^T$	a $s$ -dimensional nonnegative column vector
$\Psi = [\psi, \psi, \dots, \psi]$	a non-negative matrix
$\omega$	a value on $[0, 1]$
$\varpi$	the minimum value on $\sum_{j=1}^n \left( \sum_{i=1}^m x_{ij} - \sum_{r=1}^s g_{rj} \right) \lambda_j$
$\omega_j$	a weight to express the importance of each $j$ -th goal in regression and GP

### 1.4.3 Mathematical Concerns

This book has three mathematical concerns, all of which need to be discussed in this chapter.

- (a) *Small numbers*: This book uses three types of small number ( $\varepsilon$ ). First,  $\varepsilon_n$  is a non-Archimedean small number that has been long used by DEA researchers. However, none knows what it is in reality. See Chapters 7 and 25 for a description on how to handle the difficulty. Second,  $\varepsilon$  is used to express a small number (e.g., 0.1, 1.0 or 2.0). Finally,  $\varepsilon_s$  is used to express a very small number (e.g., 0.0001). The last two types of  $\varepsilon$  are utilized for formulations on DEA environmental assessment in Section II. The three small numbers are our mathematical conveniences. Chapters in Section I follow a traditional description on very small numbers. The research spirit to incorporate such small numbers is very important in obtaining reliable DEA results in which all dual variables (multipliers) should be positive. Otherwise, production factors in a data set are not fully utilized in DEA as they are in most studies in production economics. Such a treatment is unacceptable, in particular in DEA environmental assessment, which pays attention to not only a degree of efficiency but also other important measures (e.g., DC, UC, RTS, DTS, MRT, RSU, RTD and DTR) under natural and managerial disposability concepts.
- (b) *Italic expression*: This book uses an italic expression if a symbol is related to a mathematical formulation. Furthermore, we often use italics to emphasize important concepts or visual expressions related to the mathematical formulation in each chapter.
- (c) *Augmented form*: All chapters in Section I use “ordinary” linear programming formulations. A unique feature of these formulations is that their constraints include an inequality/equality sign (e.g.,  $\geq$  and  $\leq$ ) so that slacks are often excluded from these formulations. Meanwhile, chapters in Section II use “augmented” formulations that incorporate slack variables so that their constraints are expressed by only equality constraints. In the augmented formulations, the existence of a slack(s) implies an “inequality” constraint(s) even in their formulations. The rationale regarding why we use the augmented form is that a weight is assigned to each slack in the objective function and each constraint is associated with a dual variable (i.e., a

multiplier). Each dual should be positive because it represents a weight assigned to each production factor. Thus, all production factors (inputs, desirable and undesirable outputs) are fully utilized in DEA formulations because they need to be structured by a full dimension of positive dual variables or multipliers. This type of research concern was first discussed in the first DEA article by Charnes *et al.* (1978). See Chapter 4, as well. Note that all chapters in Section II will document the augmented formulations that are different from their original structure.

## 1.5 SUMMARY

This chapter introduces a proposal for a new use of DEA, as a holistic approach, to assess various aspects of energy and environmental issues. As discussed in this chapter, this book consists of two sections. The first of these sections, or Section I, is related to the conventional use of DEA and its related framework, which serves as a mathematical basis for environmental assessment in energy sectors and in other industry sectors. Section II, which is the gist of this book, is related to DEA-based conceptual and methodological extensions for environmental assessment in energy sectors.

Here, it is important to note that Chapter 12 summarizes the references cited in Section I (Chapters 1–12). The references are structured in the following manner:

Cooper, W.W. (2005) Origins, uses of, and relations between goal programming and data envelopment analysis. *Journal of Multi-Criteria Decision Analysis*, **15**, 3–11.

Similarly, Chapter 28 summarizes the references cited in Section II (Chapters 13–27) which classifies previous research efforts based upon energy categories discussed in Chapter 13 and sustainability. Thus, to clearly specify the classification group to which each article belongs, all references in Chapter 28 have a number within [ ] added after the article details, as follows:

Sueyoshi, T., Goto, M. (2016) Undesirable congestion under natural disposability and desirable congestion under managerial disposability in U.S. electric power industry measured by DEA environmental assessment. *Energy Economics*, **55**, 173–188. [520]

Here, the additional number [520], as an illustrative example, indicates the order of each article. The number is used to specify the group classification summarized in Chapter 28. In addition to the reference format summarized in Chapter 28, other published research works, not directly related to DEA environmental assessment, are listed in the footnotes of each chapter in Section II.