SUSTAINABILITY IN SUPPLY CHAINS: MODELS AND METRICS

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BY

Alireza Tajbakhsh, M.Sc., B.Sc., PMP

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AUTHOR:	Alireza Tajbakhsh (DeGroote School of Business) McMaster University, Hamilton, Canada
SUPERVISOR:	Dr. Elkafi Hassini
COMMITTEE:	Dr. Mahmut Parlar
COMMITTEE:	Dr. Kai Huang
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Dedication

To my beloved wife, ***Azam****,*

for her unconditional love and tremendous sacrifices

and to my loved mother, ***Esmat****,*

for her genuine affection and ceaseless prayers

and to my marvelous father, ***Karim****,*

for his exceptional fondness and great encouragement

and to my dear sister and brothers,

Simin, Masoud, Reza, Saeed, and Mahdi*,*

for their overwhelming support and sheer inspiration

Abstract

In this dissertation, we study several quantitative approaches centered on supply chain management, sustainability development, performance measurement frameworks, and environmental regulation mechanisms. The topic of sustainability has been of great interest for the past few years in academia. Many governments also have taken actions to incentivize firms to reduce their negative environmental and social impacts. It is unclear, however, how successful policy makers have been in reducing the sustainability threats. This raises the question of "how can policy makers play an effective role in helping businesses become more sustainable, while complying with entrepreneurs and investors' expectations?" This dissertation is organized on the basis of six chapters. Having reviewed the literature and research directions of sustainable supply chain management in Chapter 1, we present a review of sustainability performance measurement frameworks in Chapter 2. In addition to proposing a framework to assess sustainability efficiency in supply chains, we discuss research questions with a focus on the social aspect of sustainability development. In Chapter 3, we develop a two-stage data envelopment analysis model with an application to the energy sector. This approach measures relative efficiencies of a number of comparable decision makers and does not require predetermined weights of indicators. We relax some restricting assumptions used in previous studies and obtain a nonlinear problem, for which we develop a solution method. Chapter 4 investigates a more general multi-stage assessment framework that monitors suppliers, manufacturers, distributers, and retailers' sustainable practices. The major finding is developing a multi-stage data envelopment analysis to measure supply chains' sustainability efficiency. In Chapter 5, we investigate market-based schemes with a focus on curbing pollution emitted by business entities and develop a game-theoretic formulation. Finally, we summarize the major contributions of this dissertation and future research directions in Chapter 6.

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Chapter 1

Introduction

This chapter is composed of three sections. Section 1.1 gives a brief introduction of sustainability in the context of supply chain operations and offers a definition of sustainable supply chain management. Section 1.2 reviews the relevant literature and presents a classification of research questions through eight major problem categories. Section 1.3 explains the organizational structure of the thesis.

1.1 Motivation and Definitions

Business managers strive to direct the organizational operations towards maximal long run efficiency (Shepherd and Günter 2006). With pressure from stakeholders such as customer groups and governments, managers are now also expected to incorporate sustainability factors in their operations models (Hassini et al. 2012). As Cetinkaya et al. (2011) argue, both academics and practitioners call for the incorporation of sustainability aspects in supply chain models. They have also indicated that a number of long term business failures are due to the absence of sustainability goals in the corporation vision. Based on a three-dimension sustainability framework, referred to as the triple bottom line (TBL), that considers the economy (profit), the environment (planet), and the society (people) (Elkington 1997), businesses can create new sustainable and competitive revenue streams (Mincer 2008). This has prompted both academics and practitioners to build models and policies for sustainable operations.

The United Nations World Commission on Environment and Development (UNWCED) has defined sustainability development as "*a practice that meets the needs of* *the present without compromising the ability of future generations to meet their own needs.*" Although the foregoing definition of sustainability development has been prevalently taken into consideration, there exist distinctly different attempts at defining supply chain management and supply chain sustainability (Cooper et al. 1997, Mentzer et al. 2001, Larson and Halldórsson 2004, Stock and Boyer 2009, Chopra and Meindl 2013, Ahi and Searcy 2013). In this thesis, we adopt the definition provided by Hassini et al. (2012):

> "*Sustainable supply chain management (SSCM) is the management of supply chain operations, resources, information, and funds in order to maximize the supply chain profitability while at the same time minimizing the environmental impacts and maximizing the social well-being.*"

Hassini et al. (2012) also define business sustainability (BS) as "*the ability to conduct business with a long term goal of maintaining the well-being of the economy, environment, and society.*" Recently, corporate social responsibility (CSR) and BS have been used interchangeably in the literature, while CSR was viewed earlier as an economic-social framework (Dahlsrud 2008). It is also worthwhile to point out that other terms that are closely related to SSCM are reverse logistics (RL), closed-loop supply chain (CLSC), and green supply chain management (GSCM). RL and CLSC are mainly concerned with the management of backward flows (i.e., returning, remanufacturing, and recycling) of a supply chain, whereas GSCM focuses on economic and environmental aspects of sustainability in SCM. See Guide and Wassenhove (2006) and Ahi and Searcy (2013) for more details on these topics. We note that our perspective of SSCM encompasses that of GSCM which in turn encompasses the concepts of RL and CLSC.

1.2 Classification of SSCM Literature

We reviewed the literature from the influential journals in the operations research (OR) field to identify the major topics that has been studied in the area of SSCM. Drawing on the findings by Olson (2005), Xu et al. (2011), and Fry and Donohue (2013), a list of 14 journals (including four Financial Times Top 45 journals) was obtained, as shown in Table 1.1. We employed a selection of keywords "Sustainable", "Sustainability", "Green", "Environmental" or "Social" in the Abstract field of the journals to search publications from 2000 to 2014. Due to the large number of issues and articles, the last three journals in Table 1.1 were explored in a more limited period from 2008 to 2014.

Table 1.1: Investigated journals to find recent SSCM research in the OR field

Journal Name	**ID**	**Publisher**	**Period**
Operations Research	OR	INFORMS	2000-2014
Management Science	MS	INFORMS	2000-2014
Journal of Operations Management	JOM	ELSEVIER	2000-2014
Production and Operations Management	POM	WILEY	2000-2014
Manufacturing & Service Operations Management	MSOM	INFORMS	2000-2014
Transportation Science	TS	INFORMS	2000-2014
IIE Transactions	IIE	TAYLOR	2000-2014
Decision Sciences	DS	WILEY	2000-2014
Annals of Operations Research	AOR	SPRINGER	2000-2014
Naval Research Logistics	NRL	WILEY	2000-2014
Operations Research Letters	ORL	ELSEVIER	2000-2014
European Journal of Operational Research	EJOR	ELSEVIER	2008-2014
International Journal of Production Economics	IJPE	ELSEVIER	2008-2014
Omega	OMEGA	ELSEVIER	2008-2014

After carefully examining the results of the initial search and removing references that did not explicitly investigate supply chain applications, we ended up with a shorter list of publications. Within this refinement, we restricted our attention by excluding work that investigated sustainability development descriptively, marketing and human resource questions, strategic importance of SSCM, green technology innovation and product design, waste and disposal management, as well as forest management. On the basis of the aforementioned review, we classify the existing SSCM literature into eight broad categories which are discussed in Sections 1.2.1-1.2.8.

1.2.1 Literature Reviews on SSCM

Several studies have focused on providing a literature review together with a conceptual framework for SSCM problems and practices. A number of studies have reviewed the general literature on SSCM, while others have focused on some special topics. Examples of general reviews are Kleindorfer et al. (2005), Linton et al. (2007), Tang and Zhou (2012), and Brandenburg et al. (2014). Plambeck (2013) focuses on OR challenges faced by cleantech companies. Hassini et al. (2012) survey the SSCM literature from 2000 to 2010 and propose a framework for sustainability metrics. Finally, Galindo and Batta (2013) review the related research in disaster management.

1.2.2 Performance Measurement in SSCM

The literature on evaluating and benchmarking SSCM practices has grown rapidly over the last years. Chen and Delmas (2011), Chen and Delmas (2012), Chen et al. (2012), and Ødegaard and Roos (2014) propose some quantitative assessment approaches. Further discussion of the pertinent studies can be found in Chapter 2. In Chapters 3 and 4 we present two models that measure sustainability performance in supply chains. Correspondingly, we consider an efficiency score in Chapter 4 and use it in Chapter 5 to develop a game-theoretic emissions trading system.

1.2.3 Upstream Regulatory Schemes in SSCM

The problem of environmental pollution occurs when emissions from facilities result in ambient concentrations that are sufficiently high to cause damage to property, ecosystems, human health, and/or aesthetics. Production units may discharge pollutants irresponsibly when there is neither any attached cost to such behavior nor any incentive for reducing such emissions. In recent years, a variety of policy instruments have been introduced in order to curb pollution. Emissions trading (also known as cap-and-trade) systems have been widely accepted as policy instruments in North American and European countries and states (Nagurney and Dhanda 2000, Li and Gu 2012, Gong and Zhou 2013). This market-based mechanism has as its main purpose the control of a pollutant through the allocation of permits (or allowances) to polluting units. Each permit represents the amount of the pollutant that an entity may emit. No unit is allowed to operate unless it has sufficient permits to cover the pollutants it discharges or else it is subjected to heavy fines. Alternative emissions control mechanisms are environmental taxes, subsidies, or consumer rebates (Sheu and Chen 2012, Caro et al. 2013, Huang et al. 2013, Krass et al. 2013, Zhao et al. 2013). Apart from the similarities and differences of these two approaches, we observe that a few of these studies have focused on game-theoretic settings to provide insight into the potential surplus social welfare. More details of such practices will be spelled out in Chapter 5, where we propose a Cournot oligopoly game to study an emissions trading system.

1.2.4 Carbon-constrained Inventory in SSCM

In pursuing emissions reduction efforts, many businesses have focused on the physical processes involved. They, however, may neglect a significant source of emissions that can be lessened through momentous lot sizing decision makings. Several generalizations of the economic order quantity (EOQ) model have been developed to take into account carbon emissions (Bouchery et al. 2012, Absi et al. 2013, Chen et al. 2013, Battini et al. 2014, Konur 2014, Nouira et al. 2014).

1.2.5 CLSC within SSCM

As stated earlier, CLSC combines forward and backward supply chain flows into a single system in order to improve economic and environmental performance. In our review we found numerous studies took into consideration take-back compliance schemes, recycling procedures, remanufacturing practices, repairing operations, and green disposing options (Savaskan and Wassenhove 2006, Guide and Wassenhove 2006a, Guide and Wassenhove 2006b, Eskandarpour et al. 2013, Esenduran and Kemahlıoğlu-Ziya 2014, Faccio et al. 2014, Giovanni and Zaccour 2014, Ramos et al. 2014, Soleimani and Govindan 2014, Toso and Alem 2014, Toyasaki et al. 2014).

1.2.6 Transportation and Facility Location in SSCM

Until recently, the literature of transportation and logistics has mainly focused on cost minimization. However, with an increasing worldwide concern for the environment, logistics providers have started paying more attention to the negative externalities (i.e., pollution, accidents, noise, resource consumption, land use deterioration, and climate change risk) of their operations. Sbihi and Eglese (2010), Chen et al. (2014), and Demir et al. (2014) include reviews on how to incorporate sustainability in transportation and facility location models.

1.2.7 Humanitarian Logistics in SSCM

The literature of humanitarian logistics (HL) looks at the economic and social implications as there is ample evidence that negative impacts of natural disasters are increasing (Holguín-Veras et al. 2012). Major disasters and catastrophic events such as 2004 Indian Ocean Tsunami, 2005 Hurricane Katrina, and 2010 Haitian Earthquake illustrate how HL problems can be challenging in response to extreme events (Holguín-Veras et al. 2013). The term HL encompasses a wide range of operations including the distribution of medical supplies for routine disease prevention, food supplies to fight hunger, and critical supplies in the aftermath of a disaster. While these disasters share humanitarian goals, they are different on account of the level of urgency of the operations, the state of the social networks that orchestrate the effort, the state of the supporting systems, and the dynamic nature of the needs, among others (Sodhi and Tang 2013, Bhattacharya et al. 2014, Chakravarty 2014).

1.2.8 Green Supplier Selection in SSCM

As the green movement spreads across the globe, organizations are under pressure to reduce the emissions across their supply chain. Accordingly, companies and their decision makers must consider environmental issues in all of their administrative activities. One of the most important and difficult decisions in supplier selection is consequently the commitment to environmental causes, while at the same time cutting costs. Thus, supplier selection models need to take into account the environmental impact of the suppliers (Kannan et al. 2014, Kumar et al. 2014).

1.3 Thesis Organization

The reminder of the thesis is organized as follows.

In Chapter 2 we present a review of performance measurement of sustainable supply chains, including 140 journal and conference articles, books, graduate research theses, and official reports that were published since 1994. In addition to proposing a framework to assess sustainability in supply chains, we discuss numerous research questions and future challenges with a focus on the social aspect of sustainability development. The results of this review are accepted for publication in the *International Journal of Productivity and Performance Management* as an article entitled "Performance Measurement of Sustainable Supply Chains: A Review and Research Questions".

In Chapter 3 we develop a two-stage data envelopment analysis (DEA) model with an application to the energy sector. DEA is an analytical formulation to measure relative efficiencies of a number of comparable decision making units. In spite of the fact that this technique does not require predetermined weights of indicators, it is useful in identifying the sources and amounts of inefficiency among decision units. We relax some restricting assumptions used in previous DEA studies and obtain a nonlinear optimization problem, for which we develop an efficient solution method. To illustrate the practicability of the proposed framework, we apply it to the U.S. fossil-based electricity generation industry. As a starting point, the data was collected from the U.S. Environmental Protection Agency and Energy Information Administration resources. Although some prior studies have examined slightly similar instances, none of them has looked at the impact of these facilities on the society and people. We show that the existing DEA models can lead to suboptimal solutions. The results of this chapter are in the third round of review in the *European Journal of Operational Research*, as an article entitled "Two-Stage Data Envelopment Analysis with Heterogeneous Intermediate Values".

In Chapter 4 we investigate a general multi-stage multi-partner assessment framework that monitors all suppliers, manufacturers, distributers, and retailers' sustainable practices. The results of applying the proposed algorithm to measure sustainability efficiency in a centralized setting were published in the *Journal of Cleaner Production*, a leading peer-reviewed journal in the sustainability field, as an article entitled "A Data Envelopment Analysis Approach to Evaluate Sustainability in Supply Chain Networks".

In Chapter 5 we investigate market-based schemes and propose some future research directions on how to implement these mechanisms in the SSCM context. We develop a game-theoretic formulation by which we try to characterize the sustainable operations of a set of competitive supply chains, facing an uncertain demand for multiple products. In this chapter, market-based environmental schemes are reviewed and a game-theoretic formulation is developed by which sustainable operations of a set of competitive supply chains are characterized. In addition, the production operations lead to environmental pollution that needs to be under control subject to governmental quality standards. More especially, necessary and sufficient conditions are provided under which an efficient algorithm converges to the non-cooperative Cournot game's unique equilibrium. The results of this chapter are being prepared for submission to the *Manufacturing & Service Operations Management* journal.

Finally, Chapter 6 summarizes our results in this thesis and identifies a direction for future research.

Chapter 2

Sustainability Performance Measurement in Supply Chains

One of the hurdles to the adoption of sustainable practices across supply chains is the lack of pan-chain performance measurements and their related information and organizational structures. In this chapter, we review the literature on performance measurement of sustainable supply chains, including 140 journal articles, cases, and reports that have appeared since 1994, with a focus on comprehensive measures that include multi-partner supply chains as well as different sustainability aspects. We classify the reviewed literature according to seven sustainability dimensions (economical, environmental, social, reputable, valuable, equitable, and sustainable) as well as the type of industry and methodology used. In addition we synthesize the available performance measurements into a comprehensive framework that incorporates different stages of supply chain operations and decision making processes.

2.1 Introduction

Supply chain managers need performance measurement systems to improve the efficiency and effectiveness of their operations (Shepherd and Günter 2006, Simchi-Levi et al. 2007). In the last ten years there is an increasing interest from both academics and practitioners in incorporating sustainability practices in supply chain operations and models (Hassini et al. 2012). Sustainability is increasingly becoming a strategic business initiative as both large and small companies are realizing that sustainable practices can be economical and may create new revenue streams as well as increase customer and employee satisfaction (Mincer 2008). With this comes the need to develop key performance indicators to measure the progress of implementing these sustainability practices. As argued in Hassini et al. (2012), current supply chain performance measurement systems are not geared towards the complexities that are involved when measuring performance across supply chain interfaces. This is further complicated by the fact that different parties within the supply chain may have different, and often conflicting, views of sustainability (Salzmann et al. 2005), and that companies, such as Walmart, are enlarging their sustainability scope to all their supply chain partners all over the world (Allen et al. 2012).

With these trends it is important to understand the different aspects of sustainability and how these can be measured within the different areas of supply chain operations. That is the focus of our study. We look at existing performance measurement systems for sustainability in supply chains and propose a framework for integrating the different aspects of sustainability and supply chain operations. The rest of Chapter 2 is organized as follows. In Section 2.2, we discuss relevant terminology and related reviews. We describe our review methodology in Section 2.3. In Section 2.4, a summary of review results as well as the classification of performance measures are provided. A synthesis of performance measures by supply chain stage, type of sustainability measure, and type of operations decisions is provided Section 2.5. Finally, in Section 2.6, we propose some research questions and our conclusions.

2.2 Background

There have been different attempts at defining supply chain sustainability and in this section we report on some of them and clarify the perspective that we take in this chapter. In addition, we extend the triple bottom line concept by characterizing sustainability using seven dimensions. This characterization will be used in our performance framework. Finally, we outline our review methodology and the sources of studies that we reviewed.

2.2.1 Supply Chains and Sustainability

There have been many definitions for a supply chain (Cooper et al. 1997, Mentzer et al. 2001, Larson and Halldórsson 2004). We choose to use a customer-focused definition given by Chopra and Meindl (2013): “A supply chain is all parties and related processes that are involved in satisfying a customer order”. Using this definition we can trace the different activities that are related to a customer order. In addition, this definition links supply chain processes, including those related to sustainability, to the customer value proposition.

As in Hassini et al. (2012), and using Elkington (1997) triple bottom line (TBL) principles, we define “business sustainability” as “the ability to conduct business with a long term goal of maintaining the well-being of the economy, environment, and society”. Both practitioners and academics do not always use all three sustainability pillars, but often only a single dimension or a combination of two aspects. Zhang (2011) introduced three additional dimensions to account for these combinations:

- *valuable*, when only economic and environmental aspects are considered.
- *reputable*, when only economic and social aspects are considered.
- *equitable*, when only environmental and social aspects are considered.

We use the sustainable dimension to represent the situation where all the TBL aspects are included. Figure 2.1 illustrates all the seven sustainability dimensions under discussion. The original three pillars defined by Elkington (1997) are included in the circles. The three additional dimensions introduced by Zhang (2011) are represented in the circular arcs. Situations that incorporate all three pillars are represented in the inner triangle.

Another term that is closely related to sustainable supply chains is green supply chain management that focuses on economic and environmental aspects of sustainability in supply chains. As a matter of fact, our perspective of sustainable supply chains (which covers the social pillar as well) encompasses that of green supply chains. To acquire a more extensive understanding of these diversely defined concepts, the reader is referred to Ahi and Searcy (2013) where they review several definitions for sustainable supply chains based on a literature review of 180 articles.

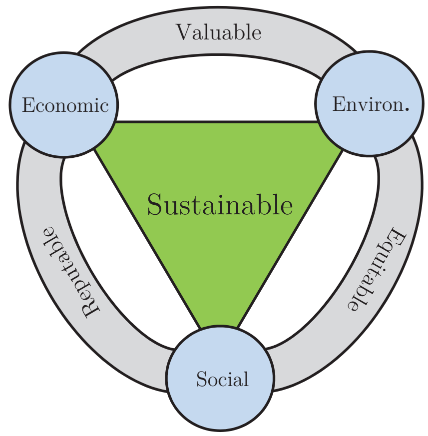


Figure 2.1: Seven sustainability dimensions based on Elkington's triple pillars

2.2.2 Performance Measurement

Performance measurement is the quantification of how a task is done efficiently and effectively (Neely et al. 1995). Efficiency is concerned with the economical use of resources and effectiveness with how well objectives are being met (Taylor 2004). These definitions have their limitations, such as their inflexibility to deal with dynamic and multi-company complex environments, as is the case with supply chains (Hassini et al. 2012). Saisana and Tarantola (2002) define indicator or measure as a piece of information that summarizes or highlights what is happening in a dynamic system. A systematic combination of a set of indicators, that have no common meaningful unit of measurement and there is no obvious way of weighting them, is called an index or a composite indicator (CI). The structure translating and analyzing raw data to transform it into a well-defined CI constructs a metric.

2.2.3 Related Reviews

There have been several recent reviews of sustainable supply chain management (SSCM). Hassini et al. (2012) reviewed 87 papers in the decision sciences field that have been published since 1999. They offered a framework for performance measurement of sustainability in supply chains as well as a practical case study in the energy sector. Seuring and Müller (2008) reviewed 191 papers published from 1994 to 2007. They classified the literature into six categories: sustainable, environmental, ecological, green, social, and ethical. Other recent surveys include Srivastava (2007), Fortes (2009), and Sarkis et al. (2011). Over the course of the last decade, there have also been several surveys on performance measures in supply chains that focus mostly on financial and economic metrics (Neely et al. 1995, Shepherd and Günter 2006, Gunasekaran and Kobu 2007, Akyuz and Erkan 2010, Nudurupati et al. 2011).

The importance of sustainability assessment has not been restricted to academia, and many studies performed by international organizations and unions have examined the aforementioned triple pillars. Although a detailed review of these frameworks, guidelines, and official reports is not in the scope of this study, we briefly report on some of them. The most cited cases are as follows (in a chronological order): Hammond and World Resources Institute (1995), Lisa (2002), Esty et al. (2005), United Nations (2007), Global Reporting Initiative (2011), United Nations (2012a), United Nations (2012b), United Nations (2012c), and Schwab and Sala-i-Martin (2012). Additionally, ISO 14000 and BS 8900 are the two most relevant standards that are developed by the International Organization for Standardization and the British Standards Institution, respectively.

2.3 Review Methodology

To the best of our knowledge there are no comprehensive literature reviews covering and comparing evaluation frameworks of all the seven dimensions of sustainability we listed above. Our objective is to review the literature on performance measurement and sustainability of supply chains for the last two decades, categorize it from various perspectives, present the best practices of each category, and propose some research questions to extend the research in this field. Using the performance measurement framework proposed in Hassini et al. (2012), reproduced in Figure 2.2, our goal is to review measures that span all supply chain stages and the seven sustainability dimensions illustrated in Figure 2.1.

We used Google Scholar in our literature review due to its wide coverage in the fields of social sciences and humanities (Harzing 2013). It is worth mentioning that the body of knowledge for this review has been studied in various academic disciplines, and consequently, a vast set of technical terms have been introduced in the literature. Therefore, we employed a large selection of keywords "Sustainable, Sustainability, Green, Environmental, or Social", and "Supply Chain, Business, Organization, Country, or Government", and "Evaluation, Assessment, Indicator, Index, Metric, Performance, Measure, Framework, or Model". Then, we focused our search only on literature that was published after 1994. This initial search led to more than 350 journal and conference articles, books or book chapters, graduate research theses, and official reports in different subjects and areas. After carefully examining the results of the search and refining it, removing references that did not investigate either a supply chain application or a definite set of metrics to evaluate sustainable performance and exploring the remaining papers and the papers that cited them, we ended up with 140 references.

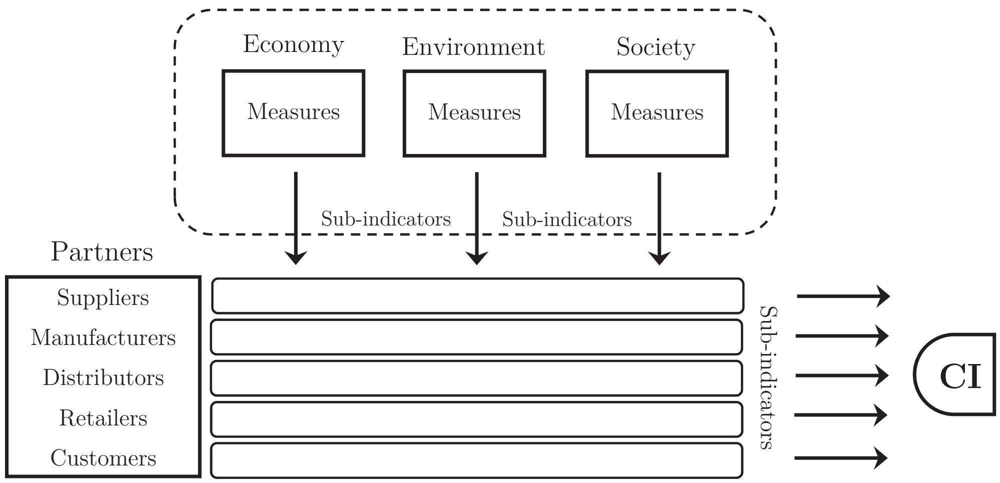


Figure 2.2: Scope of this literature review (adopted from Hassini et al. 2012)

Figures 2.3 and 2.4 show the distribution of reviewed materials by source and publication year, respectively. For visualization practicality, we had to integrate some publications into one category in Figure 2.3. Thus 31 journals that had only one article were integrated into the "Journals with One Paper" category. In addition, all conference papers have been put into the category "Conference Papers." Figure 2.4 shows an increasing number of publications in the area of interest over the last decade. The low number corresponding to the year 2013 is not unexpected since the review only covers the first three months of this year.

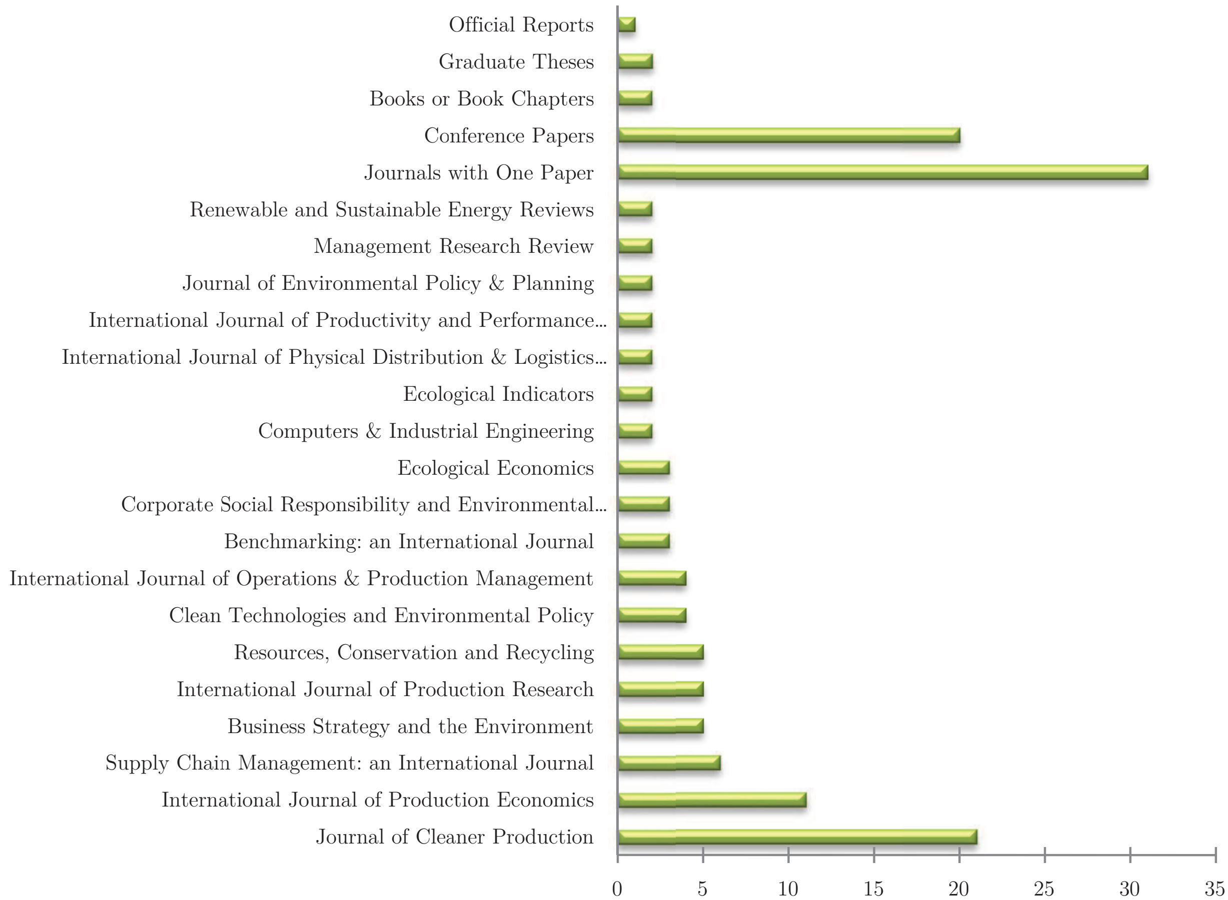


Figure 2.3: Distribution of reviewed materials by source

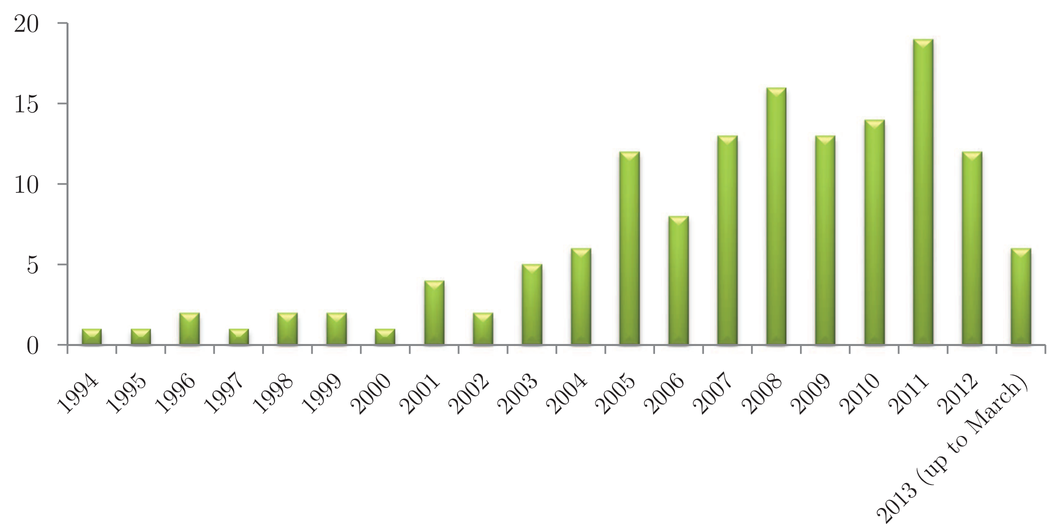


Figure 2.4: Distribution of reviewed materials by publication year

2.4 Findings

2.4.1 Distribution of Reviewed Studies by Sustainability Dimension

As presented in Figure 2.1, the sustainable frameworks could be classified into seven dimensions: economic, environmental, social, valuable, reputable, equitable, and sustainable. Having extracted all indicators from each reference and determined its related sustainability pillar, we allocated each reference to one of the foregoing seven dimensions. Table 2.1 and Figure 2.5 show the distribution of the reviewed studies according to which sustainability dimension they cover. Table 2.1 lists all references for each sustainability perspective, and Figure 2.5 presents the number of the reviewed sources of each sustainability dimension in an ascending order. We note that the valuable and sustainable measures received the most attention in the reviewed literature. Knowing that valuable includes both economic and environmental, we can conclude that the social dimension is the least employed one. Our conversations with supply chain practitioners also confirm this observation.

Table 2.1: Distribution of reviewed studies by sustainability dimension

Dimension	**References**	**No.**
Economic	Akyuz and Erkan (2010), Beamon (1999b), Beamon (1998), Bhagwat and Sharma (2007), Chae (2009), Chan (2003), Fynes et al. (2005), Gunasekaran and Kobu (2007), Gunasekaran et al. (2004), Gunasekaran et al. (2001), Hausman (2004), Kleijnen and Smits (2003), Neely et al. (1995), Nudurupati et al. (2011), Sarkis and Talluri (2002), Sarkis and Talluri (2004), Shepherd and Günter (2006)	**17**
Environmental	Baresel-Bofinger et al. (2007), Gomez and Rodriguez (2011), Hervani et al. (2005), Hickey (2008), Hooper and Greenall (2005), Patlitzianas et al. (2008), Sarkis (2006), Shen et al. (2013), Tsoulfas and Pappis (2008), Vachon (2007), Zhu et al. (2011)	**11**
Social	Hutchins et al. (2009), Hutchins and Sutherland (2008), Labuschagne and Brent (2006), Norman and MacDonald (2004), Welford and Frost (2006)	**5**

Table 2.1: Distribution of reviewed studies by sustainability dimension

Dimension	**References**	**No.**
Valuable	Amoako-Gyampah and Acquaah (2008), Azevedo et al. (2013), Bai et al. (2012), Balon et al. (2012), Beamon (1999a), Björklund et al. (2012), Cao and Chen (2007), Chen et al. (2009), Clemens (2006), Clift (2003), Darnall et al. (2008), Diabat and Govindan (2011), Felice et al. (2012), Gao et al. (2009), Jalali Naini et al. (2011), Jasch (2000), Jiansheng and Wei (2010), Kang and Juanmei (2010), Kehbila et al. (2010), Kim and Min (2011), Klassen and McLaughlin (1996), Lee et al. (2009), Lin (2013), McIntyre (1998), Molina-Azorín et al. (2009), Munda et al. (1994), Orti et al. (2010), Paulraj and Chen (2007), Perrini and Tencati (2006), Qingmin and Lipeng (2009), Rehman and Shrivastava (2011), Russo and Fouts (1997), Saadany et al. (2011), SCL (2009), Searcy et al. (2009), Shaw et al. (2010), Shuwang et al. (2005), Smeets et al. (2009), Tseng (2011), Tseng and Chiu (2013), Tseng et al. (2013), Vachon and Klassen (2008), Vachon and Klassen (2007), Wang (2012), Xue (2010), Yan and Xia (2011), Zhu and Sarkis (2004), Zhu et al. (2005), Zhu et al. (2008), Zhu et al. (2007)	**50**
Reputable	Adivar et al. (2010)	**1**
Equitable	Beske et al. (2008), Holt and Ghobadian (2009), Toke (2012), Vachon and Mao (2008)	**4**
Sustainable	Abeysundra et al. (2007), Azapagic (2004), Bai and Sarkis (2010a), Bai and Sarkis (2010b), Bos-Brouwers (2010), Brito et al. (2008), Burgess and Heap (2012), Carter and Easton (2011), Carter and Rogers (2008), Carvalho (2011), Cetinkaya et al. (2011), Cobb (2011), Dehghanian et al. (2011), Erol et al. (2011), Facanha and Horvath (2005), Farrell (1996), Gates and Germain (2010), Govindan et al. (2013), Hassini et al. (2012), Holton et al. (2010), Huang and Keskar (2007), Hussey et al. (2002), Jain (2005), Klang et al. (2003), Krajnc and Glavič (2005a), Krajnc and Glavič (2005b), Krajnc and Glavič (2003), Labuschagne et al. (2005), Mayer (2008), Mayyas et al. (2013), McKay (2006), Metta and Badurdeen (2009), Nikolaou et al. (2013), Petrie et al. (2007), Piplani et al. (2008), Rogers and Ryan (2001), Samuel et al. (2013), Searcy et al. (2005), Searcy et al. (2008), Searcy et al. (2007), Shuaib et al. (2011), Svensson (2007), Tseng (2013), Vasileiou and Morris (2006), Veleva and Ellenbecker (2001), Veleva et al. (2001), Wolfslehner and Vacik (2008), Yakovleva (2007), Yakovleva and Flynn (2004), Yao and Zhang (2011), Yusuf et al. (2013), Zhang (2011)	**52**

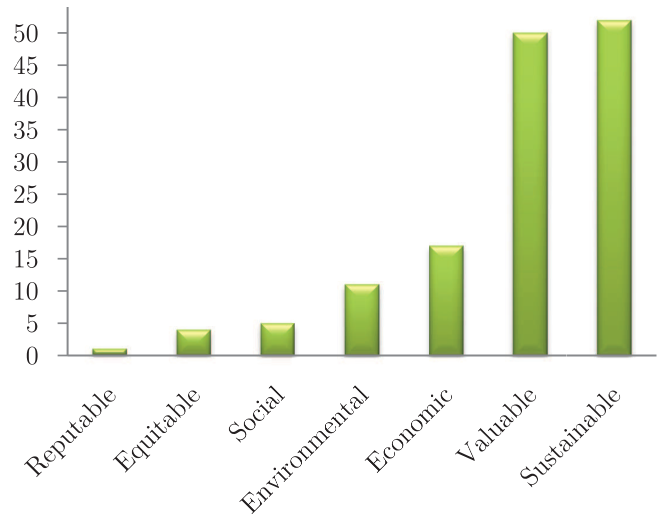


Figure 2.5: Distribution of reviewed studies by sustainability dimension

2.4.2 Classification of Studies by Sector and Research Methodologies

In Table 2.2 we classify the 140 reviewed references according to their sector. We note that some references were allocated to more than one sector. References that do not focus on any particular sector are classified under the general category.

Except for the general category, the majority of studies are related to the manufacturing sectors that include apparel, automotive, electronics, energy, fashion, materials and chemical/metals processing. One possible explanation for this is that these sectors are more regulated than non-manufacturing sectors by governments and such regulations drive companies to devise performance measures. For example, in the automotive sector the European Union (EU) End-of-Life Vehicle Directive stipulates that 95% of domestic auto parts should be reusable or recyclable by 2015. Similarly, in the electronics sector the EU has enacted, in 2006, directives that limit the use of hazardous materials, such as lead, and forced manufacturers to develop systems for recovering the associated electronic waste.

We note that to a large extent the sustainability measures that are associated with the economic and social pillars are not industry-specific. On the other hand environmental measures are often industry-specific. For example, in the automotive industry an important measure is recovery and recyclability of the used parts, but for the oil industry, such as the Oil Sands in Canada, protection of the surrounding ecology is more important. In addition, the healthcare and pharmaceuticals sector, increasingly viewed as a strategic business for governments (Dobrzykowski et al. 2012), needs further investigation.

Table 2.2: Distribution of reviewed studies by industry and application areas

Sector/Application	References	No.
Agriculture, Horticulture, and Wine	Smeets et al. (2009), Vasileiou and Morris (2006), Yakovleva (2007), Yakovleva and Flynn (2004), Zhu et al. (2011)	**5**
Automotive, Shipyard, Transportation, and Logistics	Azevedo et al. (2013), Balon et al. (2012), Beske et al. (2008), Bhagwat and Sharma (2007), Facanha and Horvath (2005), Hooper and Greenall (2005), Jalali Naini et al. (2011), Kehbila et al. (2010), Mayyas et al. (2013), Zhu et al. (2011), Zhu and Sarkis (2004), Zhu et al. (2005), Zhu et al. (2008), Zhu et al. (2007)	**14**
Education and Training	Klang et al. (2003)	**1**
Energy, Electrical, and Electronics	Carvalho (2011), Chan (2003), Facanha and Horvath (2005), Farrell (1996), Felice et al. (2012), Hassini et al. (2012), Krajnc and Glavič (2005b), Lee et al. (2009), McKay (2006), Patlitzianas et al. (2008), Searcy et al. (2009), Searcy et al. (2005), Searcy et al. (2008), Searcy et al. (2007), Welford and Frost (2006), Yusuf et al. (2013), Zhu et al. (2011), Zhu et al. (2005), Zhu et al. (2008), Zhu et al. (2007)	**20**
Ecology Management	Hickey (2008), McIntyre (1998), McKay (2006), Vachon and Mao (2008), Wolfslehner and Vacik (2008)	**5**
Fashion, Apparel, Food, and Grocery	Adivar et al. (2010), Amoako-Gyampah and Acquaah (2008), Brito et al. (2008), Cobb (2011), Dehghanian et al. (2011), Krajnc and Glavič (2005a), Welford and Frost (2006), Yakovleva (2007), Yakovleva and Flynn (2004), Zhu et al. (2011), Zhu et al. (2005), Zhu et al. (2008)	**12**
Government and NGO	Burgess and Heap (2012)	**1**
Healthcare and Pharmaceuticals	Krajnc and Glavič (2005a), Zhu and Sarkis (2004), Zhu et al. (2005)	**3**
Hospitality, Catering, and Local Tourism	Molina-Azorín et al. (2009)	**1**
Housing, Rentals, Real Estate, and Construction	Abeysundra et al. (2007), Amoako-Gyampah and Acquaah (2008), Holton et al. (2010), Wang (2012), Zhu et al. (2011)	**5**
Information and Communications Technology	Akyuz and Erkan (2010)	**1**
Materials and Chemicals	Amoako-Gyampah and Acquaah (2008), Bos-Brouwers (2010), Brito et al. (2008), Dehghanian et al. (2011), Facanha and Horvath (2005), Krajnc and Glavič (2005a), Krajnc and Glavič (2005b), Labuschagne and Brent (2006), Samuel et al. (2013), Zhu et al. (2011), Zhu and Sarkis (2004), Zhu et al. (2005), Zhu et al. (2008)	**13**

Table 2.2: Distribution of reviewed studies by industry and application areas

Sector/Application	References	No.
Metal and Mining	Adivar et al. (2010), Amoako-Gyampah and Acquaah (2008), Azapagic (2004), Bhagwat and Sharma (2007), Clemens (2006), Diabat and Govindan (2011), Facanha and Horvath (2005), Petrie et al. (2007), Sarkis (2006), Zhu et al. (2005), Zhu et al. (2008)	**11**
Package Printing	Vachon (2007), Vachon and Klassen (2008)	**2**
Small Firms	Bhagwat and Sharma (2007), Bos-Brouwers (2010), Clemens (2006), Sarkis (2006)	**4**
General	Bai and Sarkis (2010a), Bai and Sarkis (2010b), Bai et al. (2012), Baresel-Bofinger et al. (2007), Beamon (1999a), Beamon (1999b), Beamon (1998), Björklund et al. (2012), Cao and Chen (2007), Carter and Easton (2011), Carter and Rogers (2008), Cetinkaya et al. (2011), Chae (2009), Chen et al. (2009), Clift (2003), Cobb (2011), Darnall et al. (2008), Erol et al. (2011), Fynes et al. (2005), Gao et al. (2009), Gates and Germain (2010), Gomez and Rodriguez (2011), Govindan et al. (2013), Gunasekaran and Kobu (2007), Gunasekaran et al. (2004), Gunasekaran et al. (2001), Hassini et al. (2012), Hausman (2004), Hervani et al. (2005), Holt and Ghobadian (2009), Huang and Keskar (2007), Hussey et al. (2002), Hutchins et al. (2009), Hutchins and Sutherland (2008), Jain (2005), Jasch (2000), Jiansheng and Wei (2010), Kang and Juanmei (2010), Kim and Min (2011), Klassen and McLaughlin (1996), Kleijnen and Smits (2003), Krajnc and Glavič (2003), Labuschagne et al. (2005), Lin (2013), Mayer (2008), Metta and Badurdeen (2009), Munda et al. (1994), Neely et al. (1995), Nikolaou et al. (2013), Norman and MacDonald (2004), Nudurupati et al. (2011), Orti et al. (2010), Paulraj and Chen (2007), Perrini and Tencati (2006), Piplani et al. (2008), Qingmin and Lipeng (2009), Rehman and Shrivastava (2011), Rogers and Ryan (2001), Russo and Fouts (1997), Saadany et al. (2011), Sarkis and Talluri (2002), Sarkis and Talluri (2004), SCL (2009), Shaw et al. (2010), Shen et al. (2013), Shepherd and Günter (2006), Shuaib et al. (2011), Shuwang et al. (2005), Svensson (2007), Toke (2012), Tseng (2011), Tseng (2013), Tseng and Chiu (2013), Tseng et al. (2013), Tsoulfas and Pappis (2008), Vachon and Klassen (2007), Veleva and Ellenbecker (2001), Veleva et al. (2001), Xue (2010), Yan and Xia (2011), Yao and Zhang (2011), Zhang (2011)	**82**

In Table 2.3 we classify papers by their research methodology. We observe that the majority of studies are exploratory (such as reviews) and qualitative (such as case studies) in nature. The analytical and computational category includes the studies which deal with more quantitative approaches, such as mathematical programming and game theory. On the other hand, the empirical and case study class involves statistical reports, hypotheses testing and questionnaires, and adopts aggregation methods.

Table 2.3: Distribution of reviewed studies by research methodology

Methodology	References	No.
Analytical and Computational	Bai and Sarkis (2010a), Bai and Sarkis (2010b), Bai et al. (2012), Cao and Chen (2007), Chan (2003), Chen et al. (2009), Dehghanian et al. (2011), Erol et al. (2011), Farrell (1996), Felice et al. (2012), Gao et al. (2009), Govindan et al. (2013), Jalali Naini et al. (2011), Jiansheng and Wei (2010), Kang and Juanmei (2010), Krajnc and Glavič (2005a), Lee et al. (2009), Lin (2013), Metta and Badurdeen (2009), Munda et al. (1994), Qingmin and Lipeng (2009), Sarkis (2006), Sarkis and Talluri (2004), Shen et al. (2013), Shuwang et al. (2005), Toke (2012), Tseng (2011), Tseng (2013), Tseng and Chiu (2013), Tseng et al. (2013), Wang (2012)	**31**
Empirical and Case Study	Adivar et al. (2010), Amoako-Gyampah and Acquaah (2008), Azapagic (2004), Azevedo et al. (2013), Baresel-Bofinger et al. (2007), Bhagwat and Sharma (2007), Bos-Brouwers (2010), Brito et al. (2008), Burgess and Heap (2012), Carvalho (2011), Clemens (2006), Cobb (2011), Darnall et al. (2008), Facanha and Horvath (2005), Fynes et al. (2005), Gates and Germain (2010), Gomez and Rodriguez (2011), Gunasekaran et al. (2004), Hervani et al. (2005), Holt and Ghobadian (2009), Holton et al. (2010), Hooper and Greenall (2005), Hutchins and Sutherland (2008), Kehbila et al. (2010), Kim and Min (2011), Klang et al. (2003), Klassen and McLaughlin (1996), Krajnc and Glavič (2005b), Labuschagne and Brent (2006), Labuschagne et al. (2005), Mayyas et al. (2013), McIntyre (1998), Molina-Azorín et al. (2009), Nikolaou et al. (2013), Patlitzianas et al. (2008), Paulraj and Chen (2007), Perrini and Tencati (2006), Rehman and Shrivastava (2011), Rogers and Ryan (2001), Russo and Fouts (1997), Saadany et al. (2011), Samuel et al. (2013), Searcy et al. (2008), Searcy et al. (2007), Smeets et al. (2009), Tsoulfas and Pappis (2008), Vachon (2007), Vachon and Klassen (2008), Vachon and Klassen (2007), Vachon and Mao (2008), Vasileiou and Morris (2006), Veleva and Ellenbecker (2001), Veleva et al. (2001), Welford and Frost (2006), Wolfslehner and Vacik (2008), Xue (2010), Yakovleva (2007), Yakovleva and Flynn (2004), Yan and Xia (2011), Yusuf et al. (2013), Zhu et al. (2011), Zhu and Sarkis (2004), Zhu et al. (2005), Zhu et al. (2008), Zhu et al. (2007)	**65**
Review	Abeysundra et al. (2007), Akyuz and Erkan (2010), Balon et al. (2012), Beamon (1999a), Beamon (1999b), Beamon (1998), Beske et al. (2008), Björklund et al. (2012), Carter and Easton (2011), Carter and Rogers (2008), Cetinkaya et al. (2011), Chae (2009), Clift (2003), Diabat and Govindan (2011), Gunasekaran and Kobu (2007), Gunasekaran et al. (2001), Hassini et al. (2012), Hausman (2004), Hickey (2008), Huang and Keskar (2007), Hussey et al. (2002), Hutchins et al. (2009), Jain (2005), Jasch (2000), Kleijnen and Smits (2003), Krajnc and Glavič (2003), Mayer (2008), McKay (2006), Neely et al. (1995), Norman and MacDonald (2004), Nudurupati et al. (2011), Orti et al. (2010), Petrie et al. (2007), Piplani et al. (2008), Sarkis and Talluri (2002), SCL (2009), Searcy et al. (2009), Searcy et al. (2005), Shaw et al. (2010), Shepherd and Günter (2006), Shuaib et al. (2011), Svensson (2007), Yao and Zhang (2011), Zhang (2011)	**44**

Finally, in Table 2.4 we show the different methodologies and standards used in the studies. We note the use of methodologies that can handle multi-criterion and conflicting objectives the goal of which is to develop measures for use by multiple decision makers that may have conflicting goals. In addition, we note the use of ISO 14000 standards which are geared more towards individual companies. Hervani et al. (2005) suggest using ISO 14031 as they can apply it to the design and use of environmental performance indicators by all organizations, regardless of type, size, location, and complexity.

Table 2.4: Distribution of reviewed studies by methodologies and standards

Category	References	No.
Methodologies		
Multi-Objective and Goal Programming	Munda et al. (1994), Sarkis and Talluri (2004)	**2**
Fuzzy Approach	Cao and Chen (2007), Erol et al. (2011), Govindan et al. (2013), Jiansheng and Wei (2010), Kang and Juanmei (2010), Lee et al. (2009), Lin (2013), Munda et al. (1994), Shen et al. (2013), Shuwang et al. (2005), Tseng (2011), Tseng (2013), Tseng and Chiu (2013), Tseng et al. (2013), Wang (2012)	**15**
Game Theory	Jalali Naini et al. (2011)	**1**
Statistical Analysis	Amoako-Gyampah and Acquaah (2008), Burgess and Heap (2012), Clemens (2006), Darnall et al. (2008), Fynes et al. (2005), Gomez and Rodriguez (2011), Holt and Ghobadian (2009), Klassen and McLaughlin (1996), Molina-Azorín et al. (2009), Paulraj and Chen (2007), Russo and Fouts (1997), Vachon (2007), Vachon and Klassen (2008), Vachon and Mao (2008), Vasileiou and Morris (2006), Yan and Xia (2011), Yusuf et al. (2013), Zhu et al. (2011), Zhu and Sarkis (2004), Zhu et al. (2005), Zhu et al. (2008), Zhu et al. (2007)	**22**
Questionnaire and Interview	Amoako-Gyampah and Acquaah (2008), Beske et al. (2008), Bhagwat and Sharma (2007), Chan (2003), Clemens (2006), Darnall et al. (2008), Fynes et al. (2005), Gunasekaran et al. (2004), Holt and Ghobadian (2009), Labuschagne et al. (2005), Lee et al. (2009), Molina-Azorín et al. (2009), Paulraj and Chen (2007), Searcy et al. (2007), Vachon (2007), Vachon and Klassen (2008), Vasileiou and Morris (2006), Welford and Frost (2006), Yan and Xia (2011), Yusuf et al. (2013), Zhu et al. (2011), Zhu and Sarkis (2004), Zhu et al. (2005), Zhu et al. (2008), Zhu et al. (2007)	**25**
Analytical Hierarchy Process (AHP)	Bai and Sarkis (2010a), Chan (2003), Chen et al. (2009), Dehghanian et al. (2011), Farrell (1996), Felice et al. (2012), Jiansheng and Wei (2010), Krajnc and Glavič (2005a), Lee et al. (2009), Metta and Badurdeen (2009), Sarkis and Talluri (2002), Sarkis and Talluri (2004), Toke (2012)	**13**
Data Envelopment Analysis (DEA)	Qingmin and Lipeng (2009), Sarkis (2006), Sarkis and Talluri (2002), Xue (2010)	**4**

Table 2.4: Distribution of reviewed studies by methodologies and standards

Category	**References**	**No.**
Balanced Scorecard	Bhagwat and Sharma (2007), Gates and Germain (2010), Jalali Naini et al. (2011), Kang and Juanmei (2010), Kleijnen and Smits (2003), Orti et al. (2010), Shaw et al. (2010), Yao and Zhang (2011)	**8**
General Indicators Aggregation	Azevedo et al. (2013), Burgess and Heap (2012), Kim and Min (2011), Kleijnen and Smits (2003), Krajnc and Glavič (2005b), Mayyas et al. (2013), Nikolaou et al. (2013), Searcy et al. (2007), Tsoulfas and Pappis (2008), Wolfslehner and Vacik (2008)	**10**
Grey Systems Theory and Rough Set Theory	Bai and Sarkis (2010a), Bai and Sarkis (2010b), Bai et al. (2012), Cao and Chen (2007), Chen et al. (2009), Tseng and Chiu (2013)	**6**
Interpretive-Structural Modelling	Rehman and Shrivastava (2011)	**1**
Membership-Conversion Algorithm	Gao et al. (2009)	**1**
Standards		
BS 8900	Bos-Brouwers (2010), Holton et al. (2010)	**2**
ISO 14000 & Its Series	Beamon (1999a), Beske et al. (2008), Bos-Brouwers (2010), Darnall et al. (2008), Diabat and Govindan (2011), Erol et al. (2011), Gomez and Rodriguez (2011), Hervani et al. (2005), Holton et al. (2010), Jasch (2000), Kehbila et al. (2010), McIntyre (1998), Shaw et al. (2010), Toke (2012), Vachon and Mao (2008), Veleva and Ellenbecker (2001), Veleva et al. (2001)	**17**

Table 2.4: Distribution of reviewed studies by methodologies and standards

Category	References	No.
General Frameworks	Abeysundra et al. (2007), Amoako-Gyampah and Acquaah (2008), Azapagic (2004), Azevedo et al. (2013), Bai and Sarkis (2010a), Bai and Sarkis (2010b), Balon et al. (2012), Baresel-Bofinger et al. (2007), Beamon (1999a), Beamon (1999b), Beamon (1998), Bhagwat and Sharma (2007), Bos-Brouwers (2010), Brito et al. (2008), Burgess and Heap (2012), Cao and Chen (2007), Carter and Rogers (2008), Carvalho (2011), Cetinkaya et al. (2011), Chan (2003), Chen et al. (2009), Clift (2003), Cobb (2011), Dehghanian et al. (2011), Erol et al. (2011), Facanha and Horvath (2005), Farrell (1996), Gao et al. (2009), Gates and Germain (2010), Govindan et al. (2013), Gunasekaran and Kobu (2007), Gunasekaran et al. (2004), Gunasekaran et al. (2001), Hassini et al. (2012), Hausman (2004), Hervani et al. (2005), Hooper and Greenall (2005), Huang and Keskar (2007), Hussey et al. (2002), Hutchins and Sutherland (2008), Jalali Naini et al. (2011), Jasch (2000), Jiansheng and Wei (2010), Kang and Juanmei (2010), Kim and Min (2011), Klang et al. (2003), Krajnc and Glavič (2005a), Krajnc and Glavič (2005b), Krajnc and Glavič (2003), Labuschagne and Brent (2006), Labuschagne et al. (2005), Lee et al. (2009), Mayyas et al. (2013), Molina-Azorín et al. (2009), Munda et al. (1994), Nikolaou et al. (2013), Norman and MacDonald (2004), Patlitzianas et al. (2008), Perrini and Tencati (2006), Petrie et al. (2007), Qingmin and Lipeng (2009), Rogers and Ryan (2001), Saadany et al. (2011), Samuel et al. (2013), SCL (2009), Searcy et al. (2005), Searcy et al. (2008), Searcy et al. (2007), Shaw et al. (2010), Shen et al. (2013), Shepherd and Günter (2006), Shuaib et al. (2011), Shuwang et al. (2005), Smeets et al. (2009), Toke (2012), Tseng (2013), Tseng and Chiu (2013), Tseng et al. (2013), Vachon and Klassen (2007), Veleva and Ellenbecker (2001), Veleva et al. (2001), Wang (2012), Xue (2010), Yakovleva (2007), Yakovleva and Flynn (2004), Yan and Xia (2011), Yao and Zhang (2011), Yusuf et al. (2013), Zhang (2011), Zhu et al. (2005), Zhu et al. (2008)	**91**

2.5 Comprehensive Measurement Frameworks

In this section we have selected representative models for each dimensions of sustainability, in Sections 2.5.1-2.5.7. The models are selected based on their high frequency of citation and their coverage of relevant measures and practices. These selected models also reflect the ideas, approaches, and frameworks proposed in other studies allocated to the same dimension. Finally, these models consider relatively numerous indicators, in comparison with their counterparts, for the evaluation of sustainable practices. In each of these subsections, we have collated the indicators of the chosen frameworks in a single table to keep the content concise and provide a useful reference for academics and practitioners. The reader can always consult Table 2.1 for a more exhaustive classification of the reviewed publications for each of the dimensions of sustainability.

Having presented these seven tables, we propose a three-dimension sustainable set of metrics in the last subsection comprising the individual roles of supply partners introduced in Figure 2.2. Moreover, this framework categorizes indicators into two inter-functional and inter-company classes which will be described in that subsection. Explanations are not given for individual indicators, however sufficient information is given for these to be easily traced back to the original source in which they appear.

It is important to note here that there is an inconsistency in the way different studies classify the indicators. In Sections 2.5.1-2.5.7, we follow the original classification used by their authors. We attempt to reconcile these different indications and classifications in our proposed framework in Section 2.5.8.

2.5.1 Economic Dimension

The supply chain operations reference (SCOR) model, developed by the Supply Chain Council, considers both upstream and downstream activities (Bolstorff and Rosenbaum 2007). Gunasekaran et al. (2004) propose a SCOR-based model in four stages, plan, source, make, and deliver, and three indicator levels, strategic, tactical, and operational. The strategic measures influence the decisions of the highest managerial level. The tactical level deals with measures against goals to be met and evaluates mid-level decisions. Operational level indicators need accurate data and are related to the decisions of low-level managers. In a similar spirit, Shepherd and Günter (2006) review 362 articles and integrate their findings in a five-stage framework, adding a return stage to those four used by Gunasekaran et al. (2004). Each indicator is classified based on cost (c), time (t), quality (q), flexibility (f), or innovativeness (i) and whether or not it is quantitative (qn) or qualitative (ql). The integration of these approaches is depicted in Table 2.5.

Table 2.5: Economic dimension model (Gunasekaran et al. (2004) & Shepherd and Günter (2006))

SC Stage	Strategic Indicators	Tactical Indicators	Operational Indicators
Plan	• Asset turns, c, qn • Autonomy of planning, q, ql • Horizon of business relationship, t, ql • Information carrying cost, c, qn • Order lead time, t, qn • Product development cycle time, t, qn • Productivity ratio, c, qn • Profit to productivity ratio, c, qn • Profit, c, qn • Rate of return on investment, c, qn • Ratio of profit to total assets, c, qn • Sales, c, qn • Sensitivity to long-term costs, c, qn • Total cash flow time, t, qn • Total cycle time, t, qn • Total supply chain management costs, c, qn • Variations against budget, c, qn	• Accuracy of forecasting techniques, q, qn • Capital tie-up costs, c, qn • Customer response time, t, qn • Expansion capability, c, qn • Order entry methods, q, qn • Perceived effectiveness of departmental relation, q, ql • Percentage decrease in time to produce a product, t, qn • Planning process cycle time, t, qn • Product development cycle time, t, qn • Total supply chain response time, t, qn • Use of new technology, i, qn • Value added productivity, c, qn	• Cash-to-cash cycle time, t, qn • Cost of goods sold, c, qn • Fill rate, q, qn • Human resource productivity, c, qn • Incentive cost and subsides, c, qn • Intangible cost, c, qn • Mix flexibility, f, qn • New product flexibility, f, qn • Number of new products launched, i, qn • Order flexibility, q, qn • Overhead cost, c, qn • Percentage sales of new product compared with whole sales for a period, c, qn • Perfect order fulfillment, q, qn
Source	• Buyer-supplier partnership level, q, ql • Distribution of decision competences between supplier and customer, q, ql • Information availability, q, ql • Mutual trust, q, ql • Satisfaction with knowledge transfer, q, ql • Satisfaction with supplier relationship, q, ql • Supplier cost-saving initiatives, c, qn	• Extent of mutual assistance leading in problem-solving efforts, q, ql • Extent of mutual planning cooperation leading to improved quality, q, ql • Level of supplier's defect-free deliveries, q, qn • Percentage of late or wrong supplier delivery, c, qn • Supplier assistance in solving technical problems, q, ql • Supplier lead time against industry	• Efficiency of cash flow method, c, qn • Efficiency of purchase order cycle time, t, qn • Information accuracy, q, ql • Information timeliness, q, ql • Purchase order cycle time, t, qn • Quality and frequency of exchange of logistics information between supplier and customer, q, ql

Table 2.5: Economic dimension model (Gunasekaran et al. (2004) & Shepherd and Günter (2006))

SC Stage	Strategic Indicators	Tactical Indicators	Operational Indicators
		norm, t, qn • Supplier's booking-in procedures, t, qn	• Quality of perspective taking in supply networks, q, ql • Storage costs per unit of volume, c, qn • Supplier ability to respond to quality problems, f, ql • Supplier pricing against market, c, ql • Supplier rejection rate, q, qn
Make	• Capacity flexibility, f, qn • Disposal costs, c, qn • Inventory investment, c, qn • Inventory range, f, qn • Inventory turnover ratio, c, qn • Production flexibility, f, qn • Range of products and services, f, qn • Stock capacity, c, qn • Volume flexibility, f, qn • Work in process, c, qn	• Capacity utilization, c, qn • Economic order quantity, c, qn • Effectiveness of master production schedule, c, qn • Inventory accuracy, q, qn • Inventory obsolescence, c, qn • Manufacturing lead time, t, qn • Number of backorders, c, qn • Number of stock-outs, c, qn • Percentage of wrong products manufactured, q, qn • Planned process cycle time, t, qn • Stock-out probability, c, qn • Total cost of resources, c, qn	• Average backorder level, c, qn • Cost per operation hour, c, qn • Inventory cost, c, qn • Inventory flow rate, c, qn • Manufacturing cost, c, qn • Number of items produced, c, qn • Number of tasks worker can perform, f, qn • Percentage of defects, q, qn • Percentage of excess/lack of resource within a period, c, qn • Time required to produce a particular item or set of items, t, qn • Time required to produce new product mix, t, qn • Warehouse costs, c, qn
Deliver	• Delivery efficiency, c, qn • Delivery flexibility, f, qn • Delivery lead time, t, qn • Delivery performance, q, qn	• Delivery costs, c, qn • Delivery reliability performance, c, qn • Distribution costs, c, qn • Driver reliability for performance, q, qn • Effectiveness of delivery invoice	• Achievement of defect-free deliveries, q, qn • Average earliness of orders, t, qn • Average lateness of orders, t, qn • Delivery reliability performance,

Table 2.5: Economic dimension model (Gunasekaran et al. (2004) & Shepherd and Günter (2006))

SC Stage	Strategic Indicators	Tactical Indicators	Operational Indicators
	• Delivery reliability, q, qn • Effectiveness of enterprise distribution planning schedule, c, ql • Flexibility of service system to meet customer needs, f, qn • Total logistics costs, c, qn • Transport flexibility, f, qn	methods, c, qn • Effectiveness of delivery invoice methods, q, qn • Effectiveness of distribution planning schedule, q, ql • Frequency of delivery, t, qn • Number of on-time deliveries, q, qn • Percentage of on-time deliveries, t, qn • Percentage accuracy of delivery, c, qn • Percentage of finished goods in transit, c, qn • Quality of delivered goods, q, ql • Responsiveness to urgent deliveries, f, qn • Shipping errors, c, qn • Transport costs, c, qn	t, ql • Effectiveness of delivery invoice methods, t, qn • Information richness in carrying out delivery, c, qn • Number of faultless delivery notes invoiced, q, qn • On time delivery of goods, t, qn • Percentage of urgent deliveries, t, qn • Personnel costs per unit of volume moved, c, qn • Product lateness, t, qn • Quality of delivered goods, q, qn • Quality of delivery documentation, q, ql • Transport costs per unit of volume, c, qn • Transport productivity, c, qn
Return	• Customer satisfaction, q, ql • Level of customer perceived value of product, f, qn	• Customer complaints, q, qn • Customer query time, t, qn • Rate of complaint, q, qn	• Flexibility of service systems to meet particular customer needs, f, ql • Product quality, q, ql • Warranty/returns processing costs, c, qn

2.5.2 Environmental Dimension

Hervani et al. (2005) propose the use of ISO 14031. They incorporate the following environmental measures: fugitive non-point air emissions, stack or point air emissions, discharges to receiving streams and water bodies, underground injection on-site, releases to land on-site, discharges to publicly owned treatment works, other off-site transfers, on-site and off-site energy recovery, on-site and off-site recycling, on-site or off-site treatment, spill and leak prevention, total electricity use, total fuel use, total materials use other than fuel, and total water use. Patlitzianas et al. (2008) provide an operational framework of indicators to support policies for sustainable energy based on the state of security of supply, competitive market, and environmental protection. We combine the two models and present the indicators in Table 2.6.

2.5.3 Social Dimension

Norman and MacDonald (2004) concentrate on social concerns and offer the framework shown in Table 2.7. They classify social indicators into five aspects, diversity, unions/industrial relations, health and safety, child labour, and community.

2.5.4 Valuable Dimension

Despite the crucial role China plays in world trade, especially given its production capabilities, Zhu et al. (2005) believe there has been a lag in the implementation of green practices in China. They attribute this to inefficient management tools and the lack of environmental performance indicators that link to economic metrics. They argue that environmental performance, operational performance, positive economic performance, and negative economic performance are all linked to green practices performance measurement. Wang (2012) construct a green performance measurement system based on the SCOR model, taking into consideration accounts performance, operating performance, and environmental performance. Bai et al. (2012) have also proposed a SCOR-based framework, introducing five levels, cost, time, quality, flexibility, and innovation and categorizing each indicator into business (economic) or environmental indicators. In Table 2.8, we present valuable measures that integrate these three models.

Table 2.6: Environmental dimension model (Hervani et al. (2005) & Patlitzianas et al. (2008))

Environmental Aspect	**Indicators**
Security of Supply	• Dependence on imports • Dependence on imports of solid fuel • Dependence on natural gas imports • Dependence on oil imports • Differentiation of energy fuel • Differentiation of fuel of electrical energy production • Differentiation of primary fuel • Process modifications • Publicly available missions and values statements • Raw material modification • Source reduction activities • Strategic oil supplies
Competitive Market	• Adjustment of energy pricelist • Dividing of public enterprise • Efficiency of electrical energy production • Efficiency of energy conversion • Energy intensity • Energy law for the reforming and privatization of energy enterprises • Habitat improvements and damages due to enterprise operations • Independent energy regulator • Level of competition • Major awards received • Per capita electrical energy consumption • Per capita energy consumption • Per capita fuel consumption • Per capita fuel consumption • Private participation • Quantity of non-product output returned to process or market by recycling or reuse • Total electrical energy consumption • Total energy consumption

Table 2.6: Environmental dimension model (Hervani et al. (2005) & Patlitzianas et al. (2008))

Environmental Aspect	Indicators
	• Total fuel consumption • Total water consumption • Transformation of energy sector
Environmental Protection	• Application of the Kyoto Protocol • Emitted CO_2 per capita • Emitted CO_2 per electricity and steam production • Emitted CO_2 per GDP • Emitted CO_2 per gross domestic energy consumption • Environmental liabilities under applicable laws and regulations • Formal, written commitments requiring an evaluation of life cycle impacts • Indicators of intensity of emitted CO_2 • Non-production releases • On-site and off-site energy recovery • On-site and off-site recycling • On-site or off-site treatment • Percentage of renewable energy sources in the electrical energy production • Percentage of renewable energy sources in the primary energy production • Procedures to assist product and service designers to create products or services with reduced adverse life cycle impact • Programs or procedures to prevent or minimize potentially adverse impacts of products and services

Table 2.7: Social dimension model (Norman and MacDonald (2004))

Social Aspect	**Indicators**
Diversity	• Existence of equal opportunity policies or programs • Percentage of senior executives who are women • Percentage of staff who are members of visible minorities • Percentage of staff with disabilities
Unions/Industrial Relations	• Percentage of employees represented by independent trade union organizations or other bona fide employee representatives • Percentage of employees covered by collective bargaining agreements • Number of grievances from unionized employees
Health and Safety	• Evidence of substantial compliance with international labor organization guidelines for occupational health management systems • Number of workplace deaths per year • Existence of well-being programs to encourage employees to adopt healthy lifestyles • Percentage of employees surveyed who agree that their workplace is safe and comfortable
Child Labour	• Number of children working • Whether contractors are screened (or percentage screened) for use of child labour
Community	• Percentage of pre-tax earnings donated to the community • Involvement and/or contributions to projects with value to the greater community • Existence of a policy encouraging use of local contractors and suppliers

Table 2.8: Valuable dimension model (Zhu et al. (2005) & Wang (2012) & Bai et al. (2012))

SC Area	Economic Indicators	Environmental Indicators
Cost	• Capacity utilization • Cost variance from expected costs • Inventory levels • Labor efficiency • Supplier cost saving initiatives	• Amount of environmental penalties • Cost for energy consumption • Cost of purchasing environmentally friendly materials • Energy efficiency of systems • Environmental cost performance variance • Environmental costs savings • Fee for waste treatment • Frequency for environmental accidents • Scrap rate • Training costs
Time	• Amount of goods delivered on time • Efficiency of purchase order cycle time • Efficiency of the production lines • Information timeliness • Percentage of late deliveries • Purchase order cycle time • Supplier lead time against industry norm • Supplier's booking-in procedures	• Communication speed on environmental issues to supplier's suppliers • Length to time to implement environmental programs • Meeting environmental program implementation period • Speed of acquiring environmental information
Quality	• Buyer-supplier partnership level • Delivery reliability • Distribution of decision competences between supplier and customer • Extent of mutual assistance leading in problem-solving efforts • Extent of mutual planning cooperation leading to improved quality • Information accuracy • Information availability • Level of supplier's defect-free deliveries • Mutual trust	• Air emission • Consumption for hazardous/harmful/toxic materials • Environmental information accuracy • Environmental information availability • Environmental relationship and cooperation level • Exhaust emissions • Mutual assistance for environmental improvements • Mutual planning for environmental improvements • Mutual trust on environmental issues • Percentage recycled material • Recycling efficiency of the abandoned materials • Solid wastes

Table 2.8: Valuable dimension model (Zhu et al. (2005) & Wang (2012) & Bai et al. (2012))

SC Area	Economic Indicators	Environmental Indicators
	• Percentage of wrong supplier delivery • Quality and frequency of exchange of logistics information between • Quality of perspective taking in supply networks • Satisfaction with knowledge transfer • Satisfaction with supplier relationship • Supplier and customer • Supplier assistance in solving technical problems • Supplier rejection rate	• Supplier rejection rate • Waste generated from products and materials • Waste water
Flexibility	• Materials variety (number of materials available) • Product and service variety • Product development time • Product volume variability capabilities • Response to product changes • Supplier ability to respond to quality problems	• Amount of environmentally safe alternatives • Rate of the new green products development • Response to environmental programs for suppliers • Response to environmental product requests
Innovation	• Involvement in new product design • Introduction of new processes • Satisfaction with knowledge transfer satisfaction • Technological capability levels	• Environmental knowledge transfer satisfaction • Environmental technology levels • New environmentally sound product development • New environmentally sound processes introduced • Proceeds of the recycled materials to be used

2.5.5 Reputable Dimension

In a study of social welfare policy, Adivar et al. (2010) review the humanitarian literature and probe into the social welfare chain. Table 2.9 reveals their suggested economically social metric, comprising of commercial supply chain, social welfare chain, and humanitarian relief chain indicators.

Table 2.9: Reputable dimension model (Adivar et al. (2010))

Commercial Supply Chain Indicators	
Reliability	• Fill rates • Delivery performance • Order fulfillment
Responsiveness	• Lead times
Flexibility	• Supply chain response times • Production flexibility
Cost	• Total cost • Costs of goods sold • Value-added productivity • Warranty costs or returns processing cost
Assets	• Cash-to-cash cycle time • Inventory turnouts
Social Welfare Chain Indicators	
Cost	• Distribution cost • Inbound-outbound freight costs • Overhead cost • Procurement cost
Responsiveness	• Delivery performance • Fill rate • Number of beneficiaries reached
Flexibility	• Variety of aids provided
Output	• Increase in the social welfare
Humanitarian Relief Chain Indicators	
Resource	• Total cost • Distribution cost • Cost of supplies • Number of relief workers • Amount spent per aid recipient • Donor amount received per time period
Output	• Total amount of disaster supplies • Target fill rate achievement average response time • Minimum response time
Flexibility	• Units of supply provided • Number of different types of items provided

2.5.6 Equitable Dimension

Vachon and Mao (2008) link supply chain strength, at a country level, to its environmental and social sustainability performances as shown in Table 2.10. This concise model classifies indicators into three environmental performance, corporate environmental practices, and social sustainability aspects.

Table 2.10: Equitable dimension model (Vachon and Mao (2008))

Corporative Aspect	**Indicators**
Environmental Performance	• Waste recycling rate • Energy efficiency • Greenhouse gas emissions • Environmental innovation
Corporate Environmental Practices	• Number of ISO 14000 certified facilities • Participation in responsible care • Prevalence of green corporatism
Social Sustainability	• Fair labor practices • Corporate social involvement • Gini index

2.5.7 Sustainable Dimension

Farrell (1996) introduces one of the earliest three-dimension frameworks of sustainable supply chains performance measurement where he offers economic, ecological and social measures. Later, Veleva and Ellenbecker (2001) describe a sustainable supply chain framework that comprises energy and material use, natural environment (including human health), economic, community development and social justice, workers, and products aspects. Each of these aspects has five levels (facility compliance, facility material use, facility effects, supply chain life-cycle, and sustainable systems) of the supply chain and furthermore, two sets of indicators are assigned to each of the resulting thirty groups. The core indicators are standardized indicators that can be applied at any business entity. On the other hand, supplemental indicators introduce some flexibility by referring to additional attributes. Krajnc and Glavič (2003) propose indicators of sustainable production. They propose ten categories of indicators: economic-financial, economic-employees, environmental-input-energy, environmental-input-materials, environmental-input-water use, environmental-output-product, environmental-output-solid waste, environmental-output-liquid waste, environmental-output-air emissions, and finally social.

Yakovleva (2007) provides a critical analysis of the UK food supply chain. They propose a model that incorporates economy, environment, and society concerns with a focus on food industries. They consider four groups of indicators: (1) agriculture, seed production and animal breeding, and agricultural growing and production, (2) food industry, primary food processing, further food processing, and final food processing, (3) food distribution, wholesale, retail, and food service, and (4) domestic consumption. Huang and Keskar (2007) include aspects such as reliability, responsiveness, flexibility, cost and financial, assets and infrastructure, safety, and environment. Searcy et al. (2007) propose a framework for the electricity sector and introduce eight categories of indicators: public involvement, staff relations, community relations, private and crown land usage, alterations to the landscape, vegetation management practices, governance and management issues, and benefits to customers and stakeholders.

Cetinkaya et al. (2011) use the concept of a balanced scorecard and divide their indicators into three main classes: economic, environmental, and social. These are further divided into three subcategories each: quality, efficiency, and responsiveness in the economy dimension, emissions, natural resources utilization, and waste and recycling in the environment dimension, and finally health and safety, employees, and noise in the social dimension. Erol et al. (2011) use a multi-criterion framework that incorporates all the TBL aspects. Samuel et al. (2013) present a framework that includes four indicator categories: economic; environmental; social; and labour practices and decent work.

Table 2.11 presents an integration of all the frameworks for sustainable dimensions containing 143 indices. Each indicator is classified into either core or supplemental and assigned to facility compliance, facility material use, facility effects, supply chain life-cycle, or sustainable systems levels.

Table 2.11: Sustainable dimension model (Farrell (1996) & Veleva and Ellenbecker (2001) & Krajnc and Glavič (2003) & Yakovleva (2007) & Huang and Keskar (2007) & Searcy et al. (2007) & Cetinkaya et al. (2011) & Erol et al. (2011) & Samuel et al. (2013))

Aspect	Level 1: Facility Compliance	Level 2: Facility Material Use
Water, Material, and Energy Use	• Core indicators: Fossil fuel consumption • Supplemental indicators: Perceived access to necessary resources; TUR chemicals used at the facility	• Core indicators: Energy consumption; Material consumption; Percentage of energy consumption from renewables; Percentage of material consumption from renewables; Water consumption • Supplemental indicators: Percentage of water reused; Quantity of each type of energy used; Ratio of total mass to value of product sold
Environment, Wastes, and Emissions	• Core indicators: Area of contaminated sites; Total CO_2 emission • Supplemental indicators: Air emissions amount permitted; Fraction of suppliers certified under ISO 14000; Number of environmental reports; Number of reportable releases; Number of sites certified under ISO 14000; Tons of TRI releases	• Core indicators: Amount of waste generated before recycling (emissions, solid, and liquid wastes) • Supplemental indicators: Amount of hazardous waste generated; Cost of increasing intensity of vegetation management; Exposure to hazardous substances; Fraction of facilities using HFC powered units; Hectares of forest cover cleared per year; Hectares of trees planted per year; Quantity of toxic chemicals released; Total NO and SO emission; Volume of BOD discharge; Volume of non-regulated materials recycled
Health and Safety	• Core indicators: Activities created at industrial zones; Number of accidents • Supplemental indicators: Number of notices of violation; Number of recordable illnesses; Number of recordable injuries; Safety audits	• Core indicators: Lost workday injury and illness case rate • Supplemental indicators: Noise level; Number of near misses; Percentage of accident-free workstations; Percentage of work stations with high noise level
Economy	• Core indicators: Costs associated with EHS compliance • Supplemental indicators: Costs attributable to fines and penalties; Environmental liabilities; Environmental responsibility costs; Number of claims for worker compensation	• Core indicators: Organization's openness to stakeholder review and participation in decision making process; Rate of customer complaints and returns • Supplemental indicators: After tax income; Company market share; Growth in shareholder value; Revenue growth; Total annual EHS capital costs; Total EHS operating costs
Community Development and Social Justice	• Core indicators: Political stability • Supplemental indicators: Aboriginal satisfaction with the decision making process; Land in the local community used by the company for waste disposal; Number of regulatory violations; Percentage of past commitments fully met	• Core indicators: Community spending and charitable contributions; Number of community–company partnerships; Number of employees per unit of product • Supplemental indicators: Average response time to requests for publicly available information; Implementation of a program to improve community outreach efforts; Number of community outreach activities; Social and recreational benefits provided to community
Workers and Employees	• Core indicators: Workforce stability and job security • Supplemental indicators: Number of OSHA citations; Number of OSHA 200 Log entries; Staff sense of team	• Core indicators: Average number of hours of employee training per year; Rate of employees' suggested improvements in quality and social and EHS performance; Turnover rate or average length of service of employees • Supplemental indicators: Number of employees receiving EHS training; Percentage of employee suggested EHS improvements implemented in practice; Percentage of workstations with elimination of the hazards through primary (engineering) controls
Products	• Core indicators: Product durability • Supplemental indicators: In process failure rate; Percentage of products with updated and complete MSDS	• Core indicators: Inventory level; Percentage of biodegradable packaging • Supplemental indicators: Percentage of products designed to be recycled; Percentage of products from recycled material; Rate of defective products

Table 2.11: Sustainable dimension model (Farrell (1996) & Veleva and Ellenbecker (2001) & Krajnc and Glavič (2003) & Yakovleva (2007) & Huang and Keskar (2007) & Searcy et al. (2007) & Cetinkaya et al. (2011) & Erol et al. (2011) & Samuel et al. (2013))

Aspect	Level 3: Facility Effects	Level 4: Supply Chain Life-Cycle
Water, Material, and Energy Use	• Core indicators: Total annual reduction of fossil fuel consumption; Total annual reduction of water consumption • Supplemental indicators: Amount of annual acid rain; Percentage of change in specific local resources	• Core indicators: Average costs of each energy source; Energy consumption per warehouse; Total energy costs; Total material costs; Total water costs • Supplemental indicators: Energy consumption including transportation and embedded energy in used material; Total energy consumption over the life cycle of a product; Total vehicle miles traveled
Environment, Wastes, and Emissions	• Core indicators: Amount of greenhouse gases emissions; Amount of PBT chemicals used; Global warming potential; Acidification potential; Total annual reduction of CO_2 emission • Supplemental indicators: Average compensation paid; Conventional pollutants released to water; Heavy metal equivalents; Nutrification potential; Photochemical ozone creating; Summer smog potential	• Core indicators: CO_2 produced per unit delivered; Out of date items in warehouse; Reduction of cargo damage; Total waste costs • Supplemental indicators: Amount of hazardous materials used by contracted service providers; Amount of waste generated by contracted service providers; Costs fraction of purifying air; Percentage of contracted suppliers chosen for environmental reasons
Health and Safety	• Core indicators: Number of fatal accidents; Recordable incident rate • Supplemental indicators: Percentage of workers with some level of hearing loss; Percentage of workers with work-related disease	• Core indicators: Costs of health protection of employee • Supplemental indicators: Percentage of suppliers receiving safety training
Economy	• Core indicators: Customer response time; Order cycle time; Order fulfillment lead time • Supplemental indicators: Amount invested in EHS and community projects; Number of positive/negative press reports on the organization's environmental and social performance	• Core indicators: NPV/ROI of each project; Number of stockouts; Inventory carrying cost; Order fulfillment costs • Supplemental indicators: Cost of expediting delivery and transfer process; Foreign exchange rate fluctuation; Number of innovations created through supplier partnerships; Percentage of distributors supporting/implementing take-back policies; Percentage of errors during release of finished product; Percentage of suppliers participating in raw material or packaging LCA; Percentage of suppliers without EHS violations
Community Development and Social Justice	• Core indicators: Production flexibility to human needs; Time to market • Supplemental indicators: Concentration of specific contaminants in ambient air at selected monitoring locations; Concentration of specific contaminants in ground waters or surface waters; Percentage of days with poor air quality as result of a facility production; Population growth in the local area	• Core indicators: Return policy efficiency; Value fraction of investments in ethical activities • Supplemental indicators: Charity investments; Diversity of market; Importer products vs. Domestic products; Local price control efficiency; Percentage of products consumed locally; Percentage of products with explicit product stewardship plans; Percentage of suppliers from the local area; Poverty deduction rate; Revenue fraction of sustainable products
Workers and Employees	• Core indicators: Percentage of workers reporting complete job satisfaction • Supplemental indicators: Effectiveness of capturing staff feedback; Employee retention rates; Percentage of employees trained in anti-corruption policies and procedures; Percentage of employees who believe that company offers equal opportunities to its staff; Staff preparedness to represent the company in public	• Core indicators: Employment rate; Number of workers on long-term contracts; Payment ratio • Supplemental indicators: Absenteeism rate; Number of contracts canceled because of non-compliance with EHS standards; Number of suppliers from developing world communities; Number of suppliers that have been screened against ethical policy; Ratio of basic salary of men to women by employee category
Products	• Core indicators: Mass fraction of reusable packaging • Supplemental indicators: Customer satisfaction level; Percentage of products involving use of endocrine disrupting substances; Percentage of products involving use of GMOs	• Core indicators: Product lateness; Percentage of products designed for disassembly, reuse, or recycling; Percentage of products with take-back policies in place • Supplemental indicators: Average life cycle cost of products; Delivery reliability; Number of units of energy consumed during use of product; Percentage of products reused or recycled at the end of the life cycle

Table 2.11: Sustainable dimension model (Farrell (1996) & Veleva and Ellenbecker (2001) & Krajnc and Glavič (2003) & Yakovleva (2007) & Huang and Keskar (2007) & Searcy et al. (2007) & Cetinkaya et al. (2011) & Erol et al. (2011) & Samuel et al. (2013))

Aspect	**Level 5: Sustainable Systems**
Water, Material, and Energy Use	• Core indicators: Energy consumption for recycling • Supplemental indicators: Percentage of renewable materials used at a rate lower or equal to the rate of renewal; Total volume of water recovered and reused
Environment, Wastes, and Emissions	• Core indicators: Recycling mass fraction of liquid wastes; Recycling mass fraction of solid wastes • Supplemental indicators: Amount of endocrine disrupting substances used; Amount of POPs used; Ecotoxicity metric
Health and Safety	• Core indicators: Annual reduction of accident probability • Supplemental indicators: Human health metric; Incidence of specific diseases compared to the national average; Stress level compared to the healthy level
Economy	• Core indicators: Total logistics cost; Total value of investments in sustainable development; Warranty costs • Supplemental indicators: Company's image; Investment in sustainability R&D; Truck fill rate
Community Development and Social Justice	• Core indicators: Establishing new employment opportunities • Supplemental indicators: Community quality of life; Income disparity within company and compared to local community and industry; Level of trust by stakeholder category; Quarantine/hold time; Return product velocity
Workers and Employees	• Core indicators: Investments in employee development; Time of employee education • Supplemental indicators: Annual number of applied innovative ideas generated by employees; Average time of an employee illness; Number of suggested improvements by employee; Worker health status compared to other companies in the industry
Products	• Core indicators: Sustainable value-added productivity • Supplemental indicators: Increase in product durability; Percentage of products leased opposed to sold; Total delivery cost

2.5.8 A Proposed Sustainable Framework

Following the conceptual framework suggested in Hassini et al. (2012), in this section we suggest a comprehensive set of performance measures that includes all major links in a supply chain as well as the three pillars of sustainability. It illustrates the role of each partner of a supply chain, from suppliers to retailers. In addition, we classify each indicator depending on whether it is used within a firm, between their functional departments, or between firms that are part of the same supply chain. In other words, they have been categorized into two inter-functional and inter-company indicators (Chopra and Meindl 2013). Table 2.12 shows this proposed framework and integrates most of the foregoing indicators.

Table 2.12 can help practitioners choose a vast range of indices to evaluate the sustainability of their businesses. It can also serve as a compendium of sustainability indicators for research and benchmarking purposes. With regard to the number of indicators in this framework, well-defined and appropriate mathematical and statistical approaches (such as those are listed in Table 2.4) will be required to implement such a structure and then analyze the obtained data. Applying the framework illustrated in Figure 2.2 and aggregating indicators to build composite indicators could be fairly challenging (Nardo et al. 2005, OECD 2008). We are currently working on a large-scale case study to illustrate the application of the framework and indicators.

Table 2.12: A proposed set of sustainable performance measures linking supply chain partners [Economic]

Partner	Inter-functional Performance	Inter-company Performance
Supplier	Sensitivity to long-term costs; Buyer-supplier partnership level; Mutual trust level; Extent of mutual planning cooperation leading to improved quality; Level of supplier's defect-free deliveries; Supplier rejection rate; Supplier ability to respond to quality problems; Perceived access to necessary resources	Profit; After tax income; Ratio of profit to total assets; NPV/ROI; Pricing efficiency; Capacity utilization; Total supply chain management costs; Inventory and warehousing cost; Transportation cost; Facilities and handling cost; Information cost; Marketing cost; Warranty and returns processing cost; Disposal cost; Investment in sustainability R&D; Total supply chain response time; Total cash flow time; Cash-to-cash cycle time; Autonomy of planning; Horizon of business relationship; Accuracy of forecasting; Information accuracy; Information availability; Effectiveness of departmental relation; Satisfaction with partner relationship; Satisfaction with knowledge transfer; Level of customer perceived value of product; Foreign exchange rate fluctuation impacts
Manufacturer	Raw materials, procurement, and purchasing cost; Production and Manufacturing cost; Variations against budget; Productivity ratio; Order lead time; Product development cycle time; Total cycle time; Use of new technologies; Capacity flexibility; Production flexibility; New product flexibility; Value added productivity; Work in process; Effectiveness of master production schedule; Percentage of defects	
Distributer	Distribution cost; Delivery cost; Delivery flexibility; Expansion capability; Fill rate; Stock-out probability; Number of stock-outs; Order flexibility; Percentage of late, wrong, or defective deliveries; Average lateness; Average earliness; Delivery reliability; Frequency of delivery; Responsiveness to urgent deliveries; Percentage of distributors supporting return policies	
Retailer	Sales; Customer response time; Product and service variety; Customer satisfaction level; Number of backorders; Customer complaints; Customer query time; Flexibility of service systems to meet particular customer needs	

Table 2.12: A proposed set of sustainable performance measures linking supply chain partners [Environmental]

Partner	Inter-functional Performance	Inter-company Performance
Supplier	Fraction of suppliers certified under ISO 14000; Scrap rate; Mutual assistance for environmental improvements; Mutual trust on environmental issues; Sell of recycled materials; Recycling efficiency of the abandoned materials	Total energy costs; Total material costs; Total water costs; Fee for waste treatment; Costs fraction of purifying air; Area of contaminated sites; Cost of environmental activities and considerations; Environmental savings and incentives; Ecological training costs; Cost of increasing intensity of vegetation management; Amount of environmental penalties; Fossil fuel consumption; Total annual reduction of fossil fuel consumption; Water consumption; Total annual reduction of water consumption; Percentage of water reused; CO_2 emission; Total annual reduction of CO_2 emission; NO and SO emission; Amount of greenhouse gases emissions; Energy consumption; Amount of waste generated before recycling (solid, and liquid wastes); Amount of annual acid rain; Frequency of environmental violations; Meeting environmental program implementation period; Environmental information availability; Number of environmental reports; Hectares of forest cover cleared per year; Hectares of trees planted per year; Environmental knowledge transfer satisfaction
Manufacturer	Cost of purchasing environmentally friendly materials; Energy efficiency of systems and technologies; Energy consumption for recycling; Material consumption; Percentage of energy consumption from renewables; Percentage of material consumption from renewables; Consumption of hazardous/harmful/toxic materials; Consumption of recycled materials; Rate of the new green products development; Heavy metal equivalents	
Distributer	Ratio of railroad and marine transportation to road transportation; Total vehicle miles traveled; CO_2 produced per unit delivered; Out of date items in warehouse; Reduction of cargo damage	
Retailer	Response level to environmental product requests; Fraction of sites certified under ISO 14000; Mass fraction of reusable packaging	

Table 2.12: A proposed set of sustainable performance measures linking supply chain partners [Social]

Partner	Inter-functional Performance	Inter-company Performance
Supplier	Percentage of suppliers receiving safety training; Number of suppliers from developing world communities; Number of suppliers that have been screened against ethical policy	Percentage of workers reporting complete job satisfaction; Establishing new employment opportunities; Workforce stability and job security; Employment rate; Number of workers on long-term contracts; Payment ratio; Costs of health protection of employee; Lost workday injury and illness case rate; Number of recordable illnesses; Number of recordable injuries; Percentage of accident-free workstations; Percentage of days with poor air quality; Percentage of workers with work-related disease; Stress level of employees; Number of regulatory violations; Percentage of past social commitments fully met; Number of business partnerships; Average number of hours of employee training per year; Staff preparedness to represent the business in public; Ratio of basic salary of men to women by employee category; Donor amount received per year; Existence of well-being programs to encourage employees to adopt healthy lifestyles
Manufacturer	Activities created at industrial zones; Noise level; Number of near misses; Percentage of workstations with high noise level; Percentage of workers with some level of hearing loss; Production flexibility to human needs	
Distributer	Number of accidents; Number of fatal accidents; Annual reduction of accident probability	
Retailer	Importer products vs. Domestic products; Local price control efficiency; Percentage of products consumed locally; Return product velocity	

2.6 Conclusion and Future Extensions

We have reviewed 140 studies published after 1994. These have been categorized into seven dimensions, (*i*) economic, (*ii*) environmental, (*iii*) social, (*iv*) valuable (uniting economic and environmental dimensions), (*v*) reputable (uniting economic and social dimensions), (*vi*) equitable (uniting environmental and social dimensions), (*vii*) sustainable (uniting all dimensions). We then focused on 19 papers that present metrics for all the seven sustainability dimensions and summarized their metrics in Tables 2.5-2.11. These metrics were integrated into a multidimensional model in Table 2.12 that include all levels in a supply chain as well as all the three pillars of sustainability. Tables 2.5-2.1 can be used by practitioners to identify the appropriate set of indicators for their supply chain depending on their priorities. This set of indicators can serve as a guideline to develop key performance indicators and benchmarking tools for the companies.

While analyzing the different performance indicators and classifications it was a challenge for us to interpret and integrate the different approaches. For example, some authors use "business indicators" instead of "economic indicators" and in another study the authors classify freight costs and overhead costs under "social welfare chain indicators". We anticipate that practitioners will also find it difficult to directly use these concepts and ideas in their companies. Thus we were motivated to provide a unified pan-supply chain framework for measuring sustainability. However, we acknowledge that this is only a step in the right direction and more investigation is needed to bridge the gap between theory and implementation. To this end, we are currently working on developing data envelopment analysis (DEA) models for supply chain partners that can help in integrating a set of indicators to produce a common composite indicator. We anticipate that more work will be required in this area to help in designing practical multi-partner performance measures. Some questions that need to be addressed in this context include: How does the firm's internal performance measures correlate with its supply chain measures? How can a firm that is linked with more than one supply chain manage its measures so as to satisfy all its goals without being inundated with measures? For the latter question, a generalized DEA model that will allow for the possibility of having multiple network links can help supply chain partners measure their efforts within the context of multi-network supply chains. The reader is referred to Chapters 3-4 where we discuss several applications of DEA for evaluating sustainability performance of supply chains. In addition, we have identified several other possible lines of research based on our review:

- We found that social sustainability measures have not received the attention they deserve. Only one paper was found that treats reputable measures (social and economic issues). This despite the fact that in practice any erring on these dimensions can have serious economic implications for the supply chain. For example, the Hameem factory fire in Bangladesh in 2010 led to a very high human cost (29 garment workers died) and associated supply chains economic costs, due to supply cuts, and reputations costs, such as the constant criticisms of Walmart in the international press. The failure of this supply link in Bangladesh can also be viewed as supply disruption event. We hypothesize that social sustainability metrics can serve as a proper indicator for potential supply chain disruptions that are related to labour. A question worth investigating then is how can global supply chains develop performance measures that incorporate social measures, as well as other sustainable measures, that could help signal such supply disruptions?

- When we looked at the applications of performance measures in sustainable supply chains we found that there was a lack of studies in the service sector such as the healthcare and pharmaceutical sectors. With the pressure on health care budgets in most economies in the world, participants in health care supply chains should look into sustainable practices that can also save them costs. For example, reusability or extending the life of medical supplies can serve the dual purpose of decreasing costs and helping the environment, i.e., contribute to the valuable dimension. Given that in most economies the public purse funds healthcare and as such efficiencies in this sector are often driven by government policies and directives rather than market competition, it is worth investigating what regulations would drive a public health care system to embrace more sustainable practices.

- A question that is related to the previous point is to what extent are sustainability practices and metrics affected by government regulations? Preliminary findings in the review indicate that sectors that are known to have had strict environmental regulations have had more research activity in the field of sustainability performance measurement.

- We postulate that the reputable and valuable measures are more attractive for profit-oriented organizations as they both include the economic dimension in common. However, the equitable measure may be more attractive to not-for-profit and public establishments. Implementation of the valuable and reputable measures is expected to entail savings but the equitable measures may result in additional costs to the supply chain partners. The question is then how would savings and costs be shared fairly among the supply chain partners?

- The integrated set of metrics that we proposed in Table 2.12 is a good first step in devising comprehensive performance measurement systems for sustainability in supply chains. However, for practical implementation the next step is to devise aggregation measures, such as composite indicators, that would generate meaningful composite measures for multiple partners and dimensions. This line of research is especially carried out in Chapters 3 and 4. As mentioned before, these indicators require an appropriate combination of quantitative and qualitative approaches to ensure reasonable outcomes after implementing our framework to analyze the obtained data.

Chapter 3

Evaluating Sustainability Performance of Two-echelon Networks

This study presents a performance measurement system for sustainability in two-stage supply chain networks with an application to the U.S. fossil-fuel power stations. While there are other alternative sources of electricity, and despite their potential negative impact on the environment, fossil-fuel power stations are still common due to low risk, when compared to nuclear technology, and low costs, when compared to renewable energy sources. However, there is more pressure from different stakeholders to monitor the sustainability performance of fossil-fuel power sources. While the extant literature has focused on developing environmental measures, our work proposes a comprehensive performance measurement system that incorporates the social aspect of sustainability in addition to the more commonly used financial and environmental aspects. Our performance measures are developed through a two-stage data envelopment analysis (DEA) model. One common assumption of such models is the homogeneity of the values of the intermediate measures, i.e., the weights given to the intermediate measures are the same regardless of whether they are outputs or inputs. However, this assumption may not apply in some situations such as when one stage values the intermediates more than the other. This is the case in the application we address in this study where we use a two-stage network DEA model to develop performance measures for sustainability in the U.S. fossil-fuel power stations. We show that the resulting two-stage DEA model is a nonlinear programme. To solve it, we propose an efficient algorithm that involves solving a number of univariate linear equations. This model is then used to construct a comprehensive sustainability performance measure for the fossil-fuel power stations. Using nonparametric tests we provide statistical evidence to show that traditional efficiency measures do not properly account for the environmental and social impacts of fossil-fuel power generation sources.

3.1 Introduction

Businesses are increasingly recognizing that measuring their operational sustainability practices often necessitates the evaluation of their partners' sustainability efforts. Oftentimes these partners may have a different perception of sustainability efforts and their impact on their respective business operations. This has highlighted the need for the development of sustainability performance indicators that can evaluate sustainability initiatives which span multiple entities in a network and take into account such perception intricacies. The question then becomes how can we assess a network's effectiveness as a consequence of the performance of its individual components. DEA has been suggested as a suitable methodology given its ability to aggregate efficiency measures for multiple partners and stages (Chen et al. 2006). DEA, developed systematically by Charnes et al. (1978, 1979, 1981), is a data-oriented formulation setting to evaluate the relative efficiency of a set of comparable decision making units (DMUs), either single entities or networks. This nonparametric technique does not need prescribed weights attached to the indicators, and it is capable of distinguishing the benchmark entities based on an efficiency score as well as identify the amounts of inefficiency of the inefficient DMUs (Cooper et al. 2007). To form a frontier of efficient DMUs, the indicator set is divided into input and output categories, and DEA maximizes the ratio of weighed outputs to weighted inputs (Farrell 1957).

Traditional DEA models ignore intermediate measures in networks and take only the inputs of the first stage and the outputs of the last one into account (Zhu 2009). Recent studies have thus focused on extending conventional DEA models to handle multi-stage network models. Cook et al. (2010a) review the literature on assessing two-stage networks whereby all the outputs from the first stage are the only inputs to the second stage. They classify efficiency decomposition methods into two main categories. Once the stages' efficiencies are determined, evaluation of the overall efficiency of the network can be carried out either through a weighted average approach, the additive integration (Chen et al. 2009, Cook et al. 2010b), or by the use of the product of the individual scores, the multiplicative integration (Liang et al. 2008). From a decision timing standpoint, determining a set of optimal weights for the intermediate indicators is independent of whether the control is centralized or decentralized (Cook et al. 2010a). The former models the stages simultaneously with the aim of maximizing the overall performance. The latter, however, is typically characterized by a Stackelberg competition where one of the stages is the leader. In such a formation, first the leader determines its optimal weights for each of the intermediates, and then the follower stage aims to maximize its performance while at the same time making sure that the leader achieves its maximal efficiency. Chapter 4 of this thesis reviews DEA applications in supply chains and develop a general multi-stage DEA model for supply chain networks with an arbitrary number of stages as well as intermediate resources. To measure efficiency they used an additive objective that integrates the individual efficiency scores of all stages. This results in a DEA model with a linear objective but complex multi-stage network. The attractive feature of that model is the simplicity of the objective function, however it raises the question of how should the individual stage weights be determined. Our focus in this study is different. We apply a multiplicative approach to aggregate the efficiencies allowing us to investigate more complex nonlinear objectives. This is applied to a simple two-stage network without assigning any predefined weights to the stages. Another major difference is that Chapter 4 uses a retail supply chain case study while in this chapter we apply our model to the evaluation of power plants where the stages are virtual rather than real physical supply chains stages.

In DEA network models it is important to distinguish two cases (Liang et al. 2008): one when the stages are cooperating as a centralized system with the goal of simultaneously maximizing their efficiencies and the other a decentralized case where a leader stage maximizes its efficiency score in the first stage and the other stage follows by calculating the efficiency of the follower while maintaining that of the leader unchanged. One important question then is under what conditions would a decentralized model lead to the same results as a centralized model. In Chapter 4, we show that both the decentralized and centralized DEA models yield the same efficiency scores for general networks with a single partner in each stage. This result helps in reducing the computational burden when the number of indicators is large. Liang et al. (2008) had previously investigated this equivalence for the special case of a two-stage network with a single partner in each stage. They further assumed that the intermediate measures are also the inputs of the second stage. In addition, they have taken the overall efficiency to be the product of efficiencies of the individual stages and assumed that all the intermediate indicators are homogeneous. That is, the weights (decision variables) of the outputs of the first stage were assumed to be identical to those for the inputs to the second stage. These assumptions allowed them to reformulate the two-stage network DEA model as a linear program. This latter assumption, however, does not apply in some situations, especially when one stage values the intermediates more than the other, as it is the case for the application discussed in this chapter.

By allowing for the possibility of having heterogeneous intermediate indicators, we eliminate this restricting assumption in the present work and develop an exact algorithm to solve the resulting nonlinear optimization problem. We show that when we have a mixture of intermediates (having homogeneous and heterogeneous values) the principle of decomposition does not apply in the resulting DEA model, i.e., the centralized network approach does not yield to similar efficiencies for the stages as when we use standard DEA. We also show that our DEA model is a special case of indefinite fractional bilinear problems (IFBPs) where the objective function is a fraction of two bilinear functions and the constraints are linear.

We apply our model to the evaluation of sustainability efforts in fossil-fuel power plants. As illustrated in Figure 3.1, each power plant is represented by a two-stage network. For a given DMU, the first stage evaluates the “financial mission” considering all fuel consumption and monetary expenses used to operate and maintain the power plant so that it provides power to the assigned coverage region as well as employment opportunities. This first stage role is to assure the economic requirements of the decision makers, investors, and shareholders. At the same time the plant needs to also serve the sustainability needs of all involved stakeholders. This is achieved through the second stage, which we refer to as the “sustainable mission” stage. This stage monitors the environmental and social impacts of the plant.

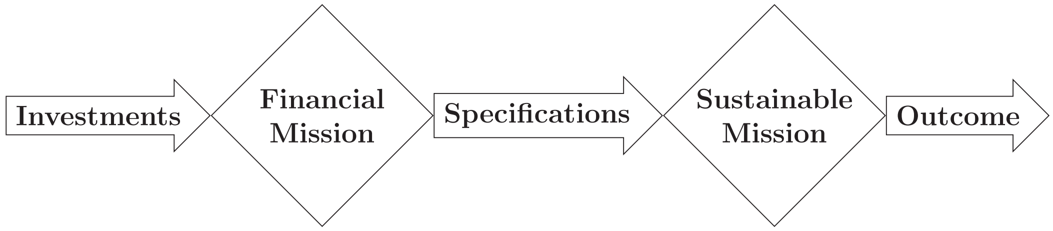


Figure 3.1: A two-stage evaluation framework for power plants

As explained in more details in Section 3.4, the annual power generated by a power plant is considered as an intermediate in the energy DEA network case study. This output from the first stage appropriately determines financial outcomes of the decision maker from the operating facility. As a result, it is more profitable to generate as much electricity as possible. On the other hand, it is clear that large-scale production leads to high levels of environmental pollution and social risks. Accordingly, the decision maker looks at this intermediate differently in the presence of sustainability expectations, where producing less is more desirable. We can think of several other examples where an intermediate may be valued differently by the two stages in the DEA network model. First, take the case of a supply chain when Stage 1 is a manufacturer and Stage 2 is a retailer and the intermediate is the impact of the bullwhip effect. It is well known that an upstream partner (such as the manufacturer) allocates a higher value to this indicator (impact of bullwhip effect) compared to its downstream partner (such as the retailer) which has more certainty in forecasting demand. This is due to the fact that the retailer has more visibility and knows that the impact of the bullwhip effect on its operations is not as significant as it is for the manufacturer. Another example of heterogeneity of intermediate measures is where a supplier (the follower, typically a small player) and a manufacturer (the leader, typically a powerful player) establish a supply chain where the manufacturer is mandating some sustainability initiatives. In such a scenario the manufacturer may have been induced by government tax incentives subject to collaborating with greener suppliers. Thus, the manufacturer compels its supply partners to invest more in sustainability training programs or in adopting environmental quality management systems. Viewing sustainability practices as an intermediate in this two stage network would likely make it take heterogeneous values as these two partners would view the value of the sustainability practices differently within their respective firms financial performance systems. A final example of a heterogeneous intermediate is supply flexibility in order size as well as in variations of deliverables. A manufacturer would prefer deliveries containing reasonable quantities of different products from its supplier so as to optimally fulfill its customer orders. However, a profit-sensitive supplier would prefer larger order quantities where the number of product types shipped out improves its internal procurement and production processes. As such the stages (supplier and manufacturer) would value flexibility in delivery differently. Overall, these examples acknowledge the importance of including heterogeneous intermediates in assessing the performance of networks.

Our study includes four main research contributions. Firstly, we extend the network DEA literature by proposing a nonlinear programming model for multi-stage DEA network models where the intermediates can be both heterogeneous and homogeneous. We apply our model to the important energy sector by adding a multi-faceted sustainability measure to the commonly used financial measures. We develop a centralized two-stage model with a multiplicative objective where the goal of the decision maker is to maximize the product of the efficiencies of the individual stages. Secondly, we fill a gap in the sustainability literature. Existing sustainability performance measurement systems have largely focused on single stages and ignored the social aspect of sustainability (Chapter 2 of this thesis, Hassini et al. 2012). In this chapter we address both of these issues by proposing a sustainability performance measurement model that may extend beyond the boundaries of an organization and accounts for all three aspects of sustainability: the economy, the environment, and the society. Thirdly, our work contributes to the field of IFBPs by investigating a special instance that can be solved efficiently. We show that our nonlinear DEA model is an IFBP and develop an exact branch-reduce-bound (BRB) algorithm to solve it. We also show that our algorithm is computationally efficient as it only involves solving single-variable linear equations in each iteration. It is important to note here that in contrast to existing DEA literature, we solve the nonlinear DEA model directly, without resort to reducing it to a variant of classical linear DEA model. We feel such approaches open the door for applying DEA principles to more realistic situations such as in supply chain management performance measurement. Numerical results from the case study indicate that our model leads to more reasonable results that are significantly different from those that would result from using current two-stage network DEA models. Finally, our model and numerical study contribute to the debate on the role of sustainability measures in ranking power generation facilities. In particular, evidence from the statistical tests on the case study suggests that, in the presence of social opportunities and threats, commonly-used technical efficiency scores do not properly reflect the capability of the facilities. To highlight the importance of using a multi-faceted sustainability measure, we provide statistical evidence that establishes the significance of incorporating environmental and social aspects when evaluating the performance of power generation facilities.

In Section 3.2 we review the literature on multi-criteria performance assessment of power plants and argue that this field provides a fertile ground for the application of network DEA models. In Section 3.3 we introduce a centralized DEA assessment framework and its related nonlinear optimization problem. After showing that the problem can be reformulated as an IFBP, we discuss the state of solution approaches in that field and propose a convergent solution method. Using 2012 data from the Unites States fossil-fuel power plants, we report results of our numerical study in Section 3.4. We finally summarize our findings and provide research limitations and further research directions in Section 3.5.

3.2 Evaluating Sustainability Performance of Fossil-Fuel Power Plants

Government agencies and policy makers rely on sectorial performance measures in order to monitor the impact of current control policies and if necessary issue new regulations. Often these economic sectors are constituted by a collection of intertwined networks of organizations. While much effort has been spent on developing performance measures for departments and individual organizations, there is a lack of models on how to measure performance that crosses the boundaries of organizations (Hassini et al. 2012). The existing performance measures in networks and supply chains focus mainly on financial metrics (Neely et al. 1995, Shepherd and Günter 2006, Gunasekaran and Kobu 2007, Akyuz and Erkan 2010, Nudurupati et al. 2011). Recently there is an increasing interest, both from academia and industry, to develop performance measures and models that cover several partners in a supply chain and at the same time incorporate multiple dimensions for measuring sustainability. In Chapter 2, we propose various sets of performance measures that include major links in a supply chain as well as the triple pillars of sustainability; economy, environment, and society (Elkington 1997). Motivated by those findings, in this study we propose a comprehensive sustainable performance measurement framework for measuring the efficiency of power stations in the U.S.

In Figure 3.2 we present the total direct greenhouse gas emissions of CO_2, N_2O, and CH_4 from large facilities in the U.S. by sector (in million metric tons of CO_2e). The data was reported by the Facility Level Information of GreenHouse Gases Tool map of the U.S. Environmental Protection Agency (EPA). We find that on average power plants are responsible for 70% of the annual emissions. These plants emit fine particles that include mixtures of solids and liquids that can be harmful to the environment and humans' health. According to the Clean Air Task Force reports, fine particle emissions from the U.S. power plants are contributing to over 7,500 deaths each year.

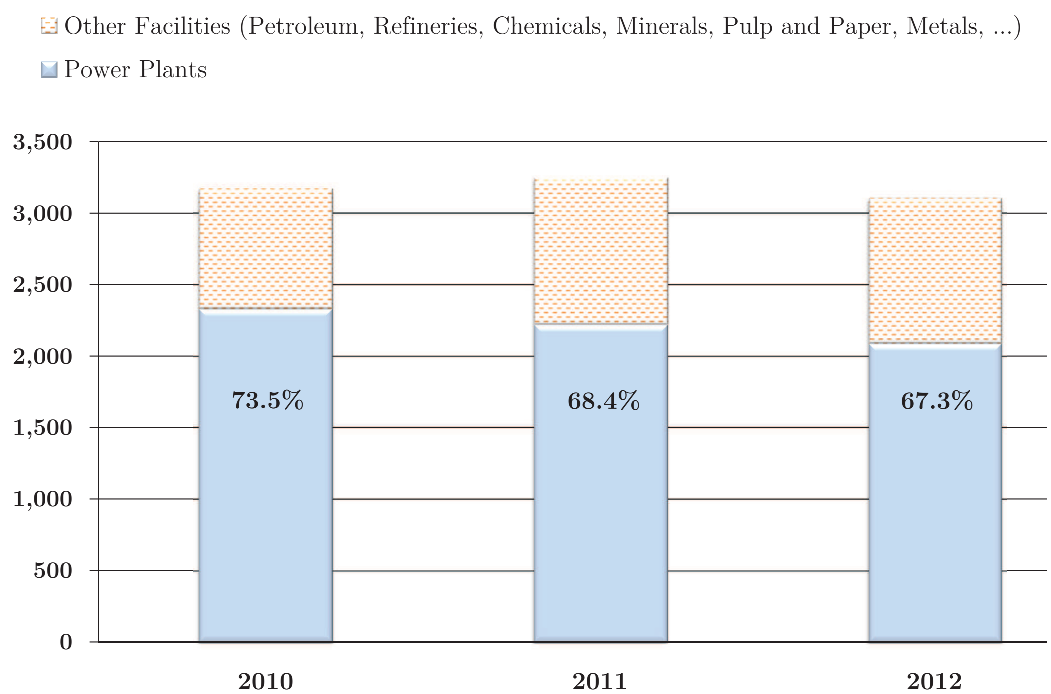


Figure 3.2: Greenhouse gas emissions from large facilities in the U.S.

Our interest in fossil-fuel power stations is driven by the prominence of the debate on fossil versus nuclear fuel in the public circles and the relatively wide availability of data on all three aspects of sustainability. Furthermore, fossil fuel stations are known to be major polluters. While there are other alternative sources of electricity, and despite their potential negative impact on the environment, fossil-fuel power stations are still common due to their low risk, when compared to nuclear technology, and low costs, when compared to renewable energy sources. However, there is more pressure from different stakeholders to monitor the sustainability performance of fossil-fuel power sources.

3.2.1 Benchmarking Power Generation Facilities

In the presence of environmental and social expectations, evaluation of performance efficiency of power stations is complex. The complexity stems from the need to cope with multiple criteria as well as many sources of uncertainty that involve capital-intensive investments. To deal with these challenges several streams of literature have emerged since the early 1960s. The interested reader is referred to the excellent reviews by Massam (1988), Huang et al. (1995), Jamasb and Pollitt (2001), and Pohekar and Ramachandran (2004). Drawing upon these studies and searching Google Scholar with a narrow focus on multi-criterion decision making (MCDM) methods for evaluating performance of power plants, we classify the commonly-used decision analysis (DA) techniques into two main categories:

- Multi-Objective Decision Making (MODM)
- Multi-Attribute Decision Making (MADM)

These methodologies share the common characteristics of the existence of conflicting criteria and difficulties in selection of alternatives (or DMUs in this study). In the MODM class, a set of objective functions is optimized subject to a set of constraints, where often a facility location problem (in particular a power plant siting decision) is of interest. Church and Cohon (1976) and Solomon and Haynes (1984) broadly address many studies of this class. In the MADM category, however, a number of alternatives are existing/generated and they are to be evaluated against a set of attributes. That is, the best alternatives are selected by making comparisons among all the alternatives with respect to each attribute. We note that as we deal with assessment of several existing power stations in this study, from now on we restrict our attention to the MADM class. Apart from applying simple aggregation tools and qualitative methods to analyze MADM problems, we have found six main subclasses for this body of research:

1. **Multi-Attribute Cost Analysis (MACA):** Since publishing the seminal paper by Komiya (1962), many studies have focused on the question of which production

cost function to use to model the cost of power generation that would take into account factors such as technology and scale (Dhrymes and Kurz 1964), regulations (Courville 1974), economies of scale (Christensen and Greene 1976), economies of density and size (Roberts 1986) and regional differences (Thompson and Wolf 1993). Some of the commonly discussed function are the Cobb-Douglas- and TransLog-type cost functions. In particular, the latter contains fewer parameters and imposes no *a priori* restrictions on the nature of technology that is used to generate power. In order to ascertain whether the cost function is good representation of the actual cost form, theses studies perform several likelihood ratio tests on the cost function assumptions. The MACA methodology has been used to address different policy issues. Among those we find interesting question comparing the efficiency of publicly- and privately-owned electric utilities (e.g., see Meyer (1975) and Pescatrice and Trapani (1980)). One serious shortcoming of the MACA methodology is the need to draw up the specification of a functional form, whereby an efficient transformation of a vector of inputs X into a vector of outputs Y is proposed. Such a function may not always be available. The functions that have been proposed in the literature suffer from a lack of fit with the real system, especially when a complex performance system is required such as the case for measuring sustainability in fossil-fuel power generation.

2. **Multi-Attribute Utility Theory (MAUT):** This method helps decision makers assign utility values to outcomes by evaluating using multiple attributes. Having established and evaluated the relevant attributes, this approach specifies a multi-attribute utility function that reflects the DMU's attitude toward risk taking (e.g., see Keeney (1979) and Golabi et al. (1981)). The individual utility values can be defined in an additive or multiplicative form. Similar to MACA, the major shortcoming of MAUT is the requirement of defining the function that represents the relation between the attributes.

3. **Analytic Hierarchy Process (AHP):** AHP has been a common tool for the MADM problems (Pohekar and Ramachandran 2004), specially on account of its ability to simplify complex problems into a hierarchy with a goal at the top of the hierarchy, criteria and sub-criteria at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy. This method includes both

subjective and objective evaluation measures, offering a useful procedure to control the consistency of the evaluation measures and alternatives preferred by decision makers. Several studies have proposed to use AHP for assessing the performance of power plants (e.g., Chatzimouratidis and Pilavachi (2008), Chatzimouratidis and Pilavachi (2009), Pilavachi et al. (2009)). Among the major shortcomings of this technique is that it does not consider risks and uncertainties. Moreover, given its reliance on human's judgment to provide comparative preferences for the alternatives, it often leads to inconsistent measures. Finally, many decision problems, such as complex multi-stage network problems, cannot be structured in a hierarchy as they may involve dependencies among alternatives, criteria, and stages.

4. **Analytic Network Process (ANP):** This approach extends AHP to allow for feedback and dependencies between and among the decision making criteria and the alternatives. ANP has been recently applied to evaluate power plants in Turkey (Atmaca and Basar 2012). While ANP has enriched AHP by allowing for modelling dependencies it is still relies on experts preferences that could lead to inconsistencies. Furthermore, the method is more complex to implement given the high number of comparisons required for the network.

5. **Data Envelopment Analysis (DEA):** Saisana and Tarantola (2002) discuss the idea of using composite indicators to systematically characterize the integration of a set of individual indicators obtained by various analytical methods. To cope with the difficulties of assigning weights to the sub-indicators, which may not be derived from expert judgment in practice, DEA has been one of the most effective mathematical approaches. A recent application of DEA models for measuring corporate social responsibility can be found in Chen and Delmas (2011). Zhou et al. (2008) review 100 papers that use DEA to model energy and environmental performance measures. Moreover, there have been several studies that focused on the application of DEA model to fossil fuel power plants in different countries: Japan (Sueyoshi and Goto 2011, Sueyoshi and Goto 2012a), Korea (Shim and Eo 2010), USA (Sueyoshi and Goto 2012b). As for applications of network DEA models, Tone and Tsutsui (2009) proposed a slack-based model where both individual and network performances can be measured. They apply their model to a vertically integrated electric power generation network. They take the generation plants as

their Stage 1 and the transmission facilities as Stage 2. The generated power is an intermediate for the network. Tone and Tsutsui (2014) have generalized this model to a dynamic version where the network is assessed for several periods. The periods are linked through carry-over activities.

6. **Stochastic Frontier Analysis (SFA):** Similar to DEA, SFA applies the Farrell efficiency score (Farrell 1957) to assess comparable alternatives. It differs from DEA in the way it forms the efficient frontier through a stochastic estimation of the cost function from regression techniques. The general idea of the Farrell efficiency score is characterizing the performance of an alternative by the distance between the outcome level attained by this entity and the level it should obtain if it were efficient. In SFA, the geometric locus of the optimal outputs is represented by a parametric cost function. Through our review of the literature we found that all applications of SFA to the assessment of power plants focus on cost and economic efficiency (e.g., see Hiebert (2002)). Unlike DEA, this method requires a stochastic error structure, whereby a vector of inputs X is mapped into a vector of outputs Y with *a priori* fixed number of parameters. In addition, the estimation of the efficiencies of each alternative is questionable, in a sense that giving statistical meaning to the estimation based on the data-oriented observations is debatable.

3.2.2 Standard DEA Models

Saisana and Tarantola (2002) discuss the idea of using composite indicators (CIs) to systematically characterize the integration of a set of individual indicators obtained by various analytical methods. To cope with the difficulties of assigning weights to the sub-indicators, which may not be derived from expert judgment in practice, data envelopment analysis (DEA) has been one of the most effective mathematical approaches. DEA, developed systematically by Charnes et al. (1978, 1979, 1981), is a data-oriented formulation setting to evaluate the relative efficiency of a set of comparable DMUs, either single entities or networks. This nonparametric technique does not need prescribed weights attached to the indicators, and it is capable of distinguishing the benchmark entities based on an efficiency score as well as identify the amounts of inefficiency of the inefficient DMUs (Cooper et al. 2007). To form a frontier of efficient DMUs, the indicator set is divided into two input and output categories, and DEA maximizes the ratio of weighed outputs to weighted inputs (Farrell 1957).

Suppose there are n comparable DMUs to be evaluated. Each DMU consumes m different input sources and produces s different output values. We note that these input and output values could be interpreted as the values of indicators or measures characterizing the mentioned DMUs. To be more specific, DMU$_j$, where $j \in \{1, ..., n\}$, consumes amount x_{ij} of Input i and produces amount y_{rj} of Output r, where $i \in \{1, ..., m\}$ and $r \in \{1, ..., s\}$. In this study, it is assumed that all x_{ij} and y_{rj} are nonnegative values. For a given DMU being evaluated, say DMU$_o$, the fractional form of DEA which measures the relative efficiency of this DMU is written as follows:

$$\begin{aligned} \text{Max} \quad & h_o = \frac{\sum_r u_r y_{ro}}{\sum_i v_i x_{io}} \\ \text{s.t.} \quad & \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \leq 1 \qquad \forall j \\ & v_i, u_r \geq 0 \qquad \forall i \quad \forall r. \end{aligned} \tag{DEA1}$$

In (DEA1), the first set of constraints ensures that the ratio of virtual outputs to virtual inputs is confined to 1 for every DMU. The objective is defined so that we obtain all weights that maximize the efficiency of DMU$_o$. We note that the optimal objective value is at most 1 by virtue of the constraints. Moreover, the nonnegativity constraints of variables v_i and u_r guarantee that there are positive weights for inputs and outputs, receptively. We note that since the weights in DEA are derived from the data, it is probable to achieve different optimal weights for each DMU by solving n models like (DEA1). Under the nonzero assumption of the vectors $(x_{1j}, ..., x_{mj})$ and $(y_{1j}, ..., y_{sj})$ for all $j \in \{1, ..., n\}$, the foregoing model could be replaced by an equivalent linear model, called the multiplier form of DEA (Charnes et al. 1978), as follows:

$$\begin{aligned} \text{Max} \quad & h_o = \sum_r u_r y_{ro} \\ \text{s.t.} \quad & \sum_i v_i x_{io} = 1 \\ & \sum_r u_r y_{rj} \leq \sum_i v_i x_{ij} \qquad \forall j \\ & v_i, u_r \geq 0 \qquad \forall i \quad \forall r. \end{aligned} \tag{DEA2}$$

DMU$_o$ is defined as a strongly efficient DMU if $h_o^* = 1$ and also there exists at least one optimal $(\mathbf{v}^*, \mathbf{u}^*)$ solution, with $\mathbf{v}^* > 0$ and $\mathbf{u}^* > 0$. Such a DMU could not be improved without worsening some inputs or outputs. In the literature, a DMU that obtains $h_o^* = 1$ without satisfying $\mathbf{v}^* > 0$ and $\mathbf{u}^* > 0$ is called Farrell efficient. In spite of the admirable efforts put in Farrell (1957), known as the first reported empirical applications of traditional productivity approaches, his findings fell short to covering strong efficiency, which finally has been characterized in Charnes et al. (1978). More details about these efficiency classes will be provided in Chapter 4.

3.3 DEA Model and Solution Approach

We consider a centralized two-stage DEA model to assess the performance of power plants and propose an efficient algorithm to solve it. Similar to Liang et al. (2008) we assume a multiplicative efficiency where the overall efficiency of a two-stage network is a product of the efficiencies of two individual partners. Unlike Liang et al. we allow for the realistic scenario where weights of the outputs of the first stage may not be equal to the weights of the inputs of the second stage. This relaxation results in an IFBP for which we develop an algorithm that is adopted from Shen et al. (2009) and Shen et al. (2011). Both studies present exact methods for solving fractional programming problems whose objectives and constraint functions are all defined as the sum of quadratic fractions or polynomial ratios. We show that applying these approaches to our nonlinear DEA model will only need finding the root of several univariate linear equations in each iteration of the algorithm.

3.3.1 DEA Formulation

Consider a generic two-stage network as shown in Figure 3.3, for each of n networks or DMUs to be evaluated. We assume in the first stage each DMU$_j$ $(j = 1, 2, \ldots, n)$ consumes x_{ij} units of the ith input $(i = 1, 2, \ldots, m)$ and produces amount z_{dj} of the dth intermediate, where $d \in \Delta = \{1, 2, \ldots, D\}$. Likewise, DMU$_j$, utilizing z_{dj} units of the dth intermediate, produces amount y_{rj} of the rth output $(r = 1, 2, \ldots, s)$ in the second stage. In this study we analyze networks in which all indicators take nonnegative values and all the outputs from the first stage are the only inputs to the second stage.

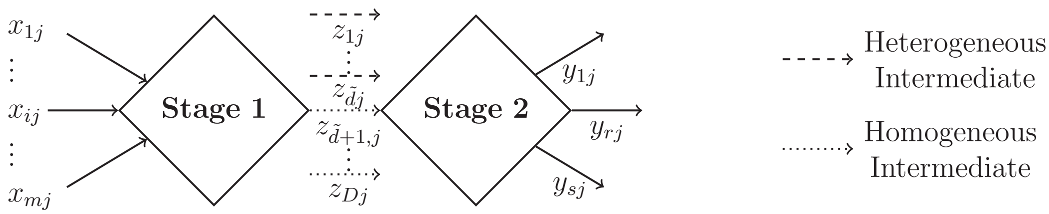


Figure 3.3: A two-stage network that includes direct and intermediate measures

The values of inputs and outputs of Stage 1 (Stage 2) are denoted by decision variables v_i and w_d ($\widetilde{w}_d$ and u_r), respectively. Unlike the previous literature of two-stage models, we consider the more general case where $w_d \not\equiv \widetilde{w}_d$ for $d \in \Delta_{\text{HT}} = \{1, ..., \tilde{d}\} \subseteq \Delta$ and $w_d \equiv \widetilde{w}_d$ for $d \in \Delta_{\text{HM}} = \{\tilde{d}+1, ..., D\} = \Delta \setminus \Delta_{\text{HT}}$. The centralized DEA model to evaluate the overall efficiency of a given two-stage network, such as DMU$_o$, can be written as a fractional problem as follows (Liang et al. 2008):

$$
\begin{aligned}
\text{Max} \quad & e_o^{\text{Centralized}} = e_o^1 \times e_o^2 = \frac{\sum_d w_d z_{do}}{\sum_i v_i x_{io}} \times \frac{\sum_r u_r y_{ro}}{\sum_d \widetilde{w}_d z_{do}} = \frac{\sum_d w_d z_{do} \times \sum_r u_r y_{ro}}{\sum_i v_i x_{io} \times \sum_d \widetilde{w}_d z_{do}} \\
\text{s.t.} \quad & e_j^2 = \frac{\sum_r u_r y_{rj}}{\sum_d \widetilde{w}_d z_{dj}} \leq 1 \qquad \forall j \\
& e_j^1 = \frac{\sum_d w_d z_{dj}}{\sum_i v_i x_{ij}} \leq 1 \qquad \forall j \\
& v_i, w_d, \widetilde{w}_d, u_r \geq 0 \qquad \forall i \quad \forall d \quad \forall r,
\end{aligned}
\tag{M0-A}
$$

where e_o^1 and e_o^2 are the scores of the first and second stages of DMU$_o$, respectively. Depending on the membership of Δ_{HT}, we have three cases:

Case 1 (Homogeneous Intermediates): $\Delta_{\text{HM}} = \Delta$. In this case all the intermediates are homogeneous, i.e., $w_d \equiv \widetilde{w}_d$, for all $d \in \Delta$. This is the case that has been assumed in the current DEA literature (e.g., see Liang et al. 2008). The fact that all intermediates are homogeneous allows us to convert (M0-A) to a standard linear DEA model, since $e_o^{\text{Centralized}} = \frac{\sum_r u_r y_{ro}}{\sum_i v_i x_{io}}$. We denote the solution to (M0-A) by e_o^{HM} in this study.

Case 2 (Heterogeneous Intermediates): $\Delta_{\text{HM}} = \emptyset$. In this case all intermediates are heterogeneous so that none of the intermediate indicators defines any relation between its corresponding incoming and outgoing weights, i.e., $w_d \not\equiv \widetilde{w}_d$, for all $d \in \Delta$. Under this condition, (M0-A) can be separated into two independent standard DEA models, since both fractions of the objective function as well as the functions of the constraint sets contain non-connected wights w_d and $\widetilde{w}_d$. We will refer to the individual stage efficiency scores by $e_o^{1,\mathrm{HT}}$ and $e_o^{2,\mathrm{HT}}$ and their product by $e_o^{\mathrm{HT}} = e_o^{1,\mathrm{HT}} \times e_o^{2,\mathrm{HT}}$.

Case 3 (Mixed Intermediates): $1 \leq \tilde{d} < D$. In this case there is at least one heterogeneous intermediate and the network has at least two intermediates, i.e., we have a mixture of heterogeneous and homogeneous intermediates. Thus, provided that $d \in \Delta_{\mathrm{HT}}$, we do not require the variables w_d and $\widetilde{w}_d$ to have any predefined relation. Accordingly, (M0-A) can be written as follows:

$$
\begin{aligned}
\text{Max} \quad & e_o^{\mathrm{Mixed}} = \frac{\sum_{d\in\Delta} w_d z_{do}}{\sum_i v_i x_{io}} \times \frac{\sum_r u_r y_{ro}}{\sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{do}} \\
\text{s.t.} \quad & e_j^2 = \frac{\sum_r u_r y_{rj}}{\sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{dj} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{dj}} \leq 1 && \forall j \\
& e_j^1 = \frac{\sum_{d\in\Delta} w_d z_{dj}}{\sum_i v_i x_{ij}} \leq 1 && \forall j \\
& v_i, w_d, u_r \geq 0 && \forall i \quad \forall d \quad \forall r \\
& \widetilde{w}_d \geq 0 && \forall d \in \Delta_{\mathrm{HT}}. \qquad \text{(M0-B)}
\end{aligned}
$$

In Theorem 3.1 we show the relationship between the two-stage network DEA efficiencies and those of the single-stage standard DEA.

Theorem 3.1 *For a given DMU_o:*

i. $e_o^{\mathrm{HT}} \geq e_o^{\mathrm{Mixed}} \geq e_o^{\mathrm{HM}}$.

ii. If $\Delta_{\mathrm{HM}} = \Delta$ *and* $D = 1$, *then* $e_o^{\mathrm{HT}} = e_o^{\mathrm{Mixed}} = e_o^{\mathrm{HM}}$.

iii. If $\Delta_{\mathrm{HM}} = \emptyset$ *then,* $e_o^{\mathrm{HT}} = e_o^{\mathrm{Mixed}}$.

The proof of Theorem 3.1 and other proofs of Chapter 3 are included in **Appendix A.1**. In Section 3.4 we provide statistical evidence showing that $e_o^{\mathrm{HT}} \neq e_o^{\mathrm{Mixed}}$ and $e_o^{\mathrm{Mixed}} \neq e_o^{\mathrm{HM}}$ under Case 3 where $1 \leq \tilde{d} < D$ in (M0-B).

3.3.2 Solution Methodology

Optimization problem (M0-B) is nonlinear. There are few other studies that have addressed nonlinearity in DEA models. Cooper et al. (1999) and Zhu (2004) have considered imprecise DEA where the data is bounded or ordinal. The nonlinear model is transformed through scale transformations and variable alterations. Despotis et al.

(2009), Cook et al. (2009), and Cook and Zhu (2009) consider nonlinearities in the function that aggregates the inputs or outputs of standard DEA models. They represent these nonlinearities with piece-wise functions that lead to the linear standard DEA models, albeit with larger problem sizes. Cook et al. (2013) extend the standard DEA model to the case where the DMUs may not have the same set of inputs and outputs. Assuming a special structure for assigning weights to subgroups of inputs and outputs, the nonlinear model can be transformed into a linear DEA model.

In a similar way to the extant literature, and without imposing any restrictive assumptions on model (M0-B), we will study its structure and develop an algorithm that would find its solution by only solving univariate linear equations. Theorem 3.2 characterizes the optimization class of (M0-B).

Theorem 3.2 *Problem (M0-B) is an IFBP.*

Given that (M0-B) is an IFBP instance, we will make use of the theory in that field to develop a solution method. To that end, we provide a brief review of solution methodologies for IFBPs.

An IFBP is a special case of nonlinear optimization problems that deals with the global optimization of a nonlinear function over a set of constraints. As defined in Horst and Pardalos (1995), global optimization is concerned with the computation and characterization of global minima or maxima of a constrained objective function. Convex optimization techniques play a fundamental role in the global optimization theory (Nesterov and Nemirovskii 1994). In contrast, no efficient general solution methods are known for solving nonconvex problems. Thus research in the area of nonconvex global optimization has mainly focused on solving special classes of these problems, often by converting them to tractable linear or convex formulations. Among the special cases that have been investigated we find quadratic programming (QP) and fractional programming (FP) problems (Horst and Pardalos 1995). A special case of QP is the bilinear programming (BP) problem. A special combination of the BP and FP problems is the optimization problem under discussion in this study, IFBP. Thus, we will briefly review these two classes of problems in the next two paragraphs.

The QP problem is comprised of a quadratic objective function and a set of linear constraints. Although this problem is known to be NP-hard in general (Garey and

Johnson 1979), minimizing a linearly constrained convex quadratic objective function has been studied since the 1950s (Frank and Wolfe 1956, Hildreth 1957, Wolfe 1959). In BP the objective function can be written as $\mathbf{x}^T Q\mathbf{y} + \mathbf{c}^T\mathbf{x} + \mathbf{b}^T\mathbf{y}$ where $\mathbf{x} \neq \mathbf{y}$ are decision variables vectors. A BP problem is thus linear in one variable given the other is fixed. Several studies have looked at BP problems and developed exact solution methods to solve them, including the case where the objective function is neither convex nor concave (Gallo and Ülkücü 1977).

The FP problem, also referred to as hyperbolic programming or ratio programming, has an objective function that is constituted by one or several ratios of functions. This class of problems was first proposed by Charnes and Cooper (1962). Dinkelbach (1967) showed that solving the FP problem $\max\{\frac{N(\mathbf{x})}{D(\mathbf{x})} \mid \mathbf{x} \in S\}$ is equivalent to the non-fractional problem $\max\{N(\mathbf{x}) - qD(\mathbf{x}) \mid \mathbf{x} \in S\}$ provided that $N(\mathbf{x})$ and $D(\mathbf{x})$ are continuous real-valued functions that are concave and convex, respectively, over S, a compact and connected subset of $\mathbb{R}^n$ and q is a real number. The FP problem has been studied extensively in the literature and a series of bibliographies have been published in this area, the latest of which is by Stancu-Minasian (2006). We have searched a list of more than 3000 references cited in these bibliographies with the aim of finding studies that developed exact solution methods for nonlinear problems that are similar to problem (M0-B). In Table 3.1 we summarize our findings of studies that look at optimizing objective functions with at least a ratio of nonlinear polynomials. In the second column of that table we describe the nature of the fractional objective function by including the form and definiteness of its numerator and denominator. Studies that deal with IFBPs that are relevant to our problem have been highlighted in bold font. In particular in our solution method we rely on the approaches discussed in Shen et al. (2009) and Shen et al. (2011). The other candidates for solving our proposed IFBP formulation are excluded from further consideration due to either their drawback in exploring the global optima or their similarity with the mentioned studies in using monotonic optimization problems.

Table 3.1: A review on the FP problems having an objective with a fraction of nonlinear polynomials

Reference	Objective Form and Definiteness	Constraints	Findings
Beck et al. (2006)	Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	A global optimal solution can be found by solving a sequence of convex problems.

Table 3.1: A review on the FP problems having an objective with a fraction of nonlinear polynomials

Reference	**Objective Form and Definiteness**	**Constraints**	**Findings**
Beck and Teboulle (2009)	Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	Propose an iterative procedure that converges superlinearly to an optimum.
Bector (1972)	Quadratic/Quadratic Indefinite/Indefinite	Linear Functions	Proposes a finite-step simplex-wise technique for finding a local minimum.
Benson (2006)	Quadratic/Arbitrary Semidefinite/Definite	Compact Convex Set	A branch and bound algorithm that solves a single nonconvex program in each iteration.
Cai et al. (2014)	Quadratic/Quadratic Definite/Definite	Quadratic Functions	The fractional problem is converted to a non-fractional one and solved by a semi-definite programming method.
Chandrasekaran and Tamir (1984)	Quadratic/Quadratic Definite/Definite	Linear Functions	Present a polynomial method to obtain global optimal solutions.
Frenk (2007)	Quadratic/Arbitrary Semidefinite/Definite	Open Convex Set	Prove the results of Benson (2006) when the feasible region may not be a nonempty compact set.
Golub and Underwood (1970)	Quadratic/Bilinear Indefinite/Definite	Quadratic Functions	Present a polynomial method to obtain global optimal solutions.
Gotoh and Konno (2001)	Quadratic/Quadratic Semidefinite/Definite	Linear Functions	An exact algorithm is developed by using Dinkelbach's scheme (Dinkelbach 1967) and a branch and bound approach.
Ibaraki et al. (1976)	Quadratic/Quadratic Definite/Semidefinite	Linear Functions	Two finite-step algorithms are proposed; one parametric programming technique, and one using Dinkelbach's scheme.
Ji et al. (2012)	Sum of Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	The problem is converted into a sum of linear ratios with quadratic constraints and solved by a branch and bound approach.
Jiao et al. (2013)	Sum of Polynomial/Polynomial Indefinite/Indefinite	Polynomial Functions	By utilizing a linear relaxation method, a sequence of linear relaxation programmings of the original problem is derived.
Kaiser and Rice (1973)	Quadratic/Quadratic Indefinite/Definite	Unconstrained	The proposed approximation method is built on the largest eigenvalue and associated eigenvector of an eigen-equation.
Malivert (1998)	Bilinear/Bilinear Indefinite/Indefinite	Linear Functions	From the special structure of the problem, the author proposes a cutting plane algorithm to solve the problem.
Mishra and Ghosh (2006)	Quadratic/Quadratic Definite/Definite	Linear Functions	An interactive fuzzy method is proposed for obtaining a satisfactory solution of the problem with two DMUs.
Pei-Ping and Gui-Xia (2007)	Sum of Polynomial/Polynomial Indefinite/Indefinite	Polynomial Functions	By utilizing an equivalent problem, a linear relaxation programming problem of the equivalent form is obtained.
Qu et al. (2007)	Sum of Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	An exact algorithm based on the rectangular partition and a Lagrangian relaxation is presented.

Table 3.1: A review on the FP problems having an objective with a fraction of nonlinear polynomials

Reference	Objective Form and Definiteness	Constraints	Findings
Shen et al. (2009)	Sum of Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	Based on reformulating the problem, a branch-reduce-bound algorithm is proposed.
Shen et al. (2011)	Sum of Polynomial/Polynomial Indefinite/Indefinite	Polynomial Functions	This study is a generalization of Shen et al. (2009).
Tigan and Stancu-Minasian (1996)	Bilinear/Bilinear Indefinite/Indefinite	Linear Functions	A stochastic max-min problem with separate linear constraints is solved using the minimum-risk approach and Kataoka's model.
Tuy et al. (2004)	Polynomial/Polynomial Indefinite/Indefinite	Linear Functions	The approach is based on a reformulation into an increasing function under monotonic constraints.
Wang and Zhang (2004)	Sum of Polynomial/Polynomial Indefinite/Indefinite	Polynomial Functions	Propose an algorithm that converges to the global minimum through successive refinements of a series of linear problems.
Xia (2013)	Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	It is shown that the minimum of the problem is attained if and only if the proposed reformulation has a unique solution.
Zhang and Hayashi (2011)	Quadratic/Quadratic Indefinite/Indefinite	Quadratic Functions	Propose an algorithm based on the bisection and the generalized Newton methods.

To facilitate the presentation of our solution method we will work with the following linearly constrained formulation of (M0-B):

$$
\begin{aligned}
\text{Min} \quad & -\frac{\sum_{d\in\Delta} w_d z_{do} \times \sum_r u_r y_{ro}}{\sum_i v_i x_{io} \times \left(\sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{do}\right)} & \\
\text{s.t.} \quad & \sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{dj} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{dj} - \sum_r u_r y_{rj} \geq 0 & \forall j \\
& \sum_i v_i x_{ij} - \sum_{d\in\Delta} w_d z_{dj} \geq 0 & \forall j \\
& 0 < \pi^l \leq v_i, w_d, u_r \leq \pi^u < \infty & \forall i \quad \forall d \quad \forall r \\
& 0 < \pi^l \leq \tilde{w}_d \leq \pi^u < \infty & \forall d \in \Delta_{\mathrm{HT}}, \qquad \text{(M1)}
\end{aligned}
$$

where π^l and π^u are the lower and upper bounds of the indicator weights, respectively, that have to be predetermined by the main decision maker. To ensure that (M1) and (M0-B) generate the same solutions, it is necessary to select the values π^l (π^u) adequately small (large). To do so, in the numerical studies in this chapter we chose 10^{-7} (10^8) for these parameters, respectively. In contrast to the work of Shen et al. (2009), we develop a solution procedure that has no optimization sub-problems. This characteristic enables us to solve our instances fast and efficiently, where preliminary operations are applied to find the final solution.

Problem (M1) can be transformed into an equivalent monotonic optimization problem where the objective function is increasing and each constraint is expressed as a difference of two increasing functions. To do that we introduce the variable $W \in [\frac{1}{U}, \frac{1}{L}]$ where

$$L = (\pi^l)^2 \times \sum_i x_{io} \times \sum_{d\in\Delta} z_{do} \leq \sum_i v_i x_{io} \times (\sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{do})$$

and

$$U = (\pi^u)^2 \times \sum_i x_{io} \times \sum_{d\in\Delta} z_{do} \geq \sum_i v_i x_{io} \times (\sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{do}).$$

We then convert (M1) into the following problem:

$$\begin{aligned}
\text{Min} \quad & -W \times \sum_{d\in\Delta} w_d z_{do} \times \sum_r u_r y_{ro} \\
\text{s.t.} \quad & \sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{dj} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{dj} - \sum_r u_r y_{rj} \geq 0 && \forall j \\
& \sum_i v_i x_{ij} - \sum_{d\in\Delta} w_d z_{dj} \geq 0 && \forall j \\
& 1 - W \times \sum_i v_i x_{io} \times (\sum_{d\in\Delta_{\mathrm{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\mathrm{HM}}} w_d z_{do}) \geq 0 \\
& \frac{1}{U} \leq W \leq \frac{1}{L} \\
& 0 < \pi^l \leq v_i, w_d, \widetilde{w}_d, u_r \leq \pi^u < \infty,
\end{aligned} \tag{M2}$$

and by grouping terms with positive coefficients and those with negative coefficients and introducing a new variable $Z \in [z^l, z^u] \equiv \left[-\left(\frac{\pi^u}{\pi^l}\right)^2 \times \frac{\sum_r y_{ro}}{\sum_i x_{io}}, -\left(\frac{\pi^l}{\pi^u}\right)^2 \times \frac{\sum_r y_{ro}}{\sum_i x_{io}}\right]$, we obtain the following monotonic problem:

$$
\begin{aligned}
\text{Min} \quad & Z \\
\text{s.t.} \quad & \sum_{d\in\Delta_{\text{HT}}} \widetilde{w}_d z_{dj} + \sum_{d\in\Delta_{\text{HM}}} w_d z_{dj} - \sum_r u_r y_{rj} \geq 0 \qquad \forall j \\
& \sum_i v_i x_{ij} - \sum_{d\in\Delta} w_d z_{dj} \geq 0 \qquad \forall j \\
& 1 - W \times \sum_i v_i x_{io} \times \Big(\sum_{d\in\Delta_{\text{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\text{HM}}} w_d z_{do} \Big) \geq 0 \\
& W \times \sum_{d\in\Delta} w_d z_{do} \times \sum_r u_r y_{ro} + Z \geq 0 \\
& \frac{1}{U} \leq W \leq \frac{1}{L} \\
& z^l \leq Z \leq z^u \\
& 0 < \pi^l \leq v_i, w_d, \widetilde{w}_d, u_r \leq \pi^u < \infty.
\end{aligned} \tag{M3}
$$

Let $\xi = (v_1, \ldots, v_m, w_1, \ldots, w_D, \widetilde{w}_1, \ldots, \widetilde{w}_{\tilde{d}}, u_1, \ldots, u_s)$ and define $x = (\xi, W, Z) \in \mathbb{R}^{N_0+2} = \mathbb{R}^N$. Then (M3) can be rewritten in the form

$$\min\{g(x) | h(x) \geq 0 \ ; \ x \in X_0 = [x^l, x^u]\}, \tag{M}$$

where $X_0 = \{x \in \mathbb{R}^N | x^l_I \leq x_I \leq x^u_I \ , \ I = 1, \ldots N\}$

$$
= \left\{ x \in \mathbb{R}^N : \begin{array}{ll}
\pi^l \leq x_I = v_I \leq \pi^u & \forall\ I = 1, \ldots, i, \ldots, m \\
\pi^l \leq x_I = w_{I-m} \leq \pi^u & \forall\ I = m+1, \ldots, m+d, \ldots, m+D \\
\pi^l \leq x_I = \widetilde{w}_{I-m-D} \leq \pi^u & \forall\ I = m+D+1, \ldots, m+D+d, \ldots, m+D+\tilde{d} \\
\pi^l \leq x_I = u_{I-m-D-\tilde{d}} \leq \pi^u & \forall\ I = m+D+\tilde{d}+1, \ldots, m+D+\tilde{d}+r, \ldots, N_0 \\
\dfrac{1}{U} \leq x_I = W \leq \dfrac{1}{L} & \forall\ I = m+D+\tilde{d}+s+1 = N_0+1 \\
z^l \leq x_I = Z \leq z^u & \forall\ I = m+D+\tilde{d}+s+2 = N_0+2 = N
\end{array} \right\},
$$

$g(x) = x_{N_0+2} = Z \ , \ h(x) = \min\Big\{\nu_k^+(x) - \nu_k^-(x) \mid k \in \{1, \ldots, K_0 = 2n+2\}\Big\},$

$$\nu_k^+(x) \equiv \begin{cases} \sum_{d\in\Delta_{\text{HT}}} \widetilde{w}_d z_{dk} + \sum_{d\in\Delta_{\text{HM}}} w_d z_{dk} & \text{if } k \in \{1, \ldots, n\} \\ \sum_i v_i x_{i(k-n)} & \text{if } k \in \{n+1, \ldots, 2n\} \\ 1 & \text{if } k = 2n+1 \\ W \times \sum_{d\in\Delta} w_d z_{do} \times \sum_r u_r y_{ro} + Z & \text{if } k = 2n+2 \end{cases}$$

and

$$\nu_k^-(x) \equiv \begin{cases} \sum_r u_r y_{rk} & \text{if } k \in \{1, \ldots, n\} \\ \sum_{d\in\Delta} w_d z_{d(k-n)} & \text{if } k \in \{n+1, \ldots, 2n\} \\ W \times \sum_i v_i x_{io} \times \big(\sum_{d\in\Delta_{\text{HT}}} \widetilde{w}_d z_{do} + \sum_{d\in\Delta_{\text{HM}}} w_d z_{do}\big) & \text{if } k = 2n+1 \\ 0 & \text{if } k = 2n+2 \end{cases}.$$

The general form of problem (M) is denoted by (P) in Shen et al. (2009). Problem (M3) is a monotonic optimization problem and as such can be solved by the BRB algorithm described in **Appendix A.2**. The algorithm uses the idea of the standard branch and bound method with three main procedures: (i) Branching that divides the feasible region into exhaustive subregions that converge to a single point; (ii) Reducing step that applies valid cuts to the subregions to exclude non-optimal solutions; (iii) Bounding where an upper bound on the optimal solution is obtained for each reduced subregion. If $\{x \in X_0 | h(x) > 0\} \neq \emptyset$ is met, a nonisolated feasible solution $\hat{x}$ of (P) is called a nonisolated ε-optimal solution if it satisfies $g(\hat{x}) - \varepsilon \leq \inf\{g(x) | h(x) \geq \varepsilon \ ; \ x \in X_0\}$, for any $\varepsilon > 0$. Shen et al. (2009) show that after a finite number of steps the algorithm either produces an evidence that (M) is a nonisolated infeasible problem or terminates at a nonisolated ε-optimal solution of (M). The algorithm in **Appendix A.2** would provide us with $\hat{x}^* = (\hat{\xi}^*, \hat{W}^*, \hat{Z}^*)$ from which we can calculate the efficiency as $e_o^{\text{Mixed}} = \frac{\nu_{K_0}^+(\hat{x}^*) - \hat{Z}^*}{\nu_{K_0-1}^-(\hat{x}^*)}$.

In the proposed algorithm one needs to establish two procedures red$[a,b]$ and UB$(X_{a,b})$ for a current interval $[a,b] \subseteq \mathbb{R}^N$, where the former finds a reduced sub-rectangle of $[a,b]$ without losing any potentially better nonisolated feasible solution of (M) in $[a,b]$, and the latter computes an efficiently-tight upper bound of the objective function of (M1) over

$[a,b]$. We detail the bounds and cut expressions in Theorem 3.3, which is an adaptation of Theorems 4.1 and 4.2 in Shen et al. (2009) to model (M3).

Theorem 3.3 (Shen et al. 2009) *For any compact interval* $[a,b]$*:*

(I) $red[a,b] = [a',b'] \subseteq [a,b] \subseteq X_0 = [x^l, x^u] \subseteq \mathbb{R}^N$, *where:*
$a' = b - \sum_{I=1}^{N}\left(\min_{\{k=1,\dots,K_0\}}\{\alpha_k^I\} \times (b_I - a_I)e^I\right) \in \mathbb{R}^N$, *and* e^I *is the* I*th unit vector*
$b' = a' + \sum_{I=1}^{N}\left(\min_{\{k=1,\dots,K_0+1\}}\{\beta_k^I\} \times (b_I - a'_I)e^I\right) \in \mathbb{R}^N$,
For all $k \in \{1,\dots,K_0\}$,

$$\alpha_k^I = \begin{cases} \bar{\alpha}_k^I, & \text{if } \varphi_k^I(\alpha) \text{ is } \underline{\text{not}} \text{ constant and } \varphi_k^I(\bar{\alpha}_k^I) = \nu_k^-(a) \text{ with } \bar{\alpha}_k^I \in (0,1), \\ 1 & \text{otherwise,} \end{cases}$$

and $\varphi_k^I(\alpha) = \nu_k^+(b - \alpha(b_I - a_I)e^I)$, *for* $\alpha \in [0,1]$,

$$\beta_k^I = \begin{cases} \bar{\beta}_k^I, & \text{if } \psi_k^I(\beta) \text{ is } \underline{\text{not}} \text{ constant and } \psi_k^I(\bar{\beta}_k^I) = \nu_k^+(b) \text{ with } \bar{\beta}_k^I \in (0,1), \\ 1 & \text{otherwise,} \end{cases}$$

and $\psi_k^I(\beta) = \nu_k^-(a' + \beta(b_I - a'_I)e^I)$, *for* $\beta \in [0,1]$,
For $k = K_0 + 1$,

$$\beta_k^I = \begin{cases} \bar{\beta}_{K_0+1}^I, & \text{if } \gamma_{K_0+1}^I(\beta) \text{ is } \underline{\text{not}} \text{ constant and } \gamma_{K_0+1}^I(\bar{\beta}_{K_0+1}^I) = \\ & V - \varepsilon \text{ with } \bar{\beta}_{K_0+1}^I \in (0,1), \\ 1 & \text{otherwise,} \end{cases}$$

and $\gamma_{K_0+1}^I(\beta) = g(a' + \beta(b_I - a'_I)e^I)$, *for* $\beta \in [0,1]$,

(II) $UB(X_{a,b}) = \max_{\{I=1,\dots,N\}}\left\{\min_{\{k=1,\dots,K_0\}}\{\nu_k^+(\rho^I) - \nu_k^-(a)\}\right\}$, *where* $\rho^I = b + (\sigma_I^{a,b} - b_I)e^I \in \mathbb{R}^N, \sigma^{a,b} = \sigma^{X_{a,b}} = a + \theta^*(b-a) \in \mathbb{R}^N$, *and* $\theta^* = \sup\{\theta \mid g(a + \theta(b-a)) < V - \varepsilon\} \in \mathbb{R}^1$.

In Theorem 3.4 we show that solving (M0-B) entails solving some univariate linear equations.

Theorem 3.4 *To solve (M) (and consequently (M0-B)), the proposed algorithm involves finding the root of a number of univariate linear equations in each iteration.*

Theorem 3.4 implies that our suggested algorithm will efficiently solve the nonlinear DEA model in reasonable times. This is important as the DEA model could potentially be solved for a large number of DMUs in a network context.

3.4 Application to Sustainability Performance Measurement in Power Plants

In this section, we present a case study to evaluate the sustainability capabilities of the U.S. fossil-fuel power industry based on data from the year 2012. We focus on this year since all needed data is currently available. We note that there is a delay in releasing statistics due to the difficulty in gathering environmental and social indicators as they require more time to accurately assess their impacts. We use the case for two purposes: (*i*) to numerically test the BRB algorithm and compare it with current network DEA models; (*ii*) to compare the proposed DEA composite scores to those obtained by other current common measures.

Table 3.2 describes the characteristics and sustainability dimension of the seventeen indicators that we use to measure the sustainability performance in the power plants. Each network is formed by connecting two stages with two intermediate measures representing the economic dimension of sustainability. The first stage consumes four different input sources, and the second stage produces eleven outputs, altogether representing the triple aspects of sustainability. It may be tempting to consider the intermediate measure of "Annual Number of Employees" as a social indicator that is a proxy for job creation. However, we felt that this is not the case in our study as the plants are well established and there is no evidence in the data for new job openings.

While the extant literature has numerous measures for the environmental and economic dimensions of sustainability, there is a lack of studies that incorporate social measures (Chapter 2 of this thesis, Hassini et al. 2012). This is more so in the energy sector where the environmental aspects are often regarded as more important. Another complicating factor is that there seems to be a lack of agreement in the literature on what constitutes social indicators, partly because of the lack of data in this area. For example, while job creation (reflected by Annual Number of Employees in our study) is often considered as a social measure, the situation for health and safety measures is different. While Veleva and Ellenbecker (2001) consider health and safety indicator under the environmental dimension, there is more consensus in the recent literature to consider them under the social dimension (e.g., see Chapter 2 of this thesis, Norman and MacDonald (2004), Cetinkaya et al. (2011)). Thus in our case study we consider the health and safety indicators (y_1 to y_6 in Table 3.2) to represent the social dimension of sustainability. Unfortunately data about other social indicators, such as employee diversity, working conditions, and impacts on communities were not available to us.

3.4.1 Data Collection

The initial raw data set had measures for 418 electricity generation units/plants. Cleaning the data by removing DMUs with missing or duplicate data points, resulted in 135 usable data sets. For this shorter list of DMUs, we found all the data on measures that are necessary to implement the proposed model. In particular, in the case that a power plant had multiple units and each of the units was reported individually, for the sake of consistency we integrated the individual measures for that facility.

We note that some of the indicators needed in this application are facility-based (i.e., the initial construction and land acquisition costs which determine the book value), and therefore it is more reasonable to look at their data from the plant perspective. Preliminary analysis on these data sets revealed that results may be biased by the plant capacity. We found that stations with extremely low capacity may generate a limited amount of electricity annually, and as a consequence get a high sustainability measure. In an extreme case, an idle power station may show high efficiency from a sustainability perspective. Thus, we decided to eliminate the low capacity plants resulting in a final count of 90 data sets. Our choice of the remaining plants was motivated by the statistics released by the U.S. Energy Information Administration (EIA 2014) that takes 20% as a minimal level of the capacity for units that primarily use fossil fuels in 2012. More analysis relating to the capacity factor will be provided in Section 3.4.

As shown in the last column of Table 3.2, the data is collected from four main online resources that has consistent annual data on most power stations in the U.S. The Environmental Protection Agency (EPA) is one of the largest sources monitoring greenhouse gas emissions in the U.S. under the President's Climate Action Plan. In addition to comprehensive information gathered by the Facility Level Information of GreenHouse Gases Tool map, this agency provides us with a plethora of environmental figures by facility through the Air Markets Program Data platform.

Table 3.2: Indicator list used in BRB to investigate the Power Plant case study

	Measure	Type	Dimension	Description	Source
Stage 1	x_1	Input	Environmental	Annual Fuel Consumed (MMBTU)	EIA
	x_2	Input	Economic	Book Value of Plant and Land ($)	FERC
	x_3	Input	Economic	Annual Production Expenses ($)	FERC
	x_4	Input	Economic	Plant Nameplate Capacity (MW)	EIA
Stage 1&2	z_1	Intermediate	Economic	Annual Electricity Net Generation (MWH)	EIA
	z_2	Intermediate	Economic	Annual Number of Employees	FERC
Stage 2	y_1	Output	Social	Annual Incidence of Deaths	CATF
	y_2	Output	Social	Annual Incidence of Heart Attacks	CATF
	y_3	Output	Social	Annual Incidence of Asthma Attacks	CATF
	y_4	Output	Social	Annual Incidence of Hospital Admissions	CATF
	y_5	Output	Social	Annual Incidence of Chronic Bronchitis	CATF
	y_6	Output	Social	Annual Incidence of Asthma ER Visits	CATF
	y_7	Output	Environmental	Carbon Dioxide (CO_2) Emission (TON)	EPA
	y_8	Output	Environmental	Nitrous Oxide (N_2O) Emission (TON)	EPA
	y_9	Output	Environmental	Methane (CH_4) Emission (TON)	EPA
	y_{10}	Output	Environmental	Sulfur Dioxide (SO_2) Emission (TON)	EPA
	y_{11}	Output	Environmental	Nitrogen Oxides (NO_x) Emission (TON)	EPA

The EIA is our second data source. EIA collects and disseminates independent and impartial energy information around the world. We especially exploit the survey Form EIA-923 in which power plants' detailed data on electricity generation and fuel consumption is stored. Our third data source comes from the Federal Energy Regulatory Commission (FERC), an independent agency that regulates the interstate transmission of natural gas, oil, and electricity. We use their Form 1 which is a comprehensive operating report submitted quarterly by energy corporations for the purpose of regulating electricity rates. In particular, we use this information to gather data on financial performance and infrastructure investment of the facilities. Finally, we use data from the Clean Air Task Force (CATF) which was launched with a goal "to enact federal policy to reduce the pollutants from America's power plants that cause respiratory death and disease, smog, acid rain, and haze" and is dedicated to help safeguard against the impacts of climate change. This last data source is important for us as it is the only source available that provides information on social impacts from power plant emissions' air pollution. It is also a new data set and to the best of our knowledge we are the first to use it for determining social sustainability measures for power plants.

To illustrate our model we will apply it the case where z_1 (Annual Electricity Net Generation) is heterogeneous and z_2 (Annual Number of Employees) is homogeneous. This will be compared to the scenario where all intermediates are homogeneous, as has been assumed in the extant two stage DEA network models. We will now explain our reasoning for picking z_1 to be heterogeneous and z_2 homogeneous [1]. The two stages are expected to interpret electricity generation differently: the financially oriented Stage 1 would prefer a large amount of power production (to more effectively recoup the massive investment to build the facility), while the sustainable mission of Stage 2 would look at high generation as a potential to make higher levels of environmental and social impacts. That is, Stage 1 and Stage 2 value the intermediate z_1 differently. Therefore we have elected to take the "Annual Electricity Net Generation" as a heterogeneous intermediate. In practice there may exist other intermediate heterogeneous factors depending on the application and data availability. For example, in countries with weaker economic growth the governments welcome private sectors to invest in power generation projects. Not surprisingly, the investors expect a portion of operating revenues from the sale of electricity. Accordingly, the rate of return on investments is always a debatable factor in negotiations. The host governments typically want to avoid financial loss as well as upsetting environmental groups, while the investors aim to increase their return on investment. As for the "Annual Number of Employees" factor, empirical evidence has found that when it comes to the employees the financial and sustainable mission of the network should be aligned. For example, Starbucks offers its employees stock and pension plans as a form of economic security and is considered a leader in both financial and sustainability performance (Bansal 2002).

Using the two-stage DEA model explained in Section 3.3 we integrate the financial and sustainable stages into a centralized model. A summary of all the data needed for the DEA model is in **Appendix A.3**. We note that the column "Movers" explains

[1] Thanks to an anonymous reviewer who has suggested using this configuration of the input/output and intermediate factors.

types of units installed in each facility including: Combined-cycle Turbine (CA/CT), Gas Turbine (GT), Internal Combustion (IC), and Steam Turbine (ST).

DEA models with a higher level of outputs generally indicate better performance. One approach to deal with undesirable outputs which do not satisfy this rule of thumb is to take the reciprocals of their values into account (Chen et al. 2012). We apply this rule for the environmental and social measures of the second stage.

To solve each problem instance, we first apply the proposed BRB algorithm which has been coded in the C Programming Language. Afterwards, the obtained results are validated by solving the same instance by a nonlinear programming solvers in GAMS 23.5 software on a 4GB RAM, 2.50GHz desktop computer. For all instances we initialize the BRB algorithm using $\varepsilon = 0.001$, $x^l = 10^{-7}$, and $x^u = 10^8$.

3.4.2 Nonparametric Statistical Analysis

As we explain later, there exist various efficiency scores to evaluate the performance of power plants. We use several nonparametric statistics to investigate potential significant differences between these efficiency scores. The statistical tests were carried out with SPSS Statistics 22. Using inferential statistics, such as the Wilcoxon statistic and the bivariate correlations, we provide empirical evidence (at the 0.05 significance level) that our results are statistically different from the existing efficiency scores. The Wilcoxon signed rank test and the sign test are procedures that are used to statistically compare two paired samples (Corder and Foreman 2014). The null hypothesis of these nonparametric tests states that "there is no significant difference between the paired samples." In addition, the Levene's test and the Bartlett's test can be used to test for differences in variances between two paired samples (Olkin 1960, Snedecor and Cochran 1989). Their null hypothesis states that "the homogeneity of the groups' variances is significant." Finally, we utilize the Spearman rank-order and Kendall τ correlations to examine the relationship between two ordinal-scaled variables, such as testing for different rankings that one may obtain from two distinct methods (Corder and Foreman 2014, Kendall 1970). Let r_s and τ_b denote the Spearman and Kendall correlation coefficients, respectively. To examine the null hypothesis that "there is no significant correlation between the ranked variables" we consider $H_0 : r_s = 0$ and $H_0 : \tau_b = 0$, respectively.

3.4.3 Homogeneous vs. Heterogeneous Intermediates

We start by applying the centralized DEA model to the data set for all 90 plants presented in **Appendix A.3**. Table 3.3 includes the different efficiency scores and rankings of the DMUs based on their performance resulting from the proposed nonlinear DEA model ($e_o^{\text{BRB}} = e_o^{\text{Mixed}}$), the linear DEA model in Liang et al. (2008), as well as the separable standard DEA models discussed in Section 3.3. The BRB algorithm takes 200 nodes to find the same solution obtained by GAMS, where $\varepsilon = 0.001$. We recall that Liang et al. (2008) evaluated the efficiency of these DMUs by assuming that $w_d \equiv \widetilde{w}_d$ for each $d \in \Delta$ and converting (M0-A) to a linear programme. As shown in Table 3.3, BRB leads to different performance efficiencies and ranking from those of Liang et al. (2008), and those of the separable models. In Figure 3.4 we show the difference between our proposed mixed intermediate model and that of Liang et al. (2008) that used homogeneous intermediates. To highlight the difference we use a line to plot the mixed scores and bars for the homogeneous scores. As shown in Theorem 3.1, we see that the mixed scores are always greater than or equal to that of the homogeneous model. In other words in cases where the network stages do not value the intermediates equally, we would underestimate the DMUs scores by using the homogeneous model. We also note that both scores follow the same trend, but with different magnitudes scaling factors. In addition, we note that there is a noticeable difference between the variables w_1 and $\widetilde{w}_1$. These observations will be confirmed through our statistical tests.

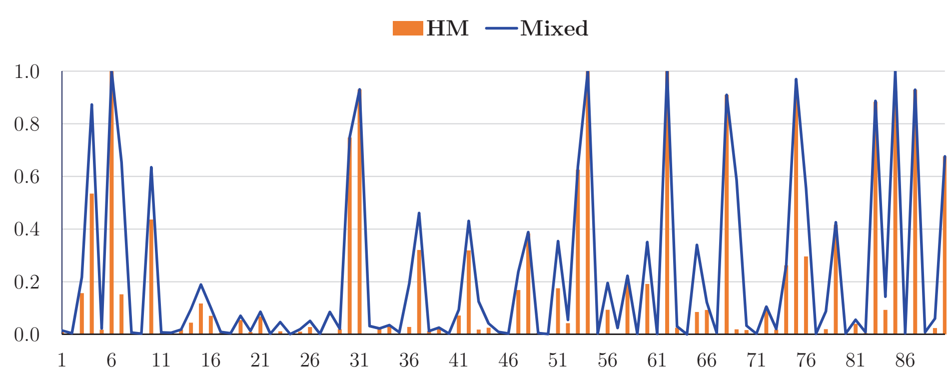


Figure 3.4: Comparison of scores between the mixed and homogeneous models

Table 3.4 summarizes the results of different comparisons between the paired groups reported in Table 3.3. Regarding the pair that includes the composite efficiency scores e_o^{BRB} and e_o^{HM}, Wilcoxon signed rank, sign, and Levene's tests result in p-values less than 5%. This implies that there is a significant difference between the two composite score vectors and that the similarity of the two vectors' variances is not significant. From the correlation tests we infer that there is a low correspondence between the DMUs rankings, given that the coefficients of determination are $R_s^2 = 0.151$ and $R_b^2 = 0.158$. We note that comparing the pair $(e_o^{\mathrm{BRB}}, e_o^{\mathrm{HT}})$ leads to a similar result, however, homogeneity of the variances cannot be rejected at the 5% significant level.

Comparing the intermediate weights w_1 and $\tilde{w}_1$ shows that there is a significant difference between the variables that represent the annual electricity generation. With regards to the homogeneity of variances, we note that both the Bartlett's test and the Levene's test strongly reject the null hypothesis (explaining a difference between the variances).

In summary, the above arguments imply that avoiding the more realistic nonlinear format in (M0-B) can result in significantly different evaluations which can lead to misleading actions by management and policy makers. This is especially critical for systems where the weights of some of the intermediate indicators outgoing from Stage 1 are not necessarily equal to that of the intermediate measures incoming into Stage 2, a situation that is quite common in complex systems such as those of power plants and supply chains.

Table 3.3: The result of evaluating DMUs of the Power Plant case study [Heterogeneous vs. Homogeneous Intermediates]

Power Plants			**The Proposed Nonlinear DEA**				**Homogeneous Case**		**Heterogeneous Case**	
#	DMU	Movers	w_1^*	$\widetilde{w}_1^*$	e_o^{BRB}	Rank	e_o^{HM}	Rank	e_o^{HT}	Rank
1	DMU1	GT; ST	0.044	0.001	0.0147	61	0.0103	59	0.0147	62
2	DMU2	ST	0.003	0.000	0.0042	75	0.0019	75	0.0042	77
3	DMU3	ST	0.009	0.000	0.2173	28	0.1567	25	0.2234	27
4	DMU4	CA; CT	0.007	0.000	0.8730	10	0.5349	13	0.8730	10
5	DMU5	CA; CT; GT	0.001	0.000	0.0223	56	0.0181	54	0.0223	57
6	DMU6	ST	0.000	0.000	1.0000	1	1.0000	1	1.0000	2
7	DMU7	CA; CT	0.305	0.000	0.6538	13	0.1523	26	0.6538	13
8	DMU8	ST	0.004	0.000	0.0068	70	0.0016	77	0.0068	71
9	DMU9	GT; IC; ST	0.010	0.000	0.0026	81	0.0012	81	0.0026	82
10	DMU10	CA; CT	0.024	0.000	0.6348	15	0.4363	14	0.6348	15
11	DMU11	GT; ST	0.001	0.000	0.0074	69	0.0044	65	0.0074	70
12	DMU12	ST	0.000	0.001	0.0063	71	0.0062	61	0.0063	72
13	DMU13	IC; ST	0.002	0.000	0.0183	60	0.0183	51	0.0183	61
14	DMU14	CA; CT; ST	0.021	0.000	0.0963	37	0.0446	37	0.0963	38
15	DMU15	ST	0.221	0.012	0.1893	31	0.1174	27	0.1893	31
16	DMU16	ST	0.022	0.000	0.1016	36	0.0705	34	0.1016	37
17	DMU17	IC; ST	159.933	1.251	0.0095	64	0.0054	62	0.0095	65
18	DMU18	GT; ST	0.001	0.000	0.0043	74	0.0025	72	0.0043	76
19	DMU19	GT; ST	33.436	0.767	0.0706	42	0.0544	36	0.0706	43
20	DMU20	GT; ST	0.001	0.000	0.0132	62	0.0090	60	0.0132	63
21	DMU21	ST	0.001	0.000	0.0858	40	0.0683	35	0.0858	41
22	DMU22	ST	0.005	0.003	0.0023	82	0.0022	74	0.0023	83
23	DMU23	ST	0.031	0.000	0.0467	47	0.0115	57	0.0467	49
24	DMU24	ST	0.000	0.000	0.0009	89	0.0008	85	0.0009	90
25	DMU25	ST	0.011	0.001	0.0197	59	0.0103	58	0.0197	60
26	DMU26	ST	0.082	0.002	0.0513	46	0.0280	42	0.0513	47
27	DMU27	ST	0.001	0.000	0.0021	84	0.0015	79	0.0021	85
28	DMU28	ST	343.113	9.661	0.0851	41	0.0001	89	0.0851	42
29	DMU29	ST	0.018	0.001	0.0216	57	0.0196	49	0.0217	58
30	DMU30	GT; ST	0.000	0.002	0.7495	11	0.7479	10	0.7495	11
31	DMU31	CA; CT	0.182	0.000	0.9306	6	0.9305	4	0.9306	6
32	DMU32	ST	0.005	0.000	0.0318	51	0.0003	88	0.0318	52
33	DMU33	GT; ST	0.001	0.084	0.0225	55	0.0220	47	0.0225	56
34	DMU34	ST	0.000	0.000	0.0351	49	0.0348	40	0.0484	48
35	DMU35	ST	0.003	0.000	0.0078	68	0.0032	68	0.0078	69
36	DMU36	CA; CT; GT	17.475	0.000	0.1927	30	0.0283	41	0.1927	30
37	DMU37	ST	0.005	0.000	0.4609	18	0.3208	17	0.4609	19
38	DMU38	ST	0.051	0.003	0.0126	63	0.0124	56	0.0126	64
39	DMU39	ST	0.001	0.000	0.0257	53	0.0237	46	0.0257	54
40	DMU40	GT; IC; ST	0.001	0.010	0.0030	79	0.0030	70	0.0030	80
41	DMU41	ST	0.004	0.000	0.0937	38	0.0718	33	0.0936	39
42	DMU42	CA; CT	0.021	0.000	0.4309	19	0.3190	18	0.4309	21
43	DMU43	CA; CT	0.109	0.000	0.1250	33	0.0183	52	0.1250	33
44	DMU44	ST	0.051	0.001	0.0416	48	0.0252	44	0.0416	50
45	DMU45	ST	0.031	0.000	0.0093	65	0.0032	67	0.0093	66

Table 3.3: The result of evaluating DMUs of the Power Plant case study [Heterogeneous vs. Homogeneous Intermediates]

Power Plants			The Proposed Nonlinear DEA				Homogeneous Case		Heterogeneous Case	
#	DMU	Movers	w_1^*	$\tilde{w}_1^*$	e_o^{BRB}	Rank	e_o^{HM}	Rank	e_o^{HT}	Rank
46	DMU46	ST	0.004	0.000	0.0033	78	0.0016	78	0.0033	79
47	DMU47	GT; ST	0.001	0.000	0.2380	26	0.1686	24	0.2380	26
48	DMU48	GT; ST	1.921	0.001	0.3884	21	0.3837	16	0.4962	18
49	DMU49	ST	0.000	0.000	0.0050	73	0.0050	63	0.0050	75
50	DMU50	ST	0.001	0.000	0.0013	88	0.0006	87	0.0013	89
51	DMU51	CA; CT	289.058	0.000	0.3544	22	0.1752	23	0.3544	22
52	DMU52	IC; ST	0.008	0.000	0.0551	45	0.0425	38	0.0551	46
53	DMU53	ST	0.000	0.003	0.6373	14	0.6257	12	0.6373	14
54	DMU54	ST	0.000	0.000	1.0000	3	1.0000	2	1.0000	2
55	DMU55	ST	0.000	0.000	0.0036	77	0.0018	76	0.0056	73
56	DMU56	CA; CT	0.084	0.000	0.1951	29	0.0933	29	0.1951	29
57	DMU57	CA; CT; GT; ST	0.020	0.000	0.0243	54	0.0023	73	0.0243	55
58	DMU58	GT; ST	0.092	0.006	0.2224	27	0.2111	21	0.2225	28
59	DMU59	GT; ST	0.003	0.000	0.0020	86	0.0009	83	0.0020	87
60	DMU60	ST	0.022	0.000	0.3508	23	0.1916	22	0.3508	23
61	DMU61	ST	0.001	0.000	0.0016	87	0.0009	84	0.0016	88
62	DMU62	CA; CT	0.000	0.000	1.0000	1	1.0000	2	1.0000	4
63	DMU63	ST	0.000	0.000	0.0300	52	0.0254	43	0.0301	53
64	DMU64	ST	0.000	0.000	0.0001	90	0.0001	90	0.0922	40
65	DMU65	CA; CT	0.082	0.000	0.3400	24	0.0850	32	0.3407	24
66	DMU66	CA; CT; GT; ST	0.001	0.000	0.1220	34	0.0928	31	0.1220	34
67	DMU67	ST	0.003	0.000	0.0053	72	0.0031	69	0.0053	74
68	DMU68	CA; CT	0.559	0.000	0.9098	8	0.9099	8	0.9098	8
69	DMU69	CA; CT	0.176	0.000	0.5862	16	0.0192	50	0.5862	16
70	DMU70	ST	0.013	0.000	0.0331	50	0.0163	55	0.0331	51
71	DMU71	IC; ST	0.001	0.000	0.0023	83	0.0011	82	0.0023	84
72	DMU72	ST	0.000	0.015	0.1051	35	0.1027	28	0.1051	35
73	DMU73	ST	35.617	0.000	0.0204	58	0.0181	53	0.0204	59
74	DMU74	ST	0.000	0.000	0.2624	25	0.2622	20	0.2624	25
75	DMU75	ST	0.005	0.059	0.9697	5	0.9243	6	0.9697	5
76	DMU76	CA; CT	0.062	0.000	0.5554	17	0.2961	19	0.5553	17
77	DMU77	ST	0.009	0.000	0.0020	85	0.0007	86	0.0020	86
78	DMU78	CA; CT; ST	1,829.396	0.000	0.0875	39	0.0198	48	0.1019	36
79	DMU79	GT; ST	0.599	0.001	0.4258	20	0.4164	15	0.4441	20
80	DMU80	ST	0.003	0.000	0.0028	80	0.0014	80	0.0028	81
81	DMU81	ST	0.001	0.000	0.0556	44	0.0404	39	0.0556	45
82	DMU82	ST	0.037	0.001	0.0083	66	0.0049	64	0.0083	67
83	DMU83	ST	0.097	0.026	0.8869	9	0.8834	9	0.8894	9
84	DMU84	ST	81.040	0.000	0.1433	32	0.0930	30	0.1433	32
85	DMU85	GT; ST	0.000	0.000	1.0000	4	0.9239	7	1.0000	1
86	DMU86	ST	0.000	0.000	0.0041	76	0.0034	66	0.0041	78
87	DMU87	CA; CT	0.412	0.000	0.9294	7	0.9294	5	0.9293	7
88	DMU88	ST	0.006	0.000	0.0080	67	0.0028	71	0.0080	68
89	DMU89	GT; ST	0.006	0.000	0.0602	43	0.0240	45	0.0602	44
90	DMU90	ST	0.002	0.000	0.6760	12	0.6760	11	0.6760	12

Table 3.4: Statistical tests comparing the pairs in Table 3.3 to investigate the Power Plant case

Test/Statistic	e_o^{BRB} vs. e_o^{HM}	$\mathrm{Rank}^{\mathrm{BRB}}$ vs. $\mathrm{Rank}^{\mathrm{HM}}$	w_1 vs. $\widetilde{w}_1$	e_o^{BRB} vs. e_o^{HT}
Median Comparison				
p-value of Wilcoxon	0.004	–	0.003	0.005
p-value of Sign	0.010	–	0.024	0.035
Variance Comparison				
p-value of Levene	0.041	–	0.041	0.110
p-value of Bartlett	0.059	–	0.000	0.002
Spearman Correlation	–	$r_s = 0.397$	–	–
	–	$R_s^2 = 0.158$	–	–
Kendall Correlation	–	$\tau_b = 0.389$	–	–
	–	$R_b^2 = 0.151$	–	–

3.4.4 DEA Composite Scores vs. Traditional Technical Scores

In this section we would like to compare the DEA sustainability composite scores to the commonly-used technical ratios in the energy sector, such as the power plants' capacity factor and thermal efficiency values. We rely on the definitions proposed by the online glossary of the EIA, which states that "the capacity factor is the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period," i.e., $\mathrm{CF} = \frac{z_1}{366\times 24\times x_4}$, and "the thermal efficiency is a measure of the efficiency of converting a fuel to useful work that is equal to energy output divided by higher heating value of input fuel times 100," i.e., $\mathrm{TE} = \frac{3.413\times z_1}{x_1}$. The results of comparing these two technical measures to our proposed DEA measure are included in Table 3.5. In Figure 3.5 we compare the scores of these three models. We note that our proposed model shows different trends from those of the other two existing measures. Under our proposed model the majority of the power plants have scores that show significant deviations from those obtained by the existing measures. Most of these deviations are on the negative side reflecting an overestimation of the plants efficiency scores when we ignore the environmental and social aspects. In particular, we may have underestimated well performing plants (such as plant 6) and overestimated low performers (such as plant 12).

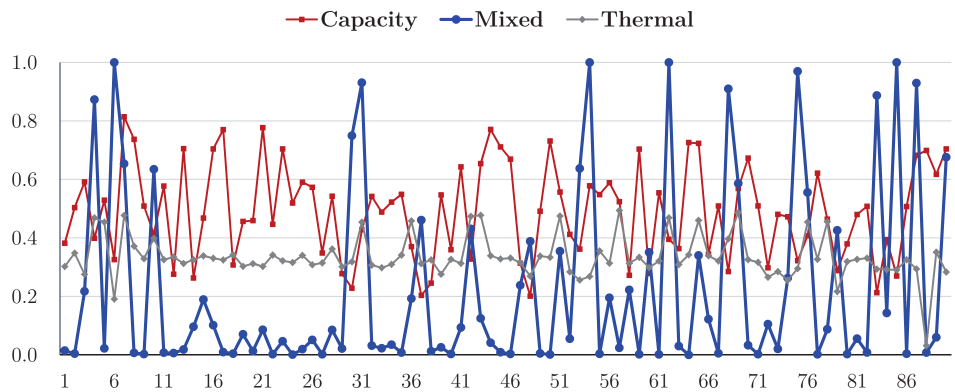


Figure 3.5: Comparison of scores between current measures and the proposed measure

To analyze these results we conduct statistical tests to compare the DEA composite score, e_o^{BRB}, and the aforementioned thermal and capacity technical ratios, the results of which are included in the sixth and eight columns of Table 3.5, respectively. Table 3.6 presents the outcome of these statistical tests. We note that all four tests confirm the significant difference between the pairs (e_o^{BRB} , CF) and (e_o^{BRB} , TE). In addition, evidence from comparing the rankings on the basis of R_s^2 and R_b^2 suggests that no significant correspondence exists between the rankings of the DEA composite sustainability measure and the rankings obtained from the capacity factor and thermal efficiency measures. This confirms our prediction that the capacity factor and thermal efficiency scores cannot necessarily reflect the environmental and social impacts when measuring the performance of power plants.

Table 3.5: The result of evaluating DMUs of the Power Plant case study [Systematic Scores vs. Technical Scores]

Power Plants			The Proposed Model					
#	DMU	Movers	e_o^{BRB}	Rank	Capacity F.	Rank	Thermal E.	Rank
1	DMU1	GT; ST	0.0147	61	0.3817	64	0.3023	69
2	DMU2	ST	0.0042	75	0.5035	46	0.3481	21
3	DMU3	ST	0.2173	28	0.5914	23	0.2753	82
4	DMU4	CA; CT	0.8730	10	0.3988	61	0.4686	8
5	DMU5	CA; CT; GT	0.0223	56	0.5290	37	0.4538	14
6	DMU6	ST	1.0000	1	0.3260	73	0.1908	89
7	DMU7	CA; CT	0.6538	13	0.8143	1	0.4771	4
8	DMU8	ST	0.0068	70	0.7373	5	0.3717	17
9	DMU9	GT; IC; ST	0.0026	81	0.5087	43	0.3289	37
10	DMU10	CA; CT	0.6348	15	0.4138	58	0.3986	15
11	DMU11	GT; ST	0.0074	69	0.5773	27	0.3256	44
12	DMU12	ST	0.0063	71	0.2762	82	0.3346	31
13	DMU13	IC; ST	0.0183	60	0.7051	10	0.3126	60
14	DMU14	CA; CT; ST	0.0963	37	0.2631	85	0.3257	42
15	DMU15	ST	0.1893	31	0.4680	52	0.3389	29
16	DMU16	ST	0.1016	36	0.7044	13	0.3305	36
17	DMU17	IC; ST	0.0095	64	0.7701	4	0.3248	47
18	DMU18	GT; ST	0.0043	74	0.3076	76	0.3426	22
19	DMU19	GT; ST	0.0706	42	0.4561	55	0.3030	67
20	DMU20	GT; ST	0.0132	62	0.4593	54	0.3120	61
21	DMU21	ST	0.0858	40	0.7770	2	0.3026	68
22	DMU22	ST	0.0023	82	0.4463	56	0.3415	24
23	DMU23	ST	0.0467	47	0.7044	11	0.3218	48
24	DMU24	ST	0.0009	89	0.5192	40	0.3160	54
25	DMU25	ST	0.0197	59	0.5907	24	0.3403	26
26	DMU26	ST	0.0513	46	0.5730	28	0.3081	65
27	DMU27	ST	0.0021	84	0.3486	70	0.3145	56
28	DMU28	ST	0.0851	41	0.5426	35	0.3624	18
29	DMU29	ST	0.0216	57	0.2779	81	0.3016	70
30	DMU30	GT; ST	0.7495	11	0.2282	87	0.3184	52
31	DMU31	CA; CT	0.9306	6	0.4282	57	0.4541	13
32	DMU32	ST	0.0318	51	0.5417	36	0.3070	66
33	DMU33	GT; ST	0.0225	55	0.4887	48	0.2982	72
34	DMU34	ST	0.0351	49	0.5226	39	0.3097	63
35	DMU35	ST	0.0078	68	0.5489	32	0.3413	25
36	DMU36	CA; CT; GT	0.1927	30	0.3700	66	0.4581	10
37	DMU37	ST	0.4609	18	0.2038	89	0.3116	62
38	DMU38	ST	0.0126	63	0.2453	86	0.3252	46
39	DMU39	ST	0.0257	53	0.5470	34	0.2758	81
40	DMU40	GT; IC; ST	0.0030	79	0.3598	69	0.3266	41
41	DMU41	ST	0.0937	38	0.6430	20	0.3130	59
42	DMU42	CA; CT	0.4309	19	0.3276	72	0.4738	6
43	DMU43	CA; CT	0.1250	33	0.6541	19	0.4773	3
44	DMU44	ST	0.0416	48	0.7709	3	0.3392	28
45	DMU45	ST	0.0093	65	0.7110	9	0.3281	38

Table 3.5: The result of evaluating DMUs of the Power Plant case study [Systematic Scores vs. Technical Scores]

Power Plants			The Proposed Model					
#	DMU	Movers	e_o^{BRB}	Rank	Capacity F.	Rank	Thermal E.	Rank
46	DMU46	ST	0.0033	78	0.6693	18	0.3311	34
47	DMU47	GT; ST	0.2380	26	0.3139	75	0.3155	55
48	DMU48	GT; ST	0.3884	21	0.2012	90	0.2693	83
49	DMU49	ST	0.0050	73	0.4913	47	0.3382	30
50	DMU50	ST	0.0013	88	0.7314	6	0.3336	33
51	DMU51	CA; CT	0.3544	22	0.5566	30	0.4747	5
52	DMU52	IC; ST	0.0551	45	0.4122	59	0.2838	79
53	DMU53	ST	0.6373	14	0.3615	68	0.2560	86
54	DMU54	ST	1.0000	3	0.5783	26	0.2684	84
55	DMU55	ST	0.0036	77	0.5484	33	0.3557	19
56	DMU56	CA; CT	0.1951	29	0.5885	25	0.3136	57
57	DMU57	CA; CT; GT; ST	0.0243	54	0.5239	38	0.4941	1
58	DMU58	GT; ST	0.2224	27	0.2721	83	0.3130	58
59	DMU59	GT; ST	0.0020	86	0.7037	14	0.3337	32
60	DMU60	ST	0.3508	23	0.2785	80	0.2984	71
61	DMU61	ST	0.0016	87	0.5543	31	0.3210	50
62	DMU62	CA; CT	1.0000	1	0.3951	62	0.4691	7
63	DMU63	ST	0.0300	52	0.3636	67	0.3092	64
64	DMU64	ST	0.0001	90	0.7262	7	0.3423	23
65	DMU65	CA; CT	0.3400	24	0.7232	8	0.4602	9
66	DMU66	CA; CT; GT; ST	0.1220	34	0.3443	71	0.3392	27
67	DMU67	ST	0.0053	72	0.5091	42	0.3213	49
68	DMU68	CA; CT	0.9098	8	0.2848	79	0.3968	16
69	DMU69	CA; CT	0.5862	16	0.5689	29	0.4866	2
70	DMU70	ST	0.0331	50	0.6728	17	0.3256	43
71	DMU71	IC; ST	0.0023	83	0.5094	41	0.3169	53
72	DMU72	ST	0.1051	35	0.2981	77	0.2656	85
73	DMU73	ST	0.0204	58	0.4808	49	0.2850	78
74	DMU74	ST	0.2624	25	0.4722	51	0.2550	87
75	DMU75	ST	0.9697	5	0.3220	74	0.2949	73
76	DMU76	CA; CT	0.5554	17	0.4074	60	0.4544	12
77	DMU77	ST	0.0020	85	0.6214	21	0.3271	40
78	DMU78	CA; CT; ST	0.0875	39	0.4641	53	0.4552	11
79	DMU79	GT; ST	0.4258	20	0.2881	78	0.2167	88
80	DMU80	ST	0.0028	80	0.3796	65	0.3193	51
81	DMU81	ST	0.0556	44	0.4802	50	0.3271	39
82	DMU82	ST	0.0083	66	0.5080	44	0.3308	35
83	DMU83	ST	0.8869	9	0.2128	88	0.2935	75
84	DMU84	ST	0.1433	32	0.3941	63	0.2920	76
85	DMU85	GT; ST	1.0000	4	0.2696	84	0.2907	77
86	DMU86	ST	0.0041	76	0.5072	45	0.3255	45
87	DMU87	CA; CT	0.9294	7	0.6826	16	0.2937	74
88	DMU88	ST	0.0080	67	0.6991	15	0.0316	90
89	DMU89	GT; ST	0.0602	43	0.6174	22	0.3511	20
90	DMU90	ST	0.6760	12	0.7044	12	0.2832	80

Table 3.6: Statistical tests comparing the pairs in Table 3.5 to investigate the Power Plant case

Test/Statistic	e_o^{BRB} vs. CF	Rank$^{\mathrm{BRB}}$ vs. Rank$^{\mathrm{C}}$	e_o^{BRB} vs. TE	Rank$^{\mathrm{BRB}}$ vs. Rank$^{\mathrm{T}}$
Median Comparison				
p-value of Wilcoxon	0.008	–	0.002	–
p-value of Sign	0.014	–	0.009	–
Variance Comparison				
p-value of Levene	0.000	–	0.001	–
p-value of Bartlett	0.005	–	0.001	–
Spearman Correlation	–	r_s = -0.297	–	r_s = -0.114
	–	$R_s^2 = 0.088$	–	$R_s^2 = 0.013$
Kendall Correlation	–	τ_b = -0.200	–	τ_b = -0.087
	–	$R_b^2 = 0.040$	–	$R_b^2 = 0.008$

3.4.5 Comparing Triple and Double Sustainability Measures

We now turn our attention to investigate the effect of aggregating several sustainability aspects in a composite measure (Elkington 1997). To this end, we performed more statistical tests between cases that include a subset of the indicators listed in Table 3.3. More specifically, through the proposed two-stage DEA assessment framework and the BRB algorithm two scenarios were studied: (i) a Double Perspective, e_o^{II}, which includes both economic and environmental indicators; (ii) a Triple Perspective, e_o^{III}, which includes all indicators. The computational results of these instances (the efficiency scores and their corresponding rankings) are summarized in Table 3.7. In Figure 3.6 the triple scores are shown with bars to contrast them to the double scores that are shown in line plots. We note that the double scores underestimate the triple scores. The two measures also show similar trends with different magnitudes. This may give the impression that the plants ranking will not change under these two measure, however as we can see from Table 3.7 there are several power plants for which the rankings differ significantly. For example for power plant 58, it is ranked 27 under the triple measure but 45 under double measure.

Table 3.7 clearly demonstrates that these settings lead to different conclusions regarding the DMUs' performance evaluation. This is also confirmed by the results of the statistical tests shown in Table 3.8. We see that all four tests support the existence of a significant difference between the Triple and Double cases. We note that the achieved rankings from this pair are lowly correlated, considering the coefficients of determination $R_s^2 = 0.239$ and $R_b^2 = 0.197$. This is expected as the Double measures are composites of indicators that are a subset of the indicators used to calculate the Triple score. From this discussion we can conclude that unless environmental/social measures are explicitly incorporated in an aggregate measure, economic performance measures will not accurately reflect their impact. This conclusion confirms the current trend that large corporations are making by being more transparent on reporting environmental/social metrics related to their business practices. For example, Apple Inc. now reports metrics such as supplier work-hour compliance, average weekly working hours, and number of worker participating in workers' rights training programs (Apple 2015). Chen and Delmas have reached similar conclusion when investigating common frontier approaches and their suitability for use for measuring corporate eco-inefficiency (Chen and Delmas 2012).

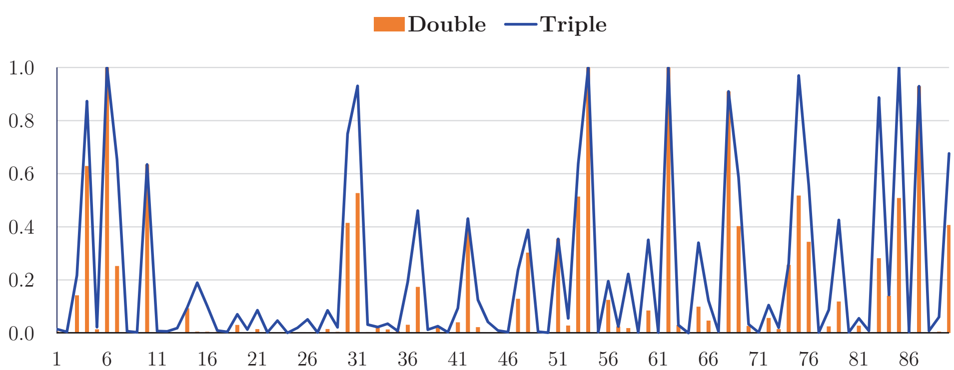


Figure 3.6: Comparison of scores between triple and double measures

Table 3.7: The result of evaluating DMUs of the Power Plant case study [Triple and Double Perspectives]

Power Plants			The Proposed Nonlinear DEA			
#	DMU	Movers	$e_o^{\text{III}} = e_o^{\text{Triple}}$	Rank	$e_o^{\text{II}} = e_o^{\text{Double}}$	Rank
1	DMU1	GT; ST	0.0147	61	0.0059	52
2	DMU2	ST	0.0042	75	0.0000	90
3	DMU3	ST	0.2173	28	0.1422	23
4	DMU4	CA; CT	0.8730	10	0.6291	7
5	DMU5	CA; CT; GT	0.0223	56	0.0140	49
6	DMU6	ST	1.0000	1	1.0000	1
7	DMU7	CA; CT	0.6538	13	0.2524	21
8	DMU8	ST	0.0068	70	0.0010	76
9	DMU9	GT; IC; ST	0.0026	81	0.0009	78
10	DMU10	CA; CT	0.6348	15	0.6348	6
11	DMU11	GT; ST	0.0074	69	0.0007	80
12	DMU12	ST	0.0063	71	0.0034	64
13	DMU13	IC; ST	0.0183	60	0.0034	63
14	DMU14	CA; CT; ST	0.0963	37	0.0931	29
15	DMU15	ST	0.1893	31	0.0051	54
16	DMU16	ST	0.1016	36	0.0048	55
17	DMU17	IC; ST	0.0095	64	0.0047	56
18	DMU18	GT; ST	0.0043	74	0.0007	81
19	DMU19	GT; ST	0.0706	42	0.0304	35
20	DMU20	GT; ST	0.0132	62	0.0035	62
21	DMU21	ST	0.0858	40	0.0149	47
22	DMU22	ST	0.0023	82	0.0020	69
23	DMU23	ST	0.0467	47	0.0036	60
24	DMU24	ST	0.0009	89	0.0006	83
25	DMU25	ST	0.0197	59	0.0020	68
26	DMU26	ST	0.0513	46	0.0035	61
27	DMU27	ST	0.0021	84	0.0007	79
28	DMU28	ST	0.0851	41	0.0152	46
29	DMU29	ST	0.0216	57	0.0046	57
30	DMU30	GT; ST	0.7495	11	0.4148	12
31	DMU31	CA; CT	0.9306	6	0.5270	8
32	DMU32	ST	0.0318	51	0.0041	58
33	DMU33	GT; ST	0.0225	55	0.0199	44
34	DMU34	ST	0.0351	49	0.0136	50
35	DMU35	ST	0.0078	68	0.0074	51
36	DMU36	CA; CT; GT	0.1927	30	0.0312	34
37	DMU37	ST	0.4609	18	0.1737	22
38	DMU38	ST	0.0126	63	0.0038	59
39	DMU39	ST	0.0257	53	0.0249	41
40	DMU40	GT; IC; ST	0.0030	79	0.0029	65
41	DMU41	ST	0.0937	38	0.0404	33
42	DMU42	CA; CT	0.4309	19	0.3860	15
43	DMU43	CA; CT	0.1250	33	0.0221	43
44	DMU44	ST	0.0416	48	0.0015	73
45	DMU45	ST	0.0093	65	0.0003	87

Table 3.7: The result of evaluating DMUs of the Power Plant case study [Triple and Double Perspectives]

Power Plants			The Proposed Nonlinear DEA			
#	DMU	Movers	$e_o^{\text{III}} = e_o^{\text{Triple}}$	Rank	$e_o^{\text{II}} = e_o^{\text{Double}}$	Rank
46	DMU46	ST	0.0033	78	0.0003	88
47	DMU47	GT; ST	0.2380	26	0.1289	25
48	DMU48	GT; ST	0.3884	21	0.3029	18
49	DMU49	ST	0.0050	73	0.0019	71
50	DMU50	ST	0.0013	88	0.0004	85
51	DMU51	CA; CT	0.3544	22	0.3544	16
52	DMU52	IC; ST	0.0551	45	0.0283	37
53	DMU53	ST	0.6373	14	0.5141	10
54	DMU54	ST	1.0000	3	1.0000	3
55	DMU55	ST	0.0036	77	0.0009	77
56	DMU56	CA; CT	0.1951	29	0.1250	26
57	DMU57	CA; CT; GT; ST	0.0243	54	0.0243	42
58	DMU58	GT; ST	0.2224	27	0.0186	45
59	DMU59	GT; ST	0.0020	86	0.0010	75
60	DMU60	ST	0.3508	23	0.0849	30
61	DMU61	ST	0.0016	87	0.0007	82
62	DMU62	CA; CT	1.0000	1	1.0000	1
63	DMU63	ST	0.0300	52	0.0300	36
64	DMU64	ST	0.0001	90	0.0001	89
65	DMU65	CA; CT	0.3400	24	0.0994	28
66	DMU66	CA; CT; GT; ST	0.1220	34	0.0467	32
67	DMU67	ST	0.0053	72	0.0019	70
68	DMU68	CA; CT	0.9098	8	0.9098	5
69	DMU69	CA; CT	0.5862	16	0.4027	14
70	DMU70	ST	0.0331	50	0.0269	39
71	DMU71	IC; ST	0.0023	83	0.0005	84
72	DMU72	ST	0.1051	35	0.0567	31
73	DMU73	ST	0.0204	58	0.0149	48
74	DMU74	ST	0.2624	25	0.2565	20
75	DMU75	ST	0.9697	5	0.5177	9
76	DMU76	CA; CT	0.5554	17	0.3435	17
77	DMU77	ST	0.0020	85	0.0004	86
78	DMU78	CA; CT; ST	0.0875	39	0.0250	40
79	DMU79	GT; ST	0.4258	20	0.1188	27
80	DMU80	ST	0.0028	80	0.0027	66
81	DMU81	ST	0.0556	44	0.0275	38
82	DMU82	ST	0.0083	66	0.0016	72
83	DMU83	ST	0.8869	9	0.2820	19
84	DMU84	ST	0.1433	32	0.1407	24
85	DMU85	GT; ST	1.0000	4	0.5086	11
86	DMU86	ST	0.0041	76	0.0025	67
87	DMU87	CA; CT	0.9294	7	0.9294	4
88	DMU88	ST	0.0080	67	0.0011	74
89	DMU89	GT; ST	0.0602	43	0.0052	53
90	DMU90	ST	0.6760	12	0.4070	13

Table 3.8: Statistical tests comparing the pairs in Table 3.7 to investigate the Power Plant case study

Test/Statistic	e_o^{III} vs. e_o^{II}	Rank$^{\mathrm{III}}$ vs. Rank$^{\mathrm{II}}$
Median Comparison		
p-value of Wilcoxon	0.000	–
p-value of Sign	0.004	–
Variance Comparison		
p-value of Levene	0.040	–
p-value of Bartlett	0.049	–
	–	$r_s = 0.444$
Spearman Correlation		
	–	$R_s^2 = 0.197$
	–	$\tau_b = 0.489$
Kendall Correlation		
	–	$R_b^2 = 0.239$

3.4.6 Comparing Stages' Scores

Our last numerical analysis concerns the question of whether one stage may be more influential in setting the performance measures than the other. In other words, do we benefit from taking a DEA multi-stage approach, rather than just focusing on individual stage measures? To investigate this question, we plot the individual DEA efficiency scores for the two stages in Figure 3.7 as obtained from e_o^{1*} and e_o^{2*} in (M0-B). We find that there is evidence that would suggest to us that the average efficiency of Stage 1 is more remarkable than that of Stage 2. In other words, the figure demonstrates that the first-stage efficiencies are all higher than 50%, while the opposite almost holds for the second-stage efficiencies. As shown in Figure 3.7, most of the DMUs (from a centralized perspective) need to boost their productivity in Stage 2 to meet the expectations of the financial and sustainable missions of the DMU. We conclude that on the basis of the network setting we conceptualized in this study and the real data from the power plants, the overall efficiency of a power plant is considerably influenced by its sustainability performance and the environmental/social risks it causes. From a policy maker's perspective, our model produces measures that would push DMUs to excel on all sustainability measures, given that excelling in a non-financial measure may make up for the poor performance in economic measures.

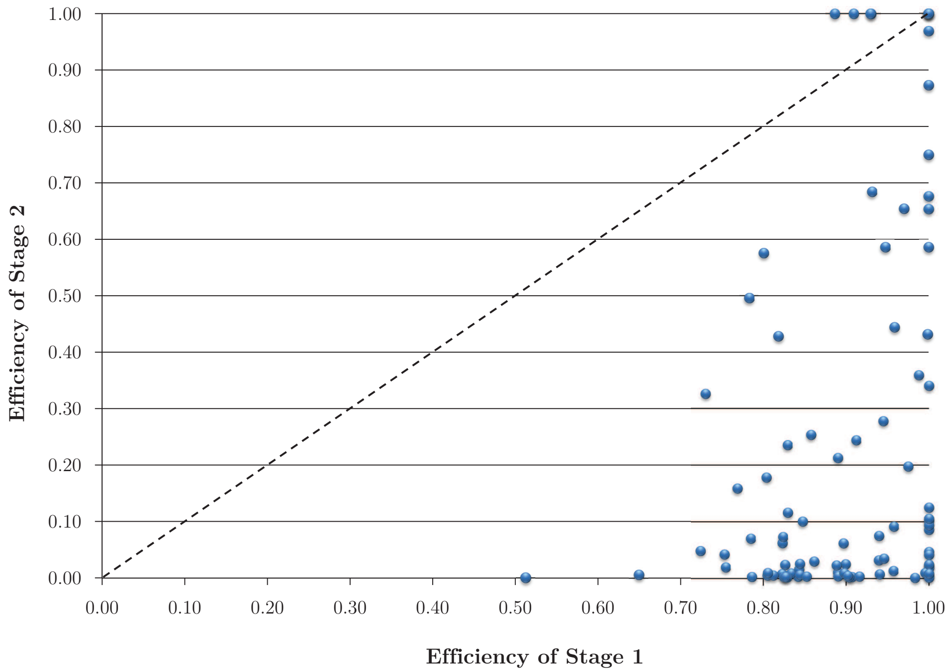


Figure 3.7: Individual DEA efficiencies of stages

3.5 Conclusion and Future Extensions

In this chapter we propose a nonlinear DEA model that generalizes a previous study on centralized DEA models for two-stage systems. Our generalization allows the possibility for weights of a set of the intermediate indicators to be different for two neighbouring stages. We show that the nonlinear DEA model is a special IFBP instance. Making use of this feature of the model, we develop an exact and efficient algorithm to solve it and test it on a real application from the energy sector. We find that our model produces considerably different outcomes from those of the existing models in the literature. Thus, we recommend that the proposed model can be applied in situations where it is unlikely that stages in a network would view intermediate incoming/outgoing weights in a similar way.

Since the nonlinear DEA model is comprised of fractions of indefinite functions in the objective function, there is no general-purpose global optimization solver that would efficiently solve our problem. We review the area of fractional programming problems and adopt a branch-reduce-bound algorithm from two recent studies. We show that in each iteration of the algorithm we only need to find the root of several univariate linear equations. This results in an exact method that efficiently solves this class of IFBPs when compared to existing general-purpose nonlinear programming solvers.

Computational results show that this algorithm produces more robust solutions in comparison with existing models in the literature. The contribution of this work, however, lies not only in the generalization of the previous studies but also in applying it to a real world case study from the U.S. fossil-fuel power plants. Our application differs from previous DEA applications in the energy sector in two important ways. Firstly, we propose a comprehensive sustainability measure that incorporates economic, environmental, and social aspects, the latter being almost absent in existing studies in the literature. Secondly, we use a two-stage network model where the first stage focuses on the financial aspects of the power plant and the second stage addresses the sustainability factors. In addition to testing our proposed solution approach, we use the case study to perform several analyses including comparing the technical performance measures, such as capacity factor and thermal efficiency ratios, to the DEA composite sustainability measures. We find that economic and environmental measures cannot explicitly account for social factors. We recommend that companies develop systematic ways to measure the social impact of their operations. In addition, we recommend that government policy makers set legislations that would facilitate the gathering of social indicators from major sectors of the economy, such as the Clean Air Task Force initiative, the data of which allowed us to gather social indicators to incorporate into our proposed DEA composite score.

Although a centralized perspective has been discussed in this study, more sophisticated approaches of game theory could be integrated with the DEA technique in future studies. In this respect, a possible drawback to the two-stage model is that the individual efficiency of any of the stages may not be unique at the optimality of the network efficiency. Hence, decentralized versions of this model can open up future avenues of research. We are currently working on an extension (Chapter 5) in this direction that considers performance measurement in a supply chain network where supply chains compete in a non-cooperative manner in their product markets, but partners of a supply chain cooperate in their pollutants trading market. Another possible extension is to consider multi-stage and multi-partner networks. This is particularly significant in light of the fact that the supply chain operations are performed in a multi-dimensional and multi-disciplinary manner in practice. This study is also limited in that the proposed framework results in multiple efficient DMUs. In this respect, super-efficiency measures can be alternatively utilized in DEA applications for ranking efficient DMUs.

Chapter 4

Evaluating Sustainability Performance of Multi-echelon Networks

Benefiting from a performance measurement system is an inevitable necessity for any supply chain management to direct the business operations towards the maximal efficiency. In particular, there has been an increasing interest in incorporating sustainability practices evaluation in supply chain operations in the last years due to various stakeholders' requirements. The sustainability paradigm calls for balancing economic, environmental, and social needs. This chapter focuses on the evaluation of supply chain operations that maximize economic returns, minimize environment impacts, and meet social expectations. In order to design a supervisory framework to measure the performance of these operations, this study develops a multi-stage data envelopment analysis model that is apt to evaluate the sustainability of a chain of business partners. In addition, the proposed mathematical model is applied to two case studies; one in the manufacturing sector and the other in the banking sector.

4.1 Introduction

Understanding different aspects of sustainability, supply chain operations, and decision making policies and relating them to performance measurement have been increasingly investigated in the last decade (Hassini et al. 2012). Globalization brings about various pressures for multi-nation enterprises to improve their environmental and social performance, as well as their economic efficiency, although they may be somewhat conflicting. As Cetinkaya et al. (2011) argue, both academics and practitioners call for the incorporation of sustainability aspects in supply chain management (SCM) models. They have also indicated that a number of long term failures are due to the absence of sustainability goals in the corporation vision. Based on a three-dimension sustainability framework (known as the triple bottom line) that deals with economy (profit), environment (planet), and society (people) (Elkington 1997), both large and small initiatives have realized its profitable potential to create new revenue streams in the competitive world (Mincer, 2008). However, such a point of view will not be completely advantageous without evaluating the organizational performance quantitatively and qualitatively. As we discussed in Chapter 2, introducing numerous performance measurement frameworks during the last two decades demonstrates the need to develop key performance indicators to measure the progress of implementing sustainable supply chain management (SSCM) practices. Furthermore, the importance of sustainability assessment has not been restricted to the academia and many practices have been performed by international organizations and unions around the triple pillars of the sustainable development (United Nations 2012a, United Nations 2012b, United Nations 2012c).

In the literature, there are various analytical methods and mathematical approaches to cope with sustainability assessment. Saisana and Tarantola (2002) focus on composite indicators' (CI) characteristics and review the methods applied to create CIs. They define an indicator or measure as a piece of information that summarizes or highlights what is happening in a dynamic system. Consequently, a systematic integration of a set of such indicators, for which there is no obvious way of weighting them, is called an index or a CI. They list several mathematical and statistical approaches for determining CIs. Among these procedures, data envelopment analysis (DEA) has been one of the most effective methods to evaluate the performance of entities (either single organizations or business cooperation chains). DEA, developed systematically by Charnes et al. (1978), is a non-parametric technique to evaluate the relative efficiencies of a set of comparable decision making units (DMUs) by mathematical programming. This approach does not require any decision maker to prescribe weights to be attached to each indicator. Not only are the indicators' weights derived directly from the existing data in DEA, but also this method is capable to distinguish the benchmark entities based on an efficiency score and also identify the sources and amounts of inefficiency of the inefficient DMUs (Cooper et al. 2007).

Our motivation for this work stemmed from the need to have comprehensive supply chain performance measurement systems that can capture the total supply chain efforts in sustainability. This need has arisen from the involvement of one of the authors with a project where one organization wanted to measure the sustainability of its procurement and was faced with the problem that they were not able to measure beyond their company. This difficulty is not only due to lack of supply chain data (e.g., that extends beyond tier 1, suppliers) but also because there were no performance measurement systems that can capture indicators beyond their company. Using the capabilities of DEA to assess sustainable supply chains is the focus of this study. The purpose of this chapter is to (*i*) review existing DEA approaches that evaluate the supply chains and propose a sustainability-based application, (*ii*) develop a multi-stage assessment framework that includes all possible partners of a supply chain, (*iii*) apply the advantages of non-discretionary and desirable indicators which frequently emerge in practical cases, (*iv*) evaluate the overall efficiency of a supply chain and the individual efficiency of its partners at the same time throughout a single model, and (*v*) utilize the concept of the strong efficiency in the proposed model, which generally decreases the number of efficient DMUs. The rest of Chapter 4 is organized as follows. In Section 4.2, we discuss relevant terminology and related reviews. In Section 4.3, a multi-stage DEA method is described to deal with the performance of sustainable supply chains. The proposed model can evaluate any supply chain comprising any number of business partners affected by several direct or intermediate indicators. The computational results of applying the proposed approach to two case studies as well as some managerial insights are provided in Section 4.4. Finally, we propose some research questions and our conclusions in Section 4.5.

4.2 Related Terminology and Literature

The supply chain concept has been defined in the literature using several viewpoints (Mentzer et al. 2001). We consider a supply chain as the integration of all parties and related processes that are involved in satisfying a customer order (Chopra and Meindl 2013). Likewise, there is no unique definition of sustainability in supply chains (Ahi and Searcy 2013), and we define "business sustainability" as "the ability to conduct business with a long term goal of maintaining the well-being of the economy, environment, and society" (Hassini et al. 2012). We remind that Chapter 2 reviews the state-of-the-art in evaluating SSCM practices, where we propose various sets of performance measures that include all major links in a supply chain as well as all three pillars of sustainability.

4.2.1 Literature Review

Supply chain managers need performance frameworks monitoring a set of the crucial indicators to improve the existing efficiency of their operations (Shepherd and Günter 2006). However they often prefer to deal with a concise amount of processed data reflecting the overall status of their business effectiveness and achieved amount of the predetermined objectives. Therefore, applying CIs, which are capable of summarizing dynamic and complex multi-entity environments and systematically combining a set of indicators, can be a helpful approach. As Saisana and Tarantola (2002) note, one of the difficulties of this process is the subjectivity in assigning weights to the sub-indicators and indicators. In spite of the availability of expert judgment to weigh measures, such a possibility may not be practical in real sophisticated cases, such as multi-partner supply chains. DEA which is a data-oriented approach to evaluate the relative efficiency of a set of comparable entities can be applied to help with such a difficulty.

The inception of DEA is presented in Farrell (1957) where economic research motivations raise the need of developing better methods for evaluating productivity functions. However, Farrell did not carry his developments to a point which distinguishes between both Farrell efficient and Pareto-Koopmans efficient categories (Pareto 1927, Koopmans 1951), referred to as weak efficiency and strong efficiency, respectively (Cooper et al. 2007). The modern version of DEA originates from the ideas of Charnes, Cooper, and Rhodes (CCR) through mathematical formulations (Charnes et al. 1978, 1979, 1981). The fundamental idea behind DEA is to provide a methodology whereby a set of benchmark DMUs forms an efficient frontier and furthermore this methodology is able to measure the level of efficiency of inefficient units. The indicator set of the DMUs is divided into two input and output categories and DEA approach attempts to maximize the ratio of weighed outputs to weighted inputs, as a conventional efficiency criterion. Since the very beginning of DEA studies, several extensions of the CCR model have been developed, such as what Banker, Charnes, and Cooper (BCC) propose to produce frontiers spanned by the convex hull of the existing DMUs (Banker et al. 1984). There have been several recent reviews that cover both practical and theoretical developments of DEA (Cooper et al. 2007, Emrouznejad et al. 2008, Cook and Seiford 2009).

As Lee and Billington (1992) argue, an important obstacle to the effective management of supply chains is the lack of effective performance measurement systems, especially when objectives conflict. Since DEA is able to characterize the performance and efficiency in the existence of multiple measures, it can be potentially an appropriate choice to be implemented in the supply chain assessment, beyond the evaluation of each member individually and the treatment of each one as a separate blackbox (Chen et al., 2006a). However, the existence of conflicting objectives among supply chain members with respect to specific measures makes the process of selecting inputs and outputs a sensitive issue. Zhu (2009) shows that conventional DEA approaches (which ignore the intermediate measures) cannot appropriately measure the efficiency of the whole chain.

4.2.2 Contributions

Within the context of DEA, there exist several methods that could be used in supply chain efficiency evaluations. Table 4.1 presents the result of a review of 45 approaches which concentrate on the implementation of DEA to evaluate SCM or SSCM practices, after publishing one of the most primary studies by Seiford and Zhu (1999) that propose a two-stage DEA method (which could be applied to evaluate a supply chain including only two partners). This table clarifies the type of the utilized DEA (single-, double-, or multi-stage) and also the investigated context (SCM or SSCM) for each reference.

As it is shown in Table 4.1, there have been 30 papers which apply a non-single-stage DEA approach and 16 studies that take the sustainability performance evaluation into consideration. What is common to all references of Table 4.1 is evaluating a set of single organizations or a number of supply chains created by at most one member of each partner type (which are supplier, manufacturer, distributer, or retailer.) To the best of our knowledge, there is no multi-stage model that examines the efficiency of a (sustainable) supply chain which includes an arbitrary number of each partner type. In addition, we do not restrict our attention to the networks in which each partner is evaluated only by intermediate indicators. The current work develops both decentralized and centralized approaches for measuring sustainable supply chain efficiency in the existence of intermediate measures that are incorporated into the performance evaluation, where there are some direct indicators for each member of every stage. In particular, this supply chain network can comprise any number of each partner type which is a realistic, and sometimes inescapable necessity in practice. We note that when there is only one partner in each stage of the network, both the decentralized and centralized models yield the same results. This is important when the list of indicators is long, as the number of linear models required to be solved to compute the overall efficiency will decrease significantly.

Table 4.1: Literature review of using DEA to evaluate (sustainable) supply chain efficiency

Reference	Context	Type	Description/Application
Amirteimoori and Khoshandam (2011)	SCM	Double-stage	Some inputs of Stage 2 are not intermediate measures and there are some direct indicators; Developing an additive DEA model to evaluate the performance
Aoki et al. (2010)	SCM	Multi-stage	Some inputs/outputs of each stage are not intermediate measures and there are some direct indicators; Proposing a slacks-based measure DEA model to evaluate the performance
Bai and Sarkis (2012)	SSCM	Single-stage	Evaluating single organizations
Belu (2009)	SSCM	Single-stage	Evaluating single organizations
Blancard and Hoarau (2013)	SSCM	Single-stage	Evaluating single organizations
Castelli et al. (2004)	SCM	Double-stage	Some inputs of Stage 2 are not intermediate measures and there are some direct indicators; Utilizing different degrees of coordination among the subunits of the hierarchical levels
Chang et al. (2011)	SSCM	Single-stage	Evaluating single organizations
Chen et al. (2012)	SSCM	Double-stage	All inputs of Stage 2 are intermediate measures; Comparing two decentralized and centralized models in the leader-follower context
Chen et al. (2006a)	SCM	Double-stage	Some inputs of Stage 2 are not intermediate measures and there are some direct indicators; Comparing two centralized and decentralized models in the leader-follower context

Table 4.1: Literature review of using DEA to evaluate (sustainable) supply chain efficiency

Reference	**Context**	**Type**	**Description/Application**
Chen et al. (2006b)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Characterizing the indirect impact of IT on the business performance
Chen et al. (2009)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Presenting two-Stage equivalent DEA approaches
Chen and Zhu (2004)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Characterizing the indirect impact of IT on the business performance
Chilingerian and Sherman (2011)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Using DEA to develop quality frontiers in health services
Cook and Hababou (2001)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Extending an additive DEA model to evaluate the performance within the branches of a Canadian bank
Cook et al. (2000)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Investigating the sales and service performance within the branches of a Canadian bank
Cook et al. (2010)	SCM	Double-stage	Reviewing the literature of two-stage DEA approaches
Färe et al. (2007)	SCM	Multi-stage	Some inputs/outputs of each stage are not intermediate measures and there are some direct indicators; Comparing three different assumptions for dealing with operations
Golany et al. (2006)	SCM	Double-stage	Some inputs of Stage 2 are not intermediate measures and there are some direct indicators; Comparing three different efficient point selection processes

Table 4.1: Literature review of using DEA to evaluate (sustainable) supply chain efficiency

Reference	**Context**	**Type**	**Description/Application**
Kao (2009a)	SCM	Multi-stage	All inputs/outputs of each stage are intermediate measures; Extending an additive DEA model to evaluate the performance
Kao (2009b)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Analyzing a case of the national forests in Taiwan
Kao and Hwang (2008)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Comparing two independent and relational models in the case of assessing Taiwanese non-life insurance companies
Liang et al. (2008)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Comparing two decentralized and centralized models in the leader-follower context in an analysis of the efficiency decomposition's uniqueness
Liang et al. (2006)	SCM	Double-stage	Some inputs of Stage 2 are not intermediate measures and there are some direct indicators; Comparing two decentralized and corporative models in the leader-follower context
Lewis and Sexton (2004)	SCM	Multi-stage	Some inputs/outputs of each stage are not intermediate measures and there are some direct indicators
Mirhedayatian et al. (2014)	SSCM	Multi-stage	Some inputs/outputs of each stage are not intermediate measures and there are some direct indicators; Proposing a slacks-based measure DEA model to evaluate the performance
Nouri et al. (2013)	SSCM	Multi-stage	Some inputs/outputs of each stage are not intermediate measures and there are some direct indicators
Paradi et al. (2011)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Extending a slacks-based measure DEA model to evaluate the performance within the branches of a Canadian bank

Table 4.1: Literature review of using DEA to evaluate (sustainable) supply chain efficiency

Reference	**Context**	**Type**	**Description/Application**
Qingmin and Lipeng (2009)	SSCM	Single-stage	Evaluating single organizations
Sarica and Or (2007)	SSCM	Single-stage	Evaluating single organizations
Sarkis (2006)	SSCM	Single-stage	Evaluating single organizations
Sarkis and Weinrach (2001)	SSCM	Single-stage	Evaluating single organizations
Seiford and Zhu (1999)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Examining the performance of the top 55 U.S. commercial banks
Sexton and Lewis (2003)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Examining the efficiency of MLB teams during the regular season, including the interleague games but excluding post-season games
Sueyoshi and Goto (2012c)	SSCM	Single-stage	Evaluating single organizations
Talluri and Baker (2002)	SCM	Single-stage	Designing supply chains network in three phases and finding the optimal number of each partner by taking into consideration their efficiencies
Talluri and Sarkis (2002)	SCM	Single-stage	Evaluating single organizations

Table 4.1: Literature review of using DEA to evaluate (sustainable) supply chain efficiency

Reference	**Context**	**Type**	**Description/Application**
Troutt et al. (2001)	SCM	Multi-stage	All inputs/outputs of each stage are intermediate measures
Vázquez-Rowe et al. (2012)	SSCM	Single-stage	Evaluating single organizations
Wong and Wong (2007)	SCM	Single-stage	Evaluating single organizations
Xue (2010)	SSCM	Single-stage	Evaluating single organizations
Yang et al. (2011)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Defining two types of supply chain production possibility sets which are proved to be equivalent to each other
Zhang et al. (2008)	SSCM	Single-stage	Evaluating single organizations
Zhou et al. (2008)	SSCM	--	Reviewing the literature of DEA developments in the energy and environmental (E&E) context
Zhu (2000)	SCM	Double-stage	All inputs of Stage 2 are intermediate measures; Characterizing the performance of 500 companies based on their data published by the Fortune magazine
Zhu (2009)	SCM	Multi-stage	Some inputs/outputs of each stage are not intermediate measures and there are some direct indicators; Proposing a DEA model for a supply chain including one member for each partner

4.3 A Data Envelopment Analysis Model

Our proposed model is able to evaluate the overall efficiency of a sustainable supply chain containing an arbitrary number of suppliers, manufacturers, distributers, and retailers. Therefore, each of the DMUs, or the supply chains in this context, is built of four stages and each stage includes a set of partners connected to the predecessor/ successor stage's members by some intermediate indicators. Moreover, each of the supply chain members is also monitored by its own direct indicators. Figure 4.1, which will be described later, shows a scheme of the type of supply chains that we study in Chapter 4.

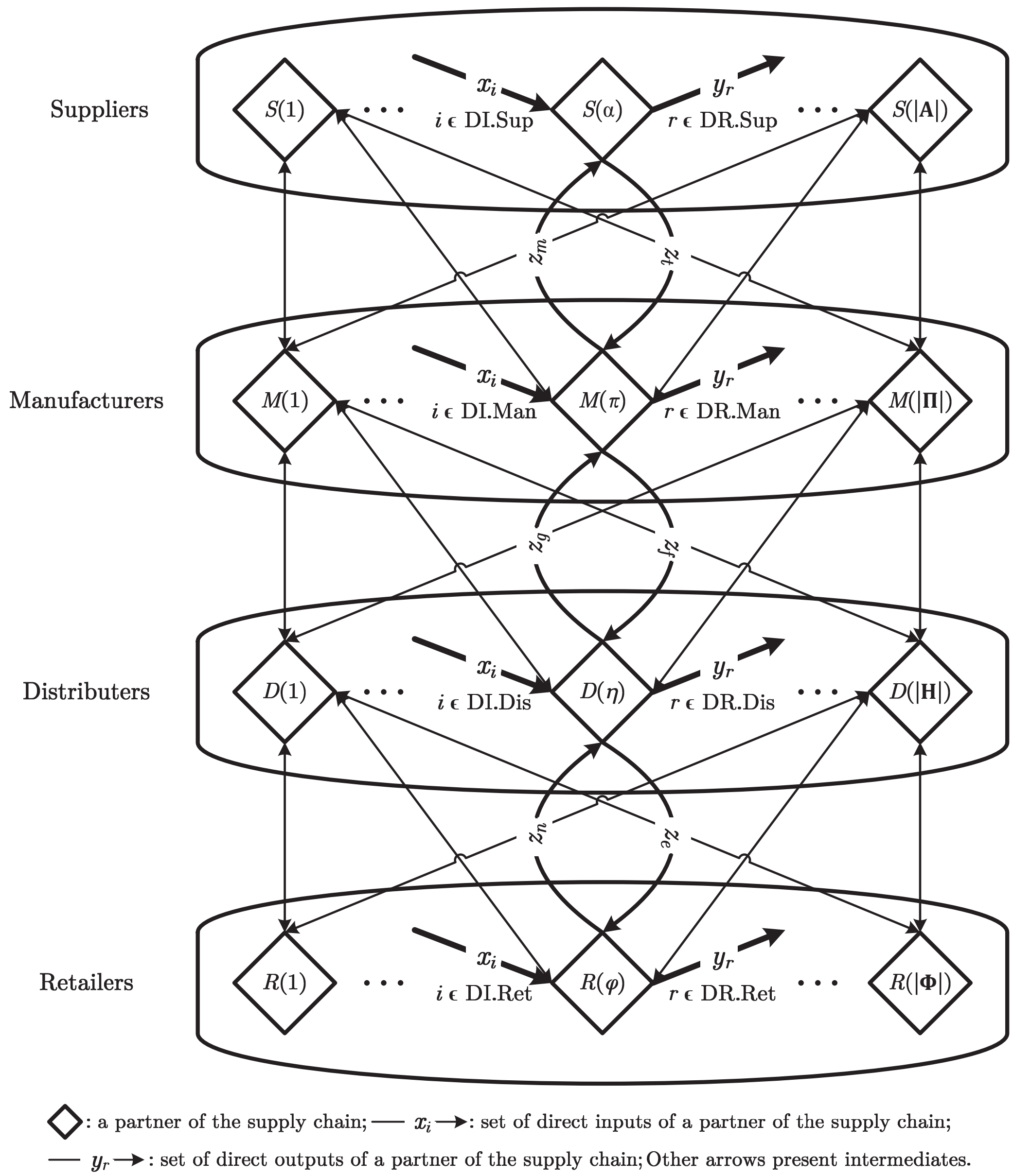


Figure 4.1: A supply chain network that includes direct and intermediate measures

4.3.1 Notation

We use the following symbols and notation (Cooper et al. 2007, Zhu 2009) in this study. We note that Chapter 4 is the only part of this thesis in which $\mathbb{N}$, $\mathbb{I}$, $\mathbb{R}$ do not refer to the number sets.

1. Indexes and Sets

   - $\mathbb{J} = \{1, ..., \bar{n}\}$: set of comparable DMUs to be evaluated, indexed by j
   - $\mathbb{I} = \{1, ..., \bar{m}\}$: set of inputs into a DMU, indexed by i
   - $\mathbb{R} = \{1, ..., \bar{s}\}$: set of outputs from a DMU, indexed by r
   - $p \in \mathbb{J}$: index of the DMU under evaluation
   - Dis($\mathbb{I}$) : set of discretionary (direct) inputs into a DMU, indexed by i
   - Non($\mathbb{I}$) : set of non-discretionary (intermediate) inputs into a DMU, indexed by i
   - $\mathrm{A} = \{1, ..., \alpha, ..., |\mathrm{A}|\}$: set of suppliers, indexed by α
   - $\Pi = \{1, ..., \pi, ..., |\Pi|\}$: set of manufacturers, indexed by π
   - $\mathrm{H} = \{1, ..., \eta, ..., |\mathrm{H}|\}$: set of distributers, indexed by η
   - $\Phi = \{1, ..., \varphi, ..., |\Phi|\}$: set of retailers, indexed by φ
   - $\Delta = \{$Sup,Man,Dis,Ret$\}$: stage index representing all four main
   - D$\mathbb{I}$.Δ: set of direct inputs into a echelon Δ of a DMU, indexed by i
   - D$\mathbb{R}$.Δ: set of direct outputs from a echelon Δ of a DMU, indexed by r
   - $\mathbb{T}$: set of intermediates from a supplier into a manufacturer, indexed by t
   - $\mathbb{M}$: set of intermediates from a manufacturer into a supplier, indexed by m
   - $\mathbb{F}$: set of intermediates from a manufacturer into a distributer, indexed by f
   - $\mathbb{G}$: set of intermediates from a distributer into a manufacturer, indexed by g
   - $\mathbb{E}$: set of intermediates from a distributer into a retailer, indexed by e
   - $\mathbb{N}$: set of intermediates from a retailer into a distributer, indexed by n

2. Parameters

   - x_{ij} : consumed amount of Input i by DMU$_j$
   - y_{rj} : consumed amount of Output r by DMU$_j$
   - ε : infinitesimal amount (known as the non-Archimedean value)
   - $w^{S(\alpha)}, w^{M(\pi)}, w^{D(\eta)}$, or $w^{R(\varphi)}$: worth of Supplier α, Manufacturer π, Distributer η, or Retailer φ, respectively
   - $x_{ij\alpha}$: consumed amount of Input i by $S(\alpha)$ of DMU$_j$
   - $y_{rj\alpha}$: consumed amount of Output r by $S(\alpha)$ of DMU$_j$
   - $z_{mj\pi\alpha}$: consumed/produced amount of Intermediate m from $M(\pi)$ into $S(\alpha)$ of DMU$_j$
   - $z_{tj\alpha\pi}$: consumed/produced amount of Intermediate t from $S(\alpha)$ into $M(\pi)$ of DMU$_j$

3. Decision Variables (Basic Model)

   - θ_p : efficiency score of DMU$_p$
   - λ_j : indicator for DMU$_j$ determining whether this DMU is a benchmark for DMU$_p$

4. Decision Variables (Decentralized Model)

   - μ_p : efficiency score of DMU$_p$
   - $\mu_p^{S(\alpha)}$: efficiency score of $S(\alpha)$ of DMU$_p$
   - λ_j : indicator for DMU$_j$ determining whether this DMU is a benchmark for DMU$_p$ at the level of suppliers

5. Decision Variables (Centralized Model)

   - θ_p : efficiency score of DMU$_p$
   - $\theta_p^{S(\alpha)}, \theta_p^{M(\pi)}, \theta_p^{D(\eta)}$, or $\theta_p^{R(\varphi)}$: efficiency score of Supplier α, Manufacturer π, Distributer η, or Retailer φ of DMU$_p$, respectively
   - λ_j : indicator for DMU$_j$ determining whether this DMU is a benchmark for DMU$_p$ at the level of suppliers

- β_j : indicator for DMU$_j$ determining whether this DMU is a benchmark for DMU$_p$ at the level of manufacturers
- δ_j : indicator for DMU$_j$ determining whether this DMU is a benchmark for DMU$_p$ at the level of distributers
- γ_j : indicator for DMU$_j$ determining whether this DMU is a benchmark for DMU$_p$ at the level of retailers

4.3.2 Model Formulation

Suppose there are $\bar{n}$ comparable DMUs to be evaluated. Each DMU consumes $\bar{m}$ different input sources and produces $\bar{s}$ different output values. We note that these input and output values could be interpreted as the values of indicators or measures characterizing the mentioned DMUs. To be more specific, DMU$_j$, where $j \in \mathbb{J} = \{1, ..., \bar{n}\}$, consumes amount x_{ij} of Input i and produces amount y_{rj} of Output r, where $i \in \mathbb{I} = \{1, ..., \bar{m}\}$ and $r \in \mathbb{R} = \{1, ..., \bar{s}\}$. In this study, it is assumed that all x_{ij} and y_{rj} are nonnegative values. Similar to arguments made in Chapter 3, for a given DMU being evaluated, say DMU$_p$, one can write the fractional and the multiplier form of DEA as (DEA3) and (DEA4), respectively:

$$\begin{aligned}
\text{Max} \quad & h_p = \frac{\sum_{r\in\mathbb{R}} u_r y_{rp}}{\sum_{i\in\mathbb{I}} v_i x_{ip}} \\
\text{s.t.} \quad & \frac{\sum_{r\in\mathbb{R}} u_r y_{rj}}{\sum_{i\in\mathbb{I}} v_i x_{ij}} \leq 1 && \forall j \in \mathbb{J} \\
& v_i, u_r \geq 0 && \forall i \in \mathbb{I} \quad \forall r \in \mathbb{R},
\end{aligned} \tag{DEA3}$$

$$\begin{aligned}
\text{Max} \quad & h_p = \sum_{r\in\mathbb{R}} u_r y_{rp} \\
\text{s.t.} \quad & \sum_{i\in\mathbb{I}} v_i x_{ip} = 1 \\
& \sum_{r\in\mathbb{R}} u_r y_{rj} \leq \sum_{i\in\mathbb{I}} v_i x_{ij} && \forall j \in \mathbb{J} \\
& v_i, u_r \geq 0 && \forall i \in \mathbb{I} \quad \forall r \in \mathbb{R}.
\end{aligned} \tag{DEA4}$$

DMU$_p$ is defined as an efficient (strongly efficient or Pareto-Koopmans efficient) DMU if $h_p^* = 1$ and also there exists at least one optimal $(\mathbf{v}^*, \mathbf{u}^*)$ solution, with $\mathbf{v}^* > 0$ and

$\mathbf{u}^* > 0$. Such a DMU could not be improved without worsening some inputs or outputs. In the literature, a DMU that obtains $h_p^* = 1$ without satisfying $\mathbf{v}^* > 0$ and $\mathbf{u}^* > 0$ is called radially efficient, weakly efficient, or Farrell efficient. In spite of the admirable efforts in Farrell (1957), known as the first reported empirical applications of conceptual traditional productivity approaches proposed in Pareto (1927) and Koopmans (1951), his findings fell short to covering strong efficiency, which finally was characterized by Charnes et al. (1978). Cooper et al. (2007) present a number of examples in Chapter 2 to highlight some drawbacks of ignoring the strong efficiency concept.

We note that the dual problem of (DEA4), called the envelopment form of DEA, is expressed by a real variable θ_p and a nonnegative vector $(\lambda_1, ..., \lambda_j, ..., \lambda_{\bar{n}})$ of variables as follows:

$$\begin{aligned} \text{Min} \quad & \theta_p \\ \text{s.t.} \quad & \sum_{j \in \mathbb{J}} x_{ij}\lambda_j \leq \theta_p x_{ip} \qquad \forall i \in \mathbb{I} \\ & \sum_{j \in \mathbb{J}} y_{rj}\lambda_j \geq y_{rp} \qquad \forall r \in \mathbb{R} \\ & \lambda_j \geq 0 \qquad\qquad\qquad \forall j \in \mathbb{J}. \end{aligned} \tag{4.1}$$

Although θ_p is a non-restricted variable in (4.1), duality theory properties guarantee that $h_p^* = \theta_p^* \in (0, 1]$ (Cooper et al. 2007). There are some important reasons behind solving the envelopment form. First of all, the computational effort of linear programming is apt to increase in proportion to powers of the number of constraints. Since the number of DMUs (i.e., $\bar{n}$) is generally larger than the cumulative number of inputs and outputs (i.e., $\bar{m} + \bar{s}$), hence solving (DEA4) relatively takes more time in comparison with solving (4.1). Secondly, the facets geometrically confining the feasible region of (4.1) present the efficient frontier, in which all DMUs are enveloped and contains DMUs that obtain the maximal efficiency score. Third, by applying the optimal variables λ_j^* of (4.1), several approaches have been proposed to find a projection of an inefficient DMU (on the basis of its reference set) on the efficient frontier which could be interpreted as a benchmark for that inefficient DMU. Finally, there is no mathematically-guaranteed method that finds an optimal solution of a strongly efficient DMU with $\mathbf{v}^* > 0$ and

$\mathbf{u}^* > 0$ in (DEA4), unless one adds some strict positivity constraints or searches implicitly all optimal solutions. However, this shortfall can be overcome through a two-phase linear programming procedure (and solving $2\bar{n}$ linear models) built upon the constraint slacks of (DEA4) (Cooper et al. 2007). This method benefits from the shadow price concept of linear programming theory to obtain the values of $\mathbf{v}^*$ and $\mathbf{u}^*$ after finding the optimal values of the mentioned slack variables. Another approach to deal with this shortage is argued in Banker et al. (1984) by using an infinitesimal amount (known as non-Archimedean ε) and solving the following single linear programming:

$$\begin{aligned}
\text{Min} \quad & \theta_p - \varepsilon \left(\sum_{i \in \mathbb{I}} s_i^- + \sum_{r \in \mathbb{R}} s_r^+ \right) \\
\text{s.t.} \quad & \sum_{j \in \mathbb{J}} x_{ij} \lambda_j + s_i^- = \theta_p x_{ip} && \forall i \in \mathbb{I} \\
& \sum_{j \in \mathbb{J}} y_{rj} \lambda_j - s_r^+ = y_{rp} && \forall r \in \mathbb{R} \\
& \lambda_j, s_i^-, s_r^+ \geq 0 && \forall j \in \mathbb{J} \quad \forall i \in \mathbb{I} \quad \forall r \in \mathbb{R}.
\end{aligned} \tag{4.2}$$

It is proved in the literature (Cooper et al. 2007) that the aforementioned definition of an efficient DMU could be equivalently replaced by "DMU$_p$ is defined as a CCR-efficient DMU if $\theta_p^* = 1$ and $(\mathbf{s}^{-*}, \mathbf{s}^{+*}) = (\mathbf{0}, \mathbf{0})$ in (4.2)" and it implies solving $\bar{n}$ models such as the last linear programme leads to distinguish between strongly efficient, weakly efficient, as well as inefficient DMUs. We remind that besides whether (4.2) shows that DMU$_p$ is efficient or not, the achieved θ_p^* by this model is a representative for the efficiency of the DMU, and thus it can be interpreted as a composite indicator aggregating the attributes of several measures in a single value.

In the above basic DEA model, it assumed that all inputs can be varied, directly or indirectly, at the discretion of management which are called discretionary inputs. In a practical situation, there are several variables that may not be subject to management control, called non-discretionary or exogenous inputs. For example, the intermediate measures that connect the members of two different stages of a supply chain could be put in this classification. Adopting the approach provided by Banker and Morey (1986), model (4.2) can be modified to include non-discretionary inputs as follows:

$$
\begin{aligned}
\text{Min} \quad & \theta_p - \varepsilon \left(\sum_{i \in \text{Dis}(\mathbb{I})} s_i^- + \sum_{r \in \mathbb{R}} s_r^+ \right) \\
\text{s.t.} \quad & \sum_{j \in \mathbb{J}} x_{ij}\lambda_j + s_i^- = \theta_p x_{ip} && \forall i \in \text{Dis}(\mathbb{I}) \\
& \sum_{j \in \mathbb{J}} x_{ij}\lambda_j + s_i^- = x_{ip} && \forall i \in \text{Non}(\mathbb{I}) \\
& \sum_{j \in \mathbb{J}} y_{rj}\lambda_j - s_r^+ = y_{rp} && \forall r \in \mathbb{R} \\
& \lambda_j, s_i^-, s_r^+ \geq 0 && \forall j \in \mathbb{J} \quad \forall i \in \mathbb{I} \quad \forall r \in \mathbb{R}.
\end{aligned} \tag{4.3}
$$

In the above model $i \in \text{Dis}(\mathbb{I})$ and $i \in \text{Non}(\mathbb{I})$ represent the indices of discretionary and non-discretionary inputs, respectively, so long as $\mathbb{I} = \text{Dis}(\mathbb{I}) \cup \text{Non}(\mathbb{I})$ and $\text{Dis}(\mathbb{I}) \cap \text{Non}(\mathbb{I}) = \emptyset$. The variables s_i^- and s_r^+ represent slack variables, stressing deficiency amount of DMU_p. Although the slacks that correspond to $i \in \text{Non}(\mathbb{I})$ do not enter in the objective function, they influence the efficiency by affecting and changing the variables λ_j.

Consider now a supply chain network as described in Figure 4.1 that includes four stages, from supplier echelon to retailer echelon. The index sets of supplier, manufacturer, distributer, and retailer stages are $\text{A} = \{1, ..., \alpha, ..., |\text{A}|\}$, $\Pi = \{1, ..., \pi, ..., |\Pi|\}$, $\text{H} = \{1, ..., \eta, ..., |\text{H}|\}$, and $\Phi = \{1, ..., \varphi, ..., |\Phi|\}$, respectively. Following the notation used by Zhu (2009), each member of each stage may have two discretionary (or direct) measure vectors, denoted by $\mathbf{x}_i$ (for inputs) and $\mathbf{y}_r$ (for outputs), and/or two non-discretionary (or intermediate) measure vectors, which both are recognizable by $\mathbf{z}$. More concretely, the latter connect the operations of two members of two different stages.

We emphasize that the entities of every pair of members (each of which belongs exclusively to one of the two consecutive stages, for example $D(1)$ and $R(\varphi)$ in Figure 4.1) are connected by a two-way arrow that is a representative of two sets of intermediate measures between that pair's members. Furthermore, without loss of generality we assume that a fixed weight value is assigned to each partner of this supply chain. For instance, for every $\alpha \in \text{A}$, $w^{S(\alpha)}$ is a predetermined worth value of Supplier α or $S(\alpha)$ from the standpoint of management. These values could be obtained through an expert opinion procedure or assumed equal to one for all of the members. We note that this study considers the same weight for all partners of a certain stage of the network.

Suppose there are $\bar{n}$ such comparable supply chains or alternatively $\bar{n}$ different observations on one supply chain, and the pth supply chain or observation (or briefly DMU$_p$) must be evaluated, where $p \in \mathbb{J} = \{1, ..., \bar{n}\}$. Since ignoring the intermediate measures results in inaccurate evaluation of this DMU, one straight alternative approach to take the effect of these indicators into consideration is measuring a decentralized network in which each member of each stage is evaluated separately by a modification of (4.3). For instance, for every $\alpha \in \mathrm{A}$, the efficiency of $S(\alpha)$ is achieved by:

$$
\begin{aligned}
\text{Min} \quad & \mu_p^{S(\alpha)} - \varepsilon \left(\sum_{i \in \mathrm{D}\mathbb{I}.\mathrm{Sup}} s_{i\alpha}^- + \sum_{r \in \mathrm{D}\mathbb{R}.\mathrm{Sup}} s_{r\alpha}^+ + \sum_{(t,\pi) \in (\mathbb{T} \times \Pi)} s_{t\alpha\pi}^+ \right) \\
\text{s.t.} \quad & \sum_{j \in \mathbb{J}} x_{ij\alpha} \lambda_j + s_{i\alpha}^- = \mu_p^{S(\alpha)} x_{ip\alpha} \qquad \forall i \in \mathrm{D}\mathbb{I}.\mathrm{Sup} \\
& \sum_{j \in \mathbb{J}} y_{rj\alpha} \lambda_j - s_{r\alpha}^+ = y_{rp\alpha} \qquad \forall r \in \mathrm{D}\mathbb{R}.\mathrm{Sup} \\
& \sum_{j \in \mathbb{J}} z_{mj\pi\alpha} \lambda_j + s_{m\alpha\pi}^- = z_{mp\pi\alpha} \qquad \forall m \in \mathbb{M} \;\; \forall \pi \in \Pi \\
& \sum_{j \in \mathbb{J}} z_{tj\alpha\pi} \lambda_j - s_{t\alpha\pi}^+ = z_{tp\alpha\pi} \qquad \forall t \in \mathbb{T} \;\; \forall \pi \in \Pi \\
& \lambda_j, s_{i\alpha}^-, s_{r\alpha}^+, s_{m\alpha\pi}^-, s_{t\alpha\pi}^+ \geq 0 \; \forall j \in \mathbb{J} \; \forall i \in \mathrm{D}\mathbb{I}.\mathrm{Sup} \; \forall r \in \mathrm{D}\mathbb{R}.\mathrm{Sup} \; \forall m \in \mathbb{M} \; \forall t \in \mathbb{T} \; \forall \pi \in \Pi,
\end{aligned}
\tag{4.4}
$$

where D$\mathbb{I}$.Sup and D$\mathbb{R}$.Sup are the index sets of direct inputs and direct outputs of the supplier stage, respectively. After finding the optimal efficiency of each member of the network by a model similar to (4.4), the efficiency of DMU$_p$ under the decentralized policy is equal to:

$$
\mu_p = \frac{\sum_\alpha w^{S(\alpha)} \mu_p^{S(\alpha)} + \sum_\pi w^{M(\pi)} \mu_p^{M(\pi)} + \sum_\eta w^{D(\eta)} \mu_p^{D(\eta)} + \sum_\varphi w^{R(\varphi)} \mu_p^{R(\varphi)}}{\sum_\alpha w^{S(\alpha)} + \sum_\pi w^{M(\pi)} + \sum_\eta w^{D(\eta)} + \sum_\varphi w^{R(\varphi)}}. \tag{4.5}
$$

The described procedure suffers from two main drawbacks. First, it needs to solve totally $|\mathrm{A}| \times |\Pi| \times |\mathrm{H}| \times |\Phi|$ linear models only to assess the performance of a given DMU. Second, it does not take into account the interactive impacts of the members of DMU$_p$ at the same time and in a single framework. To tackle these deficiencies, we propose (4.6), a centralized approach to evaluate the efficiency of every arbitrary DMU$_p$, which considers improving interactions among the supply chain's partners:

$$
\begin{aligned}
\text{Min} \quad & \theta_p - \varepsilon \times \textbf{Slack} \\
\text{s.t.} \quad &
\end{aligned}
$$

$\underline{\underline{\text{Supplier Stage}}}$

$$
\begin{aligned}
&\sum_{j\in\mathbb{J}} x_{ij\alpha}\lambda_j + s^-_{i\alpha} = \theta_p^{S(\alpha)} x_{ip\alpha} && \forall i \in \mathbb{DI}.\text{Sup} \;\; \forall \alpha \in \text{A} \\
&\sum_{j\in\mathbb{J}} y_{rj\alpha}\lambda_j - s^+_{r\alpha} = y_{rp\alpha} && \forall r \in \mathbb{DR}.\text{Sup} \;\; \forall \alpha \in \text{A} \\
&\sum_{j\in\mathbb{J}} z_{mj\pi\alpha}\lambda_j + s^-_{m\alpha\pi} = z_{mp\pi\alpha} && \forall m \in \mathbb{M} \;\; \forall \alpha \in \text{A} \;\; \forall \pi \in \Pi \;\; \star \\
&\sum_{j\in\mathbb{J}} z_{tj\alpha\pi}\lambda_j - s^+_{t\alpha\pi} = z_{tp\alpha\pi} && \forall t \in \mathbb{T} \;\; \forall \alpha \in \text{A} \;\; \forall \pi \in \Pi \\
&\lambda_j, s^-_{i\alpha}, s^+_{r\alpha}, s^-_{m\alpha\pi}, s^+_{t\alpha\pi} \geq 0 \\
&\forall j \in \mathbb{J}, i \in \mathbb{DI}.\text{Sup}, r \in \mathbb{DR}.\text{Sup}, m \in \mathbb{M}, t \in \mathbb{T}, \alpha \in \text{A}, \pi \in \Pi
\end{aligned}
$$

$\underline{\underline{\text{Manufacturer Stage}}}$

$$
\begin{aligned}
&\sum_{j\in\mathbb{J}} x_{ij\pi}\beta_j + s^-_{i\pi} = \theta_p^{M(\pi)} x_{ip\pi} && \forall i \in \mathbb{DI}.\text{Man} \;\; \forall \pi \in \Pi \\
&\sum_{j\in\mathbb{J}} y_{rj\pi}\beta_j - s^+_{r\pi} = y_{rp\pi} && \forall r \in \mathbb{DR}.\text{Man} \;\; \forall \pi \in \Pi \\
&\sum_{j\in\mathbb{J}} z_{tj\alpha\pi}\beta_j + s^-_{t\alpha\pi} = z_{tp\alpha\pi} && \forall t \in \mathbb{T} \;\; \forall \alpha \in \text{A} \;\; \forall \pi \in \Pi \;\; \star \\
&\sum_{j\in\mathbb{J}} z_{mj\pi\alpha}\beta_j - s^+_{m\alpha\pi} = z_{mp\pi\alpha} && \forall m \in \mathbb{M} \;\; \forall \alpha \in \text{A} \;\; \forall \pi \in \Pi \\
&\sum_{j\in\mathbb{J}} z_{gj\eta\pi}\beta_j + s^-_{g\pi\eta} = z_{gp\eta\pi} && \forall g \in \mathbb{G} \;\; \forall \pi \in \Pi \;\; \forall \eta \in \text{H} \;\; \star \\
&\sum_{j\in\mathbb{J}} z_{fj\pi\eta}\beta_j - s^+_{f\pi\eta} = z_{fp\pi\eta} && \forall f \in \mathbb{F} \;\; \forall \pi \in \Pi \;\; \forall \eta \in \text{H} \\
&\beta_j, s^-_{i\pi}, s^+_{r\pi}, s^-_{t\alpha\pi}, s^+_{m\alpha\pi}, s^-_{g\pi\eta}, s^+_{f\pi\eta} \geq 0 \\
&\forall j \in \mathbb{J}, i \in \mathbb{DI}.\text{Man}, r \in \mathbb{DR}.\text{Man}, t \in \mathbb{T}, m \in \mathbb{M}, g \in \mathbb{G}, f \in \mathbb{F}, \alpha \in \text{A}, \pi \in \Pi, \eta \in \text{H}
\end{aligned}
$$

Distributer Stage

$$\sum_{j\in\mathbb{J}} x_{ij\eta}\delta_j + s^-_{i\eta} = \theta_p^{D(\eta)} x_{ip\eta} \qquad \forall i \in \mathrm{D}\mathbb{I}.\mathrm{Dis} \quad \forall \eta \in \mathrm{H}$$

$$\sum_{j\in\mathbb{J}} y_{rj\eta}\delta_j - s^+_{r\eta} = y_{rp\eta} \qquad \forall r \in \mathrm{D}\mathbb{R}.\mathrm{Dis} \quad \forall \eta \in \mathrm{H}$$

$$\sum_{j\in\mathbb{J}} z_{fj\pi\eta}\delta_j + s^-_{f\pi\eta} = z_{fp\pi\eta} \qquad \forall f \in \mathbb{F} \quad \forall \pi \in \Pi \quad \forall \eta \in \mathrm{H} \quad \star$$

$$\sum_{j\in\mathbb{J}} z_{gj\eta\pi}\delta_j - s^+_{g\pi\eta} = z_{gp\eta\pi} \qquad \forall g \in \mathbb{G} \quad \forall \pi \in \Pi \quad \forall \eta \in \mathrm{H}$$

$$\sum_{j\in\mathbb{J}} z_{nj\varphi\eta}\delta_j + s^-_{n\eta\varphi} = z_{np\varphi\eta} \qquad \forall n \in \mathbb{N} \quad \forall \eta \in \mathrm{H} \quad \forall \varphi \in \Phi \quad \star$$

$$\sum_{j\in\mathbb{J}} z_{ej\eta\varphi}\delta_j - s^+_{e\eta\varphi} = z_{ep\eta\varphi} \qquad \forall e \in \mathbb{E} \quad \forall \eta \in \mathrm{H} \quad \forall \varphi \in \Phi$$

$$\delta_j, s^-_{i\eta}, s^+_{r\eta}, s^-_{f\pi\eta}, s^+_{g\pi\eta}, s^-_{n\eta\varphi}, s^+_{e\eta\varphi} \geq 0$$

$$\forall j \in \mathbb{J}, i \in \mathrm{D}\mathbb{I}.\mathrm{Dis}, r \in \mathrm{D}\mathbb{R}.\mathrm{Dis}, f \in \mathbb{F}, g \in \mathbb{G}, n \in \mathbb{N}, e \in \mathbb{E}, \pi \in \Pi, \eta \in \mathrm{H}, \varphi \in \Phi$$

Retailer Stage

$$\sum_{j\in\mathbb{J}} x_{ij\varphi}\gamma_j + s^-_{i\varphi} = \theta_p^{R(\varphi)} x_{ip\varphi} \qquad \forall i \in \mathrm{D}\mathbb{I}.\mathrm{Ret} \quad \forall \varphi \in \Phi$$

$$\sum_{j\in\mathbb{J}} y_{rj\varphi}\gamma_j - s^+_{r\varphi} = y_{rp\varphi} \qquad \forall r \in \mathrm{D}\mathbb{R}.\mathrm{Ret} \quad \forall \varphi \in \Phi$$

$$\sum_{j\in\mathbb{J}} z_{ej\eta\varphi}\gamma_j + s^-_{e\eta\varphi} = z_{ep\eta\varphi} \qquad \forall e \in \mathbb{E} \quad \forall \eta \in \mathrm{H} \quad \forall \varphi \in \Phi \quad \star$$

$$\sum_{j\in\mathbb{J}} z_{nj\varphi\eta}\gamma_j - s^+_{n\eta\varphi} = z_{np\varphi\eta} \qquad \forall n \in \mathbb{N} \quad \forall \eta \in \mathrm{H} \quad \forall \varphi \in \Phi$$

$$\gamma_j, s^-_{i\varphi}, s^+_{r\varphi}, s^-_{e\eta\varphi}, s^+_{n\eta\varphi} \geq 0$$

$$\forall j \in \mathbb{J}, i \in \mathrm{D}\mathbb{I}.\mathrm{Ret}, r \in \mathrm{D}\mathbb{R}.\mathrm{Ret}, e \in \mathbb{E}, n \in \mathbb{N}, \eta \in \mathrm{H}, \varphi \in \Phi. \tag{4.6}$$

Such a model is able to present individual DMU efficiencies in addition to calculating the overall supply chain efficiency. The proposed model is a linear programme, where DMU_p is under consideration and **Slack** is the summation of all slack variables, excluding those which are in the non-discretionary input sets and their corresponding constraint set is followed by the "$\star$" symbol. For more clarification, constraints are categorized on the basis of their relation with each partner. The parameters vectors $\mathbf{x}$, $\mathbf{y}$, and $\mathbf{z}$ represent values of direct inputs, direct outputs, and intermediates, respectively. As we explain in details later, Tables 4.2 and 4.4 illustrate some descriptive examples of these parameters.

In addition, four pairs $(\theta_p^{S(\alpha)}, \lambda_j)$, $(\theta_p^{M(\pi)}, \beta_j)$, $(\theta_p^{D(\eta)}, \delta_j)$, and $(\theta_p^{R(\varphi)}, \gamma_j)$ indicate the main decision variables of this model corresponding to suppliers, manufacturers, distributors, and retailers, respectively. We note that DMU$_p$ is efficient in this model if $\theta_p^* = 1$ and **Slack** $= 0$.

4.3.3 Analysis

Proposition 4.1 presents the relationship between (4.4) and (4.6), where:

$$\theta_p = \frac{\sum_\alpha w^{S(\alpha)}\theta_p^{S(\alpha)} + \sum_\pi w^{M(\pi)}\theta_p^{M(\pi)} + \sum_\eta w^{D(\eta)}\theta_p^{D(\eta)} + \sum_\varphi w^{R(\varphi)}\theta_p^{R(\varphi)}}{\sum_\alpha w^{S(\alpha)} + \sum_\pi w^{M(\pi)} + \sum_\eta w^{D(\eta)} + \sum_\varphi w^{R(\varphi)}}. \tag{4.7}$$

Proposition 4.1 *For each $p \in \mathbb{J} = \{1, ..., \bar{n}\}$ we have $\mu_p^* \leq \theta_p^*$.*

The proof of Proposition 4.1 and other proofs of Chapter 4 are included in **Appendix B.1**. One question of interest is whether there are necessary or sufficient conditions that establish an equality relation between θ_p^* and μ_p^* in Proposition 4.1. Liang et al. (2008) developed their models such that all decentralized and centralized linear programs led to the same efficiency scores. Their framework included a two-stage network that connected a single supplier (in Stage 1) to a single manufacturer (in Stage 2) in the presence of an intermediate measure. They dealt with the overall efficiency as the product of the efficiencies of individual stages. As they argued, the centralized model for optimizing the weighted average of the partners' efficiencies as the overall score of the network would be a nonlinear model. However, using the duality theory we are able to provide the decision maker with a centralized linear program, in which each DMU is evaluated by a linear measure of its entities' efficiencies. In Proposition 4.2 we present a sufficient condition for the proposed model which ensures the equality of θ_p^* and μ_p^*.

Proposition 4.2 *When* $|\mathrm{A}| = |\Pi| = |\mathrm{H}| = |\Phi| = 1$*, i.e., each of the supply chains has a single entity, we have $\mu_p^* = \theta_p^*$, where $p \in \mathbb{J} = \{1, ..., \bar{n}\}$.*

To see that this is also a necessary condition, we will provide an example in the next section where there are two partners in the supplier stage and there exist some DMUs that satisfy $\mu_p^* \neq \theta_p^*$.

4.4 Case Studies and Discussion

In this section, two case studies will be used to apply Model (4.6). Our purpose is to highlight the theoretical and practical merits of the model. In addition we will also outline some managerial insights from the results of the case studies. All models are solved by a linear programming solver using the GAMS 23.5 software, on a 4 GB RAM, 2.50 GHz desktop computer. Given that model (4.6) is a linear optimization problem, the runtime of the computation in this case study is negligible. In all instances, the value of ε, the non-Archimedean element, is equal to 10^{-12}.

4.4.1 Two-stage Bank Case Study

The data set for this case is adopted from Liang et al. (2008). It consists of 27 banks. It includes bank networks that are formed by connecting two partners with a single intermediate measure, where the first partner consumes three different input sources and the second entity produces two different outputs. The scheme of this case is presented in Figure 4.2. Our purpose in using this case study is to illustrate the analytical results we have in Section 4.3.3 and how they relate to the work of Liang et al. (2008).

Note that the weights of Stage 1 and Stage 2 are assumed to be equal so we can compare the result of our model to that of Liang et al. (2008). Table 4.2 presents a list of the indicators that are used in the case. In addition to showing the stage and dimension of every measure, we also describe them briefly in the sustainability context. The data values related to the indicators are presented in **Appendix B.2**.

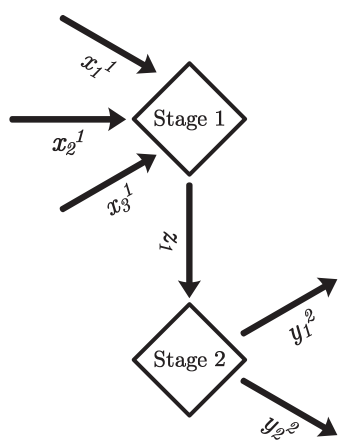


Figure 4.2: A network that includes direct and intermediate measures of the Bank case

Table 4.2: Indicator list used in Figure 4.2 to investigate the Bank case

Measure	Stage	Dimension	Description
x_1^1	Stage 1	Economic	Fixed Assets
x_2^1	Stage 1	Economic	IT Budget
x_3^1	Stage 1	Economic	Numbers of Employees
z_1	Stage 1	Economic	Deposits Generated
y_1^2	Stage 2	Economic	Profit
y_2^2	Stage 2	Economic	Fraction of Loans Recovered

In Table 4.3 we present the results of the Bank case study. We note that Liang et al. (2008) proposed a model to evaluate the efficiency of a two-stage network in which all inputs of Stage 2 are intermediate measures and there are no direct inputs for the second stage. Therefore we take their single intermediate measure as our non-discretionary input for Stage 1 as well as the direct input for Stage 2 and make the relevant set $\mathrm{D}\mathbb{I}$ nonempty in model (4.6). Borrowing from their notation of the centralized model, this modification converts the general proposed model presented in (4.6) to the following linear program, where $\mathbb{I}_{(1)}$, $\mathbb{D}$, and $\mathbb{R}_{(2)}$ denote the input indicators of Stage 1, the intermediate measures, and the output indicators of Stage 2, respectively:

$$
\begin{aligned}
\text{Min} \quad & e_p^{\text{Centralized}} - \varepsilon \left(\sum_{i \in \mathbb{I}^1} s_i^- + \sum_{d \in \mathbb{D}} s_d^+ + \sum_{r \in \mathbb{R}^2} s_r^+ + \sum_{d \in \mathbb{D}} s_d^- \right) \\
\text{s.t.} \quad & \sum_{j \in \mathbb{J}} x_{ij}^1 \lambda_j + s_i^- = e_p^1 x_{ip}^1 \qquad \forall i \in \mathbb{I}_{(1)} \\
& \sum_{j \in \mathbb{J}} z_{dj} \lambda_j - s_d^+ = z_{dp} \qquad \forall d \in \mathbb{D} \\
& \sum_{j \in \mathbb{J}} y_{rj}^2 \beta_j - s_r^+ = y_{rp}^2 \qquad \forall r \in \mathbb{R}_{(2)} \\
& \sum_{j \in \mathbb{J}} z_{dj} \beta_j + s_d^- = e_p^2 z_{dp} \qquad \forall d \in \mathbb{D} \\
& e_p^{\text{Centralized}} = (\frac{1}{2} e_p^1 + \frac{1}{2} e_p^2)/(\frac{1}{2} + \frac{1}{2}) \\
& \lambda_j, \beta_j, s_i^-, s_d^+, s_r^+, s_d^- \geq 0 \quad \forall j \in \mathbb{J} \;\; \forall i \in \mathbb{I}_{(1)} \;\; \forall d \in \mathbb{D} \;\; \forall r \in \mathbb{R}_{(2)}.
\end{aligned} \tag{4.8}
$$

We note that Proposition 4.2 implies that (4.6) (or any of its special cases such as (4.8)) is not sensitive to the predefined weights of the partners, and hence equal weights are assigned to the individual efficiency scores of the partners, i.e., e_p^1 and e_p^2 in (4.8), to evaluate the overall efficiency of the network, $e_p^{\text{Centralized}}$. As shown in Table 4.3, the achieved optimal values of e_p^1 and e_p^2 are the same as those of Table 2 in Liang et al. (2008). However, note that they have used a product measure of the individual scores to establish the centralized efficiency. In contrast we used a weighted average of e_p^1 and e_p^2. We stress here that Liang et al. (2008) considered a supply chain that has only two stages where the output weights of Stage 1 are the same as that of Stage 2. Our model relaxes these two assumptions by allowing for multiple stages and the possibility of unequal output/input weights between stages. The next case study will highlight the application of our model to more complex supply chains.

Table 4.3: Computational result of the Bank case

DMU	Liang et al. (2008)			Centralized Model			Decentralized Model		
	e_p^1	e_p^2	$e_p^1.e_p^2$	e_p^1	e_p^2	$e_p^{\text{Centralized}}$	e_p^1	e_p^2	$0.5(e_p^1+e_p^2)$
1	0.6388	0.7459	0.4764	0.6388	0.7459	0.6924	0.6388	0.7459	0.6924
2	0.6507	0.7819	0.5087	0.6507	0.7819	0.7163	0.6507	0.7819	0.7163
3	0.5179	0.7730	0.4003	0.5179	0.7730	0.6455	0.5179	0.7730	0.6455
4	0.5986	0.7142	0.4275	0.5986	0.7142	0.6564	0.5986	0.7142	0.6564
5	0.5556	0.7236	0.4020	0.5556	0.7236	0.6396	0.5556	0.7236	0.6396
6	0.7599	0.5758	0.4376	0.7599	0.5758	0.6679	0.7599	0.5758	0.6679
7	1.0000	0.5758	0.5758	1.0000	0.5758	0.7879	1.0000	0.5758	0.7879
8	0.5352	0.8250	0.4415	0.5352	0.8250	0.6801	0.5352	0.8250	0.6801
9	0.6249	0.6347	0.3966	0.6249	0.6347	0.6298	0.6249	0.6347	0.6298
10	0.4963	0.7188	0.3567	0.4963	0.7188	0.6076	0.4963	0.7188	0.6076
11	0.4945	0.7188	0.3555	0.4945	0.7188	0.6067	0.4945	0.7188	0.6067
12	0.6685	0.5949	0.3977	0.6685	0.5949	0.6317	0.6685	0.5949	0.6317
13	0.9487	0.8582	0.8141	0.9487	0.8582	0.9035	0.9487	0.8582	0.9035
14	0.5880	0.5783	0.3400	0.5880	0.5783	0.5832	0.5880	0.5783	0.5832
15	0.6582	0.6035	0.3972	0.6582	0.6035	0.6309	0.6582	0.6035	0.6309
16	0.6646	0.6434	0.4276	0.6646	0.6434	0.6540	0.6646	0.6434	0.6540
17	0.7177	0.7877	0.5653	0.7177	0.7877	0.7527	0.7177	0.7877	0.7527
18	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
19	0.8144	0.5926	0.4826	0.8144	0.5926	0.7035	0.8144	0.5926	0.7035
20	0.6934	1.0000	0.6934	0.6934	1.0000	0.8467	0.6934	1.0000	0.8467
21	0.7067	0.9936	0.7022	0.7067	0.9936	0.8502	0.7067	0.9936	0.8502
22	0.7942	0.6408	0.5089	0.7942	0.6408	0.7175	0.7942	0.6408	0.7175
23	0.7802	0.6993	0.5456	0.7802	0.6993	0.7398	0.7802	0.6993	0.7398
24	0.9300	0.7135	0.6636	0.9300	0.7135	0.8218	0.9300	0.7135	0.8218
25	0.6270	0.6516	0.4085	0.6270	0.6516	0.6393	0.6270	0.6516	0.6393
26	1.0000	0.5152	0.5152	1.0000	0.5152	0.7576	1.0000	0.5152	0.7576
27	1.0000	0.5644	0.5644	1.0000	0.5644	0.7822	1.0000	0.5644	0.7822

4.4.2 Multi-stage Beverage Supply Chain Case Study

In this case, the data values are adopted from Mirhedayatian et al. (2014). This data set is collected from 10 beverage corporations and it includes all triple pillars of sustainability. Figure 4.3 illustrates the supply chain network which includes a number of economic, social, and environmental direct/intermediate indicators connecting four partners: one supplier, one manufacturer, one distributer, and one retailer. We use this case study to illustrate the practicality of our centralized model and how it can be used to measure sustainability performance of multi-stage networks. In addition, we use a special instance of this case to illustrate the result shown in Proposition 4.2.

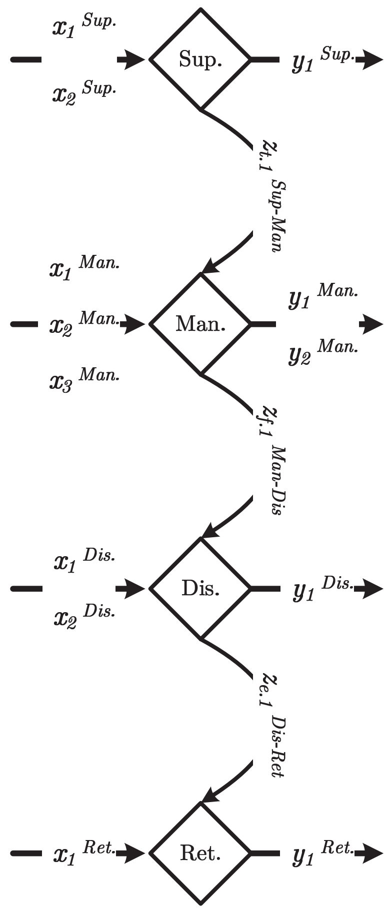


Figure 4.3: A network that includes direct and intermediate measures of the Beverage case

As Mirhedayatian et al. (2014) assume, the worths of the members are $w^S = 0.3$, $w^M = 0.4$, $w^D = 0.2$, and $w^R = 0.1$. Table 4.4 presents a list of the indicators used in this case. We note that some of these measures are followed by the "*" symbol to indicate that their reciprocal values are entered into the model. As Chen et al. (2012) argue, in DEA higher levels of outputs usually indicate better performance and therefore one approach to deal with undesirable outputs which do not satisfy this rule of thumb is taking the reciprocals of their values into account. The data values related to the indicators are shown in **Appendix B.3**.

Table 4.4: Indicator list used in Figure 4.3 to investigate the Beverage case

Measure	Stage	Dimension	Description
$x_1^{Sup.}$	Supplier	Economic	raw material cost
$x_2^{Sup.}$	Supplier	Economic	transportation cost

Table 4.4: Indicator list used in Figure 4.3 to investigate the Beverage case

Measure	Stage	Dimension	Description
$y_1^{Sup.}$	Supplier	Economic	supplier capability factor
$z_{t.1}^{Sup-Man}$	Supplier	Economic	defect-free parts per million
$x_1^{Man.}$	Manufacturer	Economic	advertisement cost
$x_2^{Man.}$	Manufacturer	Economic	transportation cost
$x_3^{Man.}$	Manufacturer	Economic	investment in sustainability design
$y_1^{Man.}$	Manufacturer	Environmental	CO_2 emission *
$y_2^{Man.}$	Manufacturer	Social	average reputation factor
$z_{f.1}^{Man-Dis}$	Manufacturer	Environmental	number of green products
$x_1^{Dis.}$	Distributer	Economic	transportation cost
$x_2^{Dis.}$	Distributer	Economic	personnel cost
$y_1^{Dis.}$	Distributer	Economic	service diversity
$z_{e.1}^{Dis-Ret}$	Distributer	Economic	lead time
$x_1^{Ret.}$	Retailer	Economic	procurement cost
$y_1^{Ret.}$	Retailer	Economic	average customer satisfaction factor

Table 4.5 shows the result of applying model (4.6) to the Beverage case. By utilizing the proposed model, DMU_1 is the unique efficient unit, while both DMU_1 and DMU_{10} are described as the efficient partners in Mirhedayatian et al. (2014). The existing difference of these rankings is the result of using different DEA approaches; the proposed model is established by a deterministic structure and a radial objective function, whereas that of Mirhedayatian et al. (2014) benefits from a fuzzy foundation and a non-radial objective.

To see that the sufficient condition of Proposition 4.2 (that implies there exists exactly one partner in each stage of the supply chain under consideration) is also a necessary condition, we consider a modified version of the Beverage case. In this instance, there are two partners in the supplier stage with two intermediates affecting the manufacturer and the data of this artificial supplier as well as the new intermediate is randomly generated. The data values related to the indicators of these two suppliers are shown in **Appendix B.4**. Table 4.6 illustrates the result of using models (4.4) and (4.6) for this instance and demonstrates that the optimal values of the decentralized and centralized models are different, in spite of the presence of the common weight 0.2 for all five echelons of the supply chain. Specifically, there exist some DMUs (all excluding DMU_3, DMU_5, and DMU_8) in this example that satisfy $\mu_p^* \neq \theta_p^*$.

Table 4.5: Computational result of the Beverage case

DMU	Proposed Centralized Model							Mirhedayatian (2014)	
	Slack	θ_p	$\theta_p^{Sup.}$	$\theta_p^{Man.}$	$\theta_p^{Dis.}$	$\theta_p^{Ret.}$	Rank	θ_p	Rank
1	0.00	1.0000	1.0000	1.0000	1.0000	1.0000	1	1.0000	1
2	556.28	0.9291	0.9610	1.0000	0.9807	0.4464	6	0.2500	8
3	48.84	0.9447	1.0000	1.0000	0.9348	0.5769	3	0.4670	7
4	36.58	0.9664	0.9025	1.0000	0.9784	1.0000	2	0.6040	4
5	45.36	0.9126	1.0000	0.8488	1.0000	0.7309	8	0.2430	9
6	0.00	0.9253	1.0000	1.0000	0.8751	0.5034	7	0.5000	5
7	6,808.85	0.9362	0.8940	1.0000	1.0000	0.6803	5	0.7000	3
8	20,307.82	0.8303	0.8976	0.8025	1.0000	0.4000	10	0.5000	6
9	0.00	0.9067	0.8300	1.0000	1.0000	0.5769	9	0.8000	2
10	5.86	0.9413	0.9775	1.0000	1.0000	0.4808	4	1.0000	1

Table 4.6: The Beverage case study including an extra supplier in (4.6)

DMU	Centralized	Decentralized					
	θ_p	μ_p	μ_p^{Sup1}	μ_p^{Sup2}	$\mu_p^{Man.}$	$\mu_p^{Dis.}$	$\mu_p^{Ret.}$
1	1.0000	0.9500	1.0000	0.7502	1.0000	1.0000	1.0000
2	0.8585	0.8118	0.9610	0.6712	1.0000	0.9807	0.4464
3	0.9024	0.9024	1.0000	1.0000	1.0000	0.9348	0.5769
4	0.9043	0.8463	0.9632	0.2899	1.0000	0.9784	1.0000
5	0.9268	0.9268	1.0000	1.0000	0.9032	1.0000	0.7309
6	0.8757	0.7540	1.0000	0.3918	1.0000	0.8751	0.5034
7	0.9162	0.8703	0.8951	0.7759	1.0000	1.0000	0.6803
8	0.8522	0.8522	1.0000	1.0000	0.8608	1.0000	0.4000
9	0.9154	0.8814	0.8300	1.0000	1.0000	1.0000	0.5769
10	0.8434	0.8160	0.9775	0.6216	1.0000	1.0000	0.4808

4.4.3 Discussion and Managerial Insights

From the results of the Bank case study we confirmed that our proposed model does lead to similar results as those found by Liang et al. (2008). This is not surprising as we have used a special case of our model that mimics the setup used by Liang et al. (2008). However, our implementation used an average of efficiencies to calculate the scores as opposed to a product of the efficiencies. While Liang et al. (2008) avoided the average format due to the difficulty of dealing with the resulting nonlinear model, we were able to use duality theory, through (4.1), to avoid a nonlinear structure. In addition, Liang et al. (2008) have assumed that incoming and outgoing weights of each intermediate are equal so as to simplify their model structure and obtain the equivalency between scores in decentralized and centralized settings. We have also relaxed this assumption in our model by considering more general and realistic model structure that allows for unequal intermediate weights as well as additional new direct inputs into each stage. The latter is an important feature as it allows for considering networks where some external input factors, that may be completely independent from previous stages such as environmental and third party factors, can be considered in the model. While both our model and that of Liang et al. (2008) lead to equality of decentralized and centralized scores for the Bank case study, we note that the actual scores and ranks of DMUs in Table 4.3 are different. In fact eight DMUs (3, 4, 16, 17, 23, 25, 26, and 27) were ranked differently; four of them (3, 4, 26, and 27) had lower ranks in the Liang et al. (2008) model while the remaining other four had higher ranks.

For the Beverage case, our model leads to only one efficient DMU (DMU_1), while that of Mirhedayatian et al. (2014) had two efficient DMUs (DMU_1 and DMU_{10}). This shows that for this case study our model has more discriminatory power. It is also interesting to compare the ratings of the different supply chain partners vertically (by stage) and horizontally (by supply chain). Looking vertically at Table 4.5, we find that the highest efficient stage is that of the manufacturers (80% of the manufacturers are efficient), followed by the distributors (60%), the suppliers (40%), and the retailers (20%). Horizontally, we find that except for two (DMU_2 and DMU_8) all inefficient supply chains had two efficient partners. In addition, all supply chains have at least one efficient partner. We also note that for the two supply chains (DMU_2 and DMU_8) that have only one efficient partner, their rank differ significantly; DMU_2 is ranked 6 while DMU_8 is ranked 10, or last. Similar remarks can be made for the case when we added an extra supplier to each supply chain in Table 4.6. Assuming this case covers all major supply chains in the beverage sector, such an analysis can help individual supply chains when making decisions about strategic sustainable sourcing and supplier partnerships. For example, based on the results of this case study we can say that the supply chain that wants to improve its sustainability performance should put more emphasis on the retailer echelon.

4.5 Conclusion and Future Extensions

In this chapter, in addition to reviewing a vast range of existing DEA approaches that evaluate supply chain practices, a new multi-stage DEA model is proposed. This model presents both the overall efficiency score of a supply chain and the individual efficiency score of its partners at the same time. In addition, the condition that guarantees the equivalence of results obtained by decentralized and centralized approaches is described. More importantly, the developed multi-stage DEA approach could evaluate the efficiency of a (sustainable) supply chain when there exists an arbitrary number of suppliers, manufacturers, distributers, and retailers, allowing for the possibility of having unequal weights between stages as well as new inputs to intermediary stages. The novelty in our approach is that we employ duality theory to model an additive efficiency measure and thus avoid dealing with nonlinear DEA models.

The methodology we have developed in this study can be applied to measure other performances within the supply chain as long as such a performance is believed to be impacted by the action of more than one partner. As examples, we think our model can also be applied to measure quality and delivery performance in multi-partner supply chains.

Although a centralized perspective has been introduced in this study, more complicated approaches of game theory could be integrated with the DEA technique in future studies. Furthermore, all indicators are assumed independent in the current chapter, while they could be generalized for practical cases that deal with correlated and non-separable direct/intermediate measures. In addition, investigating the impact of the missed data of some DMUs on the overall score and also beneficiating the privileges of super-efficiency models to overcome the infeasibility and multi-efficiency appearance could be analyzed in the future.

Chapter 5

Game Theory Models for Climate Change Initiatives

There is ample literature about regional, nationwide, and international efforts in establishing mechanisms to curb pollution and emissions. In this study, we first review a variety of these policy instruments, with a focus on emissions trading systems, and then propose a game-theoretic model in the presence of uncertain demand. To do so, through a static Cournot oligopoly game we investigate a perfectly competitive multi-product multi-pollutant market in which a number of supply chains compete in a non-cooperative manner in their product markets. In order to investigate the equilibria of this game, we present a variational inequality approach. Meanwhile, within each supply chain, its partners establish a cooperative triopoly game in a non-superadditive characteristic function form, by which initial permit allocations of the pollutants are given on the basis of the whole supply chain's sustainability efficiency. In particular, drawing on the cooperative game theory literature we propose a rational distribution of the pollution permits between the supply chain's partners (two suppliers and one manufacturer) while taking into account sustainability expectations.

5.1 Introduction

The topic of environmental sustainability has been of great interest for the last decade both in academia and among industry practitioners. In recent years, many governments have taken actions to incentivize firms to invest in disruptive technologies in order to reduce environmental and social impacts of their business operations (Chevallier 2012). It is unclear, however, how successful were these policies in achieving the goals that were intended for them. This has provided ammunition for the climate change deniers to argue that it is better if governments focus on improving the economy rather than spending on lofty environmental initiatives. Environmentalists raise the question of "how can policy makers play an effective role in helping businesses become more sustainable while at the same time maintain a flourishing economy?" To provide insights to policy makers in this regard, in this chapter we focus on the environmental pollution control systems.

Environmental pollution occurs when emissions from facilities result in ambient concentrations that are sufficiently high to cause damage to property, ecosystems, human health, and/or aesthetics. Production units may discharge pollutants irresponsibly when there is neither any attached cost to such behavior nor any incentive for reducing such emissions. Integration of environmental sustainability and business globalization is the principal focus of many governments in the 21st century. For example, during the Canadian Leaders' Debates televised for the federal elections in 2015, environmental sustainability was a common concern highlighted by all party leaders. However, the plan of the federal government in Canada aimed to cut greenhouse gas emissions by 30% below 2005 levels by 2030 has its own challenges [1]. Some environmental economists believe that the only way to achieve national sustainability objectives are to change the pollution per unit prices by implementing marketable frameworks and regulating green technologies.

5.1.1 Environmental Control Mechanisms

In this section we review some of the pollution control systems that are proposed in the literature. The first mechanism is referred to as a marketable pollution permit system, which can be traced back to Crocker (1966). Briefly, each emitter who needs more pollution permits can purchase some from emitters having a less polluting technology or production program. Another approach to restrain pollution is that in which polluters are charged a fixed penalty for their negative discharges. Montgomery (1972) argues that charging all firms the same per unit cost leads to an appropriate level of pollution

[1] http://www.cbc.ca/news/politics/greenhouse-gas-emissions-how-can-canada-cut-30-by-2030-1.3080447

when cost minimization is the goal of firms. In this approach polluting firms pay a price equal to the marginal external cost of their polluting activities which leads to corrective behavior on the part of the polluting firms (Nagurney and Dhanda 1996). As stated by Krass et al. (2013), the taxation approach (as well as the subsidy mechanism) recently gained significant attraction among regulators and in the business media. We note that a classic example is the US tax on chlorofluorocarbons following the 1987 adoption of the Montreal Protocol aimed at eliminating ozone-destroying substances. Another approach is described by Nagurney et al. (1996) in which a competitive market is developed in the presence of targets. More particularly, the environmental targets are set by a decision maker and the firms in the industry can prioritize their goals in order to meet these targets. Taxes or subsidies are then determined according to the achieved goals by the firms.

In this study, we are interested in a generalization of the ambient-based permit system (APS) introduced by Montgomery (1972). In the literature, the APS, cap-and-trade scheme, and emissions trading system (ETS) terms are used interchangeably, however the latter is the most frequently used. This scheme deals with allowable pollution concentrations at a set of receptor points, where a set of polluters produce a homogeneous product. Therefore, the initial allocation of the pollution permits can be only dependent on the sum of those for each receptor point. We generalize the ETS model of Montgomery (1972) by allowing the firms (or the supply chains in our context) to compete in a non-cooperative manner in their product markets and to interact in a perfectly competitive manner in the pollutant permit market. More specifically, each supply chain as a source of pollution purchases the permits to pollute at a certain receptor point at a predetermined per unit price. Nagurney and Dhanda (1996) provide several reasons for why the ETS model should be chosen by regulatory bodies. This approach enables the policy makers to monitor the quantity of emissions in each geographical point and meet requirements of environmental standards. On the other hand, such mechanisms provide the emitters with financial incentives, for example through assigning more free emissions allowances to greener businesses.

5.1.2 Implementing Emissions Trading Systems

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) emphasized a pressing need for addressing climate change issues. Many countries agreed to form an international treaty to cooperatively consider measures as to how to slow the pace of global warming. The Kyoto Protocol consequently defined the industrialized countries' contractual obligations to reduce their greenhouse gas emissions in 1997. To do so, the Kyoto Protocol extended the 1992 UNFCCC and paved the way for the creation of an ETS called "the carbon market" that allows participants to trade permits.

The underlying logic behind any ETS is that permits take on value and put a price on the right to pollute, due to the imposed central authority limits. From the economic perspective, business foundations and industrial sectors can determine whether it is worth to continue polluting or to reduce their pollution on the basis of market signals (Chevallier 2012). The interested reader is referred to Hansjürgens (2005), Faure and Peeters (2008), and Altvater and Brunnengräber (2011) for more detailed discussions on ETSs and their successful implementations around the world. In particular, the following subsections regarding experiences in the U.S. and the European Union are adopted from Chevallier (2012).

Implementation in the U.S.

At the federal level, the negotiations concerning a national ETS have been more or less stalled. More importantly, the Waxman-Markey American Clean Energy and Security Act failed to pass in July 2009 in the hands of the Congress.

In the absence of a federal U.S. emissions trading scheme, several regional initiatives are worth mentioning. First, ten North-Eastern states have been auctioning CO_2 permits through the Regional Greenhouse Gas Initiative since January 2009. Moreover, the Western Regional Carbon Action Initiative was launched for a number of states in the Mid West and the West in 2012. In this scheme, a 15% emissions reduction target established by 2020 compared to 2005 levels. The California Global Warming Solutions Act in 2006, the Midwestern Greenhouse Gas Reduction Accord in 2007, as well as the California Air Resources Board in 2012 are other designed market-based instruments for climate protection in the U.S.

Implementation in the European Union

The European Union has set up an ETS which concerns around 11,300 installations across the Members-States. In the Kyoto Protocol, the European Union established its reduction target to 8% by 2012 compared to 1990 levels. This goal was modified later to ensure further emissions reduction at the Member/State level following the so-called "Burden Sharing Agreement". In 2002, the European Union stated that 15 Member-States (known as the EU-15) would make use of a new provision to fulfill their emissions commitment jointly. Therefore, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom designed a mutual compliance mechanism to reduce their collective greenhouse gas emissions. Under the Burden Sharing Agreement, the EU-15 consented to meet the targets according to each Member-State's relative wealth at the time of the agreement.

The three main characteristics of the European Union ETS may be summarized as follows. First, the allocation is principally free during the first phases according to a grandfathering permit allocation. In such allocation approaches, a free distribution of the permits is assigned to the participants in proportion of their recent emissions as a benchmark. By contrast, the last phases constitute a rapid shift to costly allowances, with the introduction of auctioning. Second, this ETS has a twofold structure, which is decentralized at the national level to monitor operational practices, and centralized at the European Union Commission level to harmonize its strategic functioning. That is, the European Union Commission is in charge to oversee national registries and to ensure that the targets of the Kyoto Protocol are met. Third, the perimeter of the scheme is gradually broadening, with the inclusion of additional sectors and industries.

5.1.3 Research Contributions

Several studies in the OR literature have looked at the ETS. Some of the interesting topics include lot sizing, production planning and pricing, as well as empirical studies (Drake et al. 2012, Li and Gu 2012, Clò et al. 2013, Gong and Zhou 2013, Zhang and Xu 2013, He et al. 2014, Zakeri et al. 2015). The techniques mostly used are multi-attribute decision making and dynamic/stochastic optimization. Studies that have investigated a game-theoretic framework include Nagurney and Dhanda (1996), Nagurney and Dhanda

(2000a), Nagurney and Dhanda (2000b), Haurie and Viguier (2003), Subramanian et al. (2007), Bernard et al. (2008), Woolley et al. (2009), Du et al. (2011), and Chung et al. (2012). Despite their substantial contributions, these studies have a major limitation in that they assume demand of products or services is deterministic. We relax this assumption in our model by allowing demand to be uncertain, where it is continuously distributed over positive values.

The other contribution of this work is letting each entity competing in the proposed setting represents a supply chain, rather than a single-partner firm. Each supply chain includes a number of partners aiming to maximize their individual payoffs as well as the network outcome. To the best of our knowledge, there is no study that examines the behavior of supply chains in the presence of an ETS formation. We assume that each of these homogeneous supply chains establishes a cooperative game of three partners, including two suppliers and one manufacturer. As we discuss later, such a game is not well-behaved, however, a closed-form core solution is provided. At the same time, we are interested in characterizing equilibria of a Cournot game whereby the supply chains compete in a non-cooperative manner in their product markets.

Furthermore, we note that this study is the first to apply social measures in the context of ETS schemes. To do so, we incorporate all sustainability pillars of businesses into the solution of the mentioned cooperative games. We use the centralized efficiency framework proposed in Chapter 4 to solve these games, where this centralized framework can account for the environmental-social performance of the supply chains such that more sustainable networks receive more incentives.

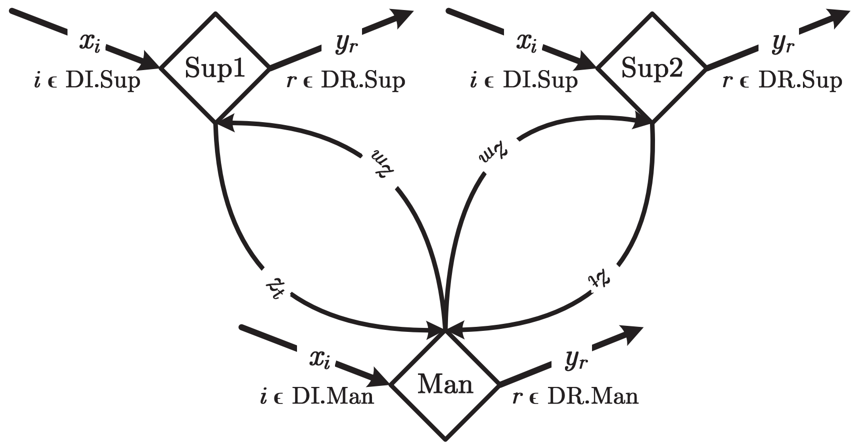
Our analysis of optimality conditions for the non-cooperative game relies on the variational inequality literature, originally developed to solve partial differential equations. To find various applications of this approach in the context of game theory, the reader is referred to the excellent book by Nagurney (1999). In this regard, first an optimization problem is introduced for each of the profit-sensitive supply chains, and then all the problems are integrated in order to develop a single optimization problem which can be solved easily. More particularly, the modified projection method introduced by Korpelevich (1976) is adopted in this study as an algorithm for exploring the solution of the obtained problem. We provide sufficient conditions under which this solution method converges to the equilibria of the non-cooperative game under investigation. We show that under realistic necessary and sufficient conditions the proposed Cournot setting has a unique equilibrium. We also provide the closed-form solution of both sub-problems developed for the iterative procedure solving the mentioned new problem. Finally, we examine the proposed framework through several numerical examples where the impact of the model parameters on the equilibrium is investigated.

The rest of this chapter is organized as follows. We pose our research questions and describe the problem in Section 5.2. A cooperative setting is discussed in Section 5.3, where the core solution of a triopoly is derived. Having investigated this triopoly, in Section 5.4 we develop a non-cooperative oligopoly and present a convergent procedure in order to calculate its Nash equilibria. In addition, several numerical examples are discussed to highlight managerial insights of the proposed control mechanism. Finally, we propose some research questions and our conclusions in Section 5.5.

5.2 Problem Description

In this section, we develop a static Cournot oligopoly game that represents a perfectly competitive multi-product multi-pollutant market in which all the supply chains (or the sources of pollution) compete in a non-cooperative manner in their product markets. Since each supply chain is small relative to the entire business environment, it takes the price of the permits at a certain point as given. Our model differs from previous research in that we allow product demand to be uncertain.

We consider a three-partner network (including two suppliers and one manufacturer) for each of the supply chains, as shown in Figure 5.1. This network can be interpreted as a supply chain if at least one of the suppliers cooperates with the manufacturer. In other words, only the following coalitions promote feasible cooperation between the partners: (*i*) {Supplier1 , Manufacturer}; (*ii*) {Supplier2 , Manufacturer}; (*iii*) {Supplier1 , Supplier2 , Manufacturer}.



◇: a partner of the supply chain; — x_i →: set of direct inputs of a partner of the supply chain; — y_r →: set of direct outputs of a partner of the supply chain; Other arrows present intermediates.

Figure 5.1: A two-supplier supply chain network

We pose our research questions as follows: (1) How are the initial allocations calculated and assigned to the supply chains of the ETS? (2) How are the initial permits allocated to a supply chain distributed rationally between its partners? (3) How do the supply chains behave at optimality in the product/pollutant markets?

5.2.1 Notation

In addition to the notation presented in Chapter 4, we use the following notation (Nagurney and Dhanda 2000a):

1. Indexes, Sets, and Players

   - $\{1, ..., \bar{n}\}$: set of supply chains, indexed by j
   - $\{1, ..., \bar{k}\}$: set of receptor points, indexed by k
   - $\{1, ..., \bar{c}\}$: set of pollutants, indexed by c
   - $\{1, ..., \bar{d}\}$: set of products, indexed by d
   - SC_p : typical supply chain under investigation in the cooperative game
   - SC_j : typical supply chain under investigation in the non-cooperative game

2. Parameters (Initial Allocation and Cooperative Game)

   - ℓ^0_{kc} : total initial allowable pollution concentrations of Pollutant c at Point k

- ℓ^0_{pkc} : initial pollution allocation of Pollutant c at Point k for SC$_p$

3. <u>Parameters (Non-cooperative Game)</u>

   - ℓ^0_{kc} : total initial allowable pollution concentrations of Pollutant c at Point k
   - ℓ^0_{jkc} : initial pollution allocation of Pollutant c at Point k for SC$_j$
   - h_{jkc} : contribution that one unit of emission by SC$_j$ makes to average the cth pollutant's concentration at Point k
   - $\vec{\rho} \in \mathbb{R}_+^{\bar{k}\times\bar{c}}$: permit price vector
   - ρ_{kc} : typical element of $\vec{\rho}$, representing the fixed purchasing price of Pollutant c at Point k
   - ν_{kc} : per unit penalty for every additional emitted unit of Pollutant c at Point k
   - $A_d > 0$: parameter of the price function
   - $B_d > 0$: parameter of the price function
   - $\hat{s}_{jd} > 0$: per unit lost opportunity cost of Product d for SC$_j$

4. <u>Variables and Functions (Initial Allocation and Cooperative Game)</u>

   - I_1 : Supplier1 of SC$_p$ (see Figure 5.1)
   - I_2 : Supplier2 of SC$_p$ (see Figure 5.1)
   - I_3 : Manufacturer of SC$_p$ (see Figure 5.1)
   - Ω_p : set of all partners of SC$_p$, $\{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$ (grand coalition)
   - S_p : typical subset of Ω_p (coalition)
   - θ^{13}_p : efficiency score of $\{\mathrm{I}_1, \mathrm{I}_3\}$
   - θ^{23}_p : efficiency score of $\{\mathrm{I}_2, \mathrm{I}_3\}$
   - θ^{123}_p : efficiency score of $\{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$
   - $\mathbf{G}(\Omega_p, \tau_p)$: cooperative triopoly game
   - $\tau_p(S_p)$: characteristic function of $\mathbf{G}$
   - $\mathbf{C}(\Omega_p, \tau_p)$: core of $\mathbf{G}(\Omega_p, \tau_p)$

- $\mathbf{G}^*(\Omega_p, \tau_p^*)$: superadditive cover of $\mathbf{G}(\Omega_p, \tau_p)$
- $\tau_p^*(S_p)$: characteristic function of $\mathbf{G}^*$
- $\mathbf{C}(\Omega_p, \tau_p^*)$: core of $\mathbf{G}^*(\Omega_p, \tau_p^*)$
- $\mathcal{CS}_{S_p}$: set of all possible coalition structures (or partitions) of S_p with a typical element CS
- $\mathcal{CS}_{\Omega_p}$: set of five grand partitions, $\{CS_{\mathrm{I}}, CS_{\mathrm{II}}, CS_{\mathrm{III}}, CS_{\mathrm{IV}}, CS_{\mathrm{V}}\}$

5. Variables and Functions (Non-cooperative Game)

- $\mathbf{Q} \in \mathbb{R}_+^{\bar{n}\times\bar{d}}$: production quantity matrix corresponding to all supply chains
- $\mathbf{Q}_j \in \mathbb{R}_+^{\bar{d}}$: typical element of $\mathbf{Q}$, representing the production quantity vector of SC_j
- Q_{jd} : typical element of $\mathbf{Q}_j$, representing the quantity of Product d produced by this supply chain
- $\mathbf{Q}_{-j} \in \mathbb{R}_+^{(\bar{n}-1)\times\bar{d}}$: complement of $\mathbf{Q}_j$, or $(\mathbf{Q}_1, ..., \mathbf{Q}_{j-1}, \mathbf{Q}_{j+1}, ..., \mathbf{Q}_{\bar{n}})$
- $\mathbf{E} \in \mathbb{R}_+^{\bar{n}\times\bar{c}}$: emissions matrix corresponding to all supply chains
- $\mathbf{E}_j \in \mathbb{R}_+^{\bar{c}}$: typical element of $\mathbf{E}$, representing the emissions vector of SC_j
- E_{jc} : typical element of $\mathbf{E}_j$, representing the amount of Pollutant c emitted by SC_j
- $\mathbf{L} \in \mathbb{R}_+^{\bar{n}\times\bar{k}\times\bar{c}}$: license matrix corresponding to all supply chains
- $\mathbf{L}_j \in \mathbb{R}_+^{\bar{k}\times\bar{c}}$: typical element of $\mathbf{L}$, representing the license vector of SC_j
- L_{jkc} : typical element of $\mathbf{L}_j$, representing the number of licenses for emitting Pollutant c at Point k possessed by SC_j
- $P_d \equiv P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})$: per unit price of selling Product d
- $F_{jd}(Q_{jd})$: production cost function of SC_j related to Product d
- $G_j(\mathbf{Q}_j, \mathbf{E}_j)$: emissions cost of SC_j
- D_{jd} : non-negative continuous random variable addressing demand of Product d satisfied by SC_j with mean μ_{jd}
- $\varepsilon_{jd} \lneq 1$: cumulative distribution function (CDF) of D_{jd}

- $\epsilon_{jd} = \varepsilon'_{jd}$: probability density function (PDF) of D_{jd}
- $\Pi_j(\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j) \equiv \Pi_j(\mathbf{Q}_j, \mathbf{Q}_{-j}, \mathbf{E}_j, \mathbf{L}_j)$: expected profit of SC_j

We note that we investigate random variables for which $\varepsilon_{jd} \lneq 1$ is met, i.e., the line $y = 1$ can be only a horizontal asymptote of ε_{jd}. It is worth mentioning that $\varepsilon_{jd} \lneq 1$ is not a restrictive assumption in the operations research literature. To justify this argument, we note that increasing (or, decreasing) generalized failure rate (that is, IGFR or DGFR) random variables over an unbound domain satisfy this property (Lariviere and Porteus 2001, Lariviere 2006, Kocabiyikoglu and Popescu 2011, Banciu and Mirchandani 2013). In particular, IGFR distributions have useful applications in supply chain management and provide an appealing implication (Lariviere and Porteus 2001). Other symbols are defined in this work as needed. In addition, a vector is assumed to be a column vector, unless stated explicitly otherwise.

5.2.2 Initial Allocation Rules

Different initial permit allocation methodologies have been chosen in the literature, such as grandfathering, auctioning, or per capita allocation schemes (Hahn 1984, Egteren and Weber 1996, Jouvet et al. 2005, Stavins 2007, Chevallier et al. 2009). We note that Montgomery (1972) formally proved that the ultimate allocation will be cost-efficient regardless of the initial allocation as long as the firms behaved in a perfectly competitive manner both in the product markets and in the permit markets. However, other studies have explored how the initial distribution of the pollution permits can lead to economic inefficiencies in more general ESTs (Hahn 1984, Egteren and Weber 1996).

In this study, we relax this assumption and let the supply chains compete in a non-cooperative manner in their product markets. Toward this end, on the basis of Figure 5.1 we apply a centralized efficiency framework to the allocation process. For all $k \in \{1, ..., \bar{k}\}$ and $c \in \{1, ..., \bar{c}\}$, to distribute the pollution amount ℓ^0_{kc} among all $\bar{n}$ competing supply chains in such a way that $\ell^0_{kc} = \sum_{j=1}^{\bar{n}} \ell^0_{jkc}$, we use a linear transformation on the basis of the centralized approach in Chapter 4. Thus, for a given supply chain, say p, let $\ell^0_{pkc} = \frac{\theta_p^{123}}{\sum_{j=1}^{\bar{n}} \theta_j^{123}} \times \ell^0_{kc}$ denote the portion of cth pollution concentrations at Point k allocated initially to SC_p. These centralized efficiency scores are computed based on the current performance of the supply chain, and the proposed initial distribution transformation endows more (free of charge) credit to the more efficient supply chains.

Given that the efficiency score of each entity is calculated by using the sustainable indicators (inputs, outputs, or intermediates), by relating the obtained incentives from the regulatory body to these scores the supply chains have a motive for pollution reduction. This initial allocation is employed at the beginning of the decision making process, before the supply chains behave in the oligopolistic market. This is particularly important when they play a multi-period game, in which each period starts with evaluating previous performance efficiencies of the supply chains that leads to a competition to receive more free of charge permits in the next period.

5.3 A Triopoly Game for Intra Supply Chain Cooperations

Thus far, we have proposed an efficiency-oriented way to distribute ℓ^0_{kc} between the supply chains, where $k \in \{1, ..., \bar{k}\}$ and $c \in \{1, ..., \bar{c}\}$. Assume that the supply chain p, namely SC_p, is under investigation. In answering the question how ℓ^0_{pkc} can be allocated to the partners within SC_p, we draw on the theory of cooperative games.

5.3.1 Game Formation

From now on, let "I_1", "I_2", and "I_3" denote Supplier1, Supplier2, and Manufacturer of SC_p, respectively. As stated before, we consider a subset of $\Omega_p = \{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$, say S_p, as a feasible supply chain if it contains I_3 as well as at least one of I_1 and I_2. Now that we take into account either $\{\mathrm{I}_1, \mathrm{I}_3\}$, or $\{\mathrm{I}_2, \mathrm{I}_3\}$, or $\{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$ as the acceptable coalitions for SC_p, we can assess the overall efficiency of each coalition through the aforementioned centralized DEA approach. This provides us with three efficiency scores, one for each of the foregoing coalitions. Let θ^{13}_p, θ^{23}_p, and θ^{123}_p denote these scores corresponding with the options $\{\mathrm{I}_1, \mathrm{I}_3\}$, $\{\mathrm{I}_2, \mathrm{I}_3\}$, and $\{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$, respectively.

Having found ℓ^0_{pkc}, θ^{13}_p, θ^{23}_p, and θ^{123}_p, we now introduce a cooperative triopoly game among the SC_p's partners. We try to determine a rational allocation of ℓ^0_{pkc} among I_1, I_2, and I_3 (Barron 2013). First, we need to quantify the benefits of a coalition through the use of a real-valued characteristic function, say τ_p. The key consideration here is relating the payoff of each feasible coalition S_p to its efficiency score. We thus define $\tau_p(S_p) = \frac{\psi_p(S_p)}{\Psi_p} \times \ell^0_{pkc}$, where $\Psi_p = \max_{S_p \subseteq \Omega_p} \{\psi_p(S_p)\} = \max\{\theta_p^{13}, \theta_p^{23}, \theta_p^{123}\}$ and:

S_p	$\emptyset$	$\{\mathrm{I}_1\}$	$\{\mathrm{I}_2\}$	$\{\mathrm{I}_3\}$	$\{\mathrm{I}_1, \mathrm{I}_2\}$	$\{\mathrm{I}_1, \mathrm{I}_3\}$	$\{\mathrm{I}_2, \mathrm{I}_3\}$	$\{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$
$\psi_p(S_p)$	0	0	0	0	0	θ_p^{13}	θ_p^{23}	θ_p^{123}

For obvious reasons, τ_p allocates no pollution permits to the infeasible coalitions $\emptyset$, $\{\mathrm{I}_1\}$, $\{\mathrm{I}_2\}$, $\{\mathrm{I}_3\}$, and $\{\mathrm{I}_1, \mathrm{I}_2\}$. We note that since $\tau_p(\Omega_p) \geq [\tau_p(\{\mathrm{I}_1\}) + \tau_p(\{\mathrm{I}_2\}) + \tau_p(\{\mathrm{I}_3\})]$ and $\tau_p(\emptyset) = 0$, τ_p is well-defined as the characteristic function of a cooperative game (Barron 2013). We remind that $\mathbf{G}(\Omega_p, \tau_p)$ represents our cooperative triopoly game.

5.3.2 Non-superadditivity of τ_p

It is worth to point out that most of the proposed solution concepts on cooperative games (i.e., the core, the Shapley value, the kernel, and the nucleolus) need superadditivity of the characteristic function, since it guarantees the formation of the grand coalition, Ω_p in our formation, as the solution of the games (Chalkiadakis et al. 2012). The characteristic function τ_p is said to be superadditive if it satisfies

$$\forall\ \tilde{S}_p, \bar{S}_p \subseteq \Omega_p \quad \left(\tilde{S}_p \cap \bar{S}_p = \emptyset \Longrightarrow \tau_p(\tilde{S}_p \cup \bar{S}_p) \geq \tau_p(\tilde{S}_p) + \tau_p(\bar{S}_p)\right), \tag{5.1}$$

which ensures that the players have the incentive to join the grand coalition.

As emphasized by Chalkiadakis et al. (2012), in practice non-superadditive cooperative games occasionally arise as a result of anti-trust or anti-monopoly laws or in cases where merging coalitions can be detrimental to the society. In particular, the aforementioned function τ_p behaves in a non-superadditive manner. We present numerical evidence corroborating this behavior by the use of a randomly-generated example, which includes ten supply chains. Having adapted the data related to this instance presented in **Appendix C.2**, we need to solve 10×3 linear problems in order to calculate all the θ_p^{13}, θ_p^{23}, and θ_p^{123}, as shown in Table 5.1. We note that excluding the randomly generated values for the second supplier the data set in **Appendix C.2** is borrowed from Chapter 4, where several economic, environmental, and social measures are quantified. In particular, the indicators x, y, and z represent input, output, and intermediate sustainability measures, respectively, which ultimately determine the efficiency score of each supply chain. SC_2 clearly contradicts the superadditive property defined in (5.1), where $0.26674 = \tau_p(\{I_1, I_3\} \cup \{I_2\}) < \tau_p(\{I_1, I_3\}) + \tau_p(\{I_2\}) = 0.28576$ and $p = 2$.

Table 5.1: Efficiency scores of the example including the data set of Appendix C.2

DMU	$\{1_p, 3_p\}$		$\{2_p, 3_p\}$		$\{1_p, 2_p, 3_p\}$	
	θ_p^{13}	Rank	θ_p^{23}	Rank	θ_p^{123}	Rank
SC_1	1.00000	1	1.00000	1	1.00000	1
SC_2	0.28576	10	0.21831	10	0.26674	10
SC_3	0.29954	7	0.31461	8	0.38678	8
SC_4	0.43461	4	0.45117	5	0.45117	5
SC_5	0.45066	3	0.39712	7	0.44942	7
SC_6	0.34326	5	0.45148	3	0.45148	3
SC_7	0.33066	6	0.28932	9	0.35825	9
SC_8	0.45087	2	0.45087	6	0.45087	6
SC_9	0.28745	9	0.45167	2	0.45167	2
SC_{10}	0.29111	8	0.45128	4	0.45128	4

Existing literature reports a few answers for this difficulty, but some researchers have explored some solutions for these cooperative games (Arnold and Schwalbe 2002, Peleg and Sudhölter 2007, Huang and Sjöström 2010, Xu et al. 2013). In their seminal article, Aumann and Dreze (1974) define the so-called "superadditive cover" and "games with coalition structure" by which every arbitrary cooperative game can be investigated by a superadditive cooperative game. In spite of the fact that the core solution concept dominates this body of research, a few number of studies have investigated other solution concepts for non-superadditive cooperative games (Aumann 2010).

5.3.3 Superadditive Cover

The goal is to find the core solution of $\mathbf{G}(\Omega_p, \tau_p)$ by the use of its counterpart game $\mathbf{G}^*(\Omega_p, \tau_p^*)$, commonly referred to as the superadditive cover of $\mathbf{G}(\Omega_p, \tau_p)$.

Defining the characteristic function τ_p^* is drawn on the coalition structure concept (Chalkiadakis et al. 2012). For any nonempty $S_p \subseteq \Omega_p$, a coalition structure (typically denoted by CS) for S_p is a partition of the set S_p. Let $\mathcal{CS}_{S_p}$ denote the set of all possible coalition structures related to S_p. That is, $\mathcal{CS}_{S_p} = \{CS \mid CS \text{ is a partition of } S_p\}$. We note that the social welfare of a coalition structure $CS \in \mathcal{CS}_{S_p}$ is defined by $\tau_p(CS) = \sum_{C_0 \in CS} \tau_p(C_0)$. For example, $\mathcal{CS}_{\Omega_p}$ can be defined by

$$\begin{aligned}
CS_{\mathrm{I}} &= \{\{\mathrm{I}_1\},\{\mathrm{I}_2\},\{\mathrm{I}_3\}\} = \mathrm{I}_1|\mathrm{I}_2|\mathrm{I}_3 \;\;\&\;\; \tau_p(CS_{\mathrm{I}}) = 0+0+0 = 0\\
CS_{\mathrm{II}} &= \{\{\mathrm{I}_1\},\{\mathrm{I}_2,\mathrm{I}_3\}\} = \mathrm{I}_1|\mathrm{I}_2\mathrm{I}_3 \;\;\&\;\; \tau_p(CS_{\mathrm{II}}) = 0 + \frac{\theta_p^{23}}{\Psi_p} \times \ell^0_{pkc} = \frac{\theta_p^{23}}{\Psi_p} \times \ell^0_{pkc}\\
CS_{\mathrm{III}} &= \{\{\mathrm{I}_2\},\{\mathrm{I}_1,\mathrm{I}_3\}\} = \mathrm{I}_2|\mathrm{I}_1\mathrm{I}_3 \;\;\&\;\; \tau_p(CS_{\mathrm{III}}) = \frac{\theta_p^{13}}{\Psi_p} \times \ell^0_{pkc}\\
CS_{\mathrm{IV}} &= \{\{\mathrm{I}_3\},\{\mathrm{I}_1,\mathrm{I}_2\}\} = \mathrm{I}_3|\mathrm{I}_1\mathrm{I}_2 \;\;\&\;\; \tau_p(CS_{\mathrm{IV}}) = 0\\
CS_{\mathrm{V}} &= \{\{\mathrm{I}_1,\mathrm{I}_2,\mathrm{I}_3\}\} = \mathrm{I}_1\mathrm{I}_2\mathrm{I}_3| \;\;\&\;\; \tau_p(CS_{\mathrm{V}}) = \frac{\theta_p^{123}}{\Psi_p} \times \ell^0_{pkc},
\end{aligned} \tag{5.2}$$

that is, $\mathcal{CS}_{\Omega_p} = \{CS_{\mathrm{I}}, CS_{\mathrm{II}}, CS_{\mathrm{III}}, CS_{\mathrm{IV}}, CS_{\mathrm{V}}\}$. Having calculated $\mathcal{CS}_{S_p}$ for all nonempty sets $S_p \subseteq \Omega_p$, we define the superadditive cover $\mathbf{G}^*(\Omega_p, \tau_p^*)$, where:

$$\tau_p^*(S_p) = \begin{cases} \max\limits_{CS \in \mathcal{CS}_{S_p}} \{\tau_p(CS)\} = \max\limits_{CS \in \mathcal{CS}_{S_p}} \Big\{ \sum\limits_{C_0 \in CS} \tau_p(C_0) \Big\} & S_p \neq \emptyset \quad (5.3\text{a}) \\ 0 & S_p = \emptyset \quad (5.3\text{b}) \end{cases}$$

Theorem 5.1 *The characteristic function τ_p^* is superadditive.*

The proof of Theorem 5.1 and other proofs of Chapter 5 are included in **Appendix C.1**. Given that $\Omega_p = \{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$, it is not hard to see that:

S_p	$\emptyset$, $\{\mathrm{I}_1\}$, $\{\mathrm{I}_2\}$, $\{\mathrm{I}_3\}$, or $\{\mathrm{I}_1, \mathrm{I}_2\}$	$\{\mathrm{I}_1, \mathrm{I}_3\}$	$\{\mathrm{I}_2, \mathrm{I}_3\}$	$\{\mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3\}$
$\tau_p^*(S_p)$	0	$\frac{\theta_p^{13}}{\Psi_p} \times \ell^0_{pkc}$	$\frac{\theta_p^{23}}{\Psi_p} \times \ell^0_{pkc}$	ℓ^0_{pkc}

5.3.4 The Core Solution

For each $CS \in \mathcal{CS}_{\Omega_p}$ let the triple (Ω_p, τ_p, CS) be a game with coalition structure CS. As defined in Peleg and Sudhölter (2007), the core of this coalitional game is

$$\mathbf{C}(\Omega_p, \tau_p, CS) = \Big\{ \mathbf{X} \mid \forall\, C_0 \in CS \;\; \aleph(C_0) \leq \tau_p(C_0) \;\;\&\;\; \forall\, S_p \subseteq \Omega_p \;\; \aleph(S_p) \geq \tau_p(S_p) \Big\},$$

where $\mathbf{X} = (\mathrm{X}_1, \mathrm{X}_2, \mathrm{X}_3) \in \mathbb{R}^3_+$ and for all sets $\mathcal{T} \subseteq \Omega_p$ the notation "$\aleph(\mathcal{T})$" represents $\sum_{q_p \in \mathcal{T}} \mathrm{X}_q$ (Peters 2008). Chalkiadakis et al. (2012) shows that the core of a superadditive game is always characterized by its grand coalition. In particular, the core of $\mathbf{G}^*(\Omega_p, \tau_p^*)$

can be simplified as

$$\mathbf{C}(\Omega_p, \tau_p^*) = \Big\{\mathbf{X} = (\mathrm{X}_1, \mathrm{X}_2, \mathrm{X}_3) \in \mathbb{R}_+^3 \mid \aleph(\Omega_p) = \tau_p^*(\Omega_p) \ \ \& \ \ \forall \ S_p \subseteq \Omega_p \ \ \aleph(S_p) \geq \tau_p^*(S_p)\Big\},$$

where τ_p^* satisfies (5.3). Although exploring the core of an arbitrary coalitional game may cause computational difficulties, the following observation shows how to overcome this problem by replacing the game with its superadditive cover.

Theorem 5.2 *For all $CS \in \mathcal{CS}_{\Omega_p}$:*

1. $\mathbf{C}(\Omega_p, \tau_p, CS) \neq \emptyset \Longleftrightarrow \Big(\mathbf{C}(\Omega_p, \tau_p^*) \neq \emptyset \ \ \& \ \ \tau_p^*(\Omega_p) = \sum_{C_0 \in CS} \tau_p(C_0)\Big)$.
2. $\mathbf{C}(\Omega_p, \tau_p, CS) \neq \emptyset \Longrightarrow \mathbf{C}(\Omega_p, \tau_p, CS) = \mathbf{C}(\Omega_p, \tau_p^*)$.

To take advantage of the aforementioned theorem, we need to find $\mathbf{C}(\Omega_p, \tau_p^*)$, through solving the following system of linear inequalities

$$\begin{cases} \mathrm{X}_1 + \mathrm{X}_2 + \mathrm{X}_3 = \ell_{pkc}^0 \\ \mathrm{X}_1 + \mathrm{X}_3 \geq \frac{\theta_p^{13}}{\Psi_p} \times \ell_{pkc}^0 \\ \mathrm{X}_2 + \mathrm{X}_3 \geq \frac{\theta_p^{23}}{\Psi_p} \times \ell_{pkc}^0 \\ \mathrm{X}_1, \mathrm{X}_2, \mathrm{X}_3 \geq 0 \end{cases} \tag{5.4}$$

where $\mathrm{X}_q \in \mathbb{R}$. We note that the specially-formed system (5.4) can greatly simplify Theorem 5.2, by the use of the following proposition and corollary.

Proposition 5.1 *The set $\mathbf{C}(\Omega_p, \tau_p^*)$ is nonempty.*

Corollary 5.1 *For all $CS \in \mathcal{CS}_{\Omega_p}$:*

1. $\mathbf{C}(\Omega_p, \tau_p, CS) \neq \emptyset \Longleftrightarrow \tau_p^*(\Omega_p) = \sum_{C_0 \in CS} \tau_p(C_0)$.
2. $\tau_p^*(\Omega_p) = \sum_{C_0 \in CS} \tau_p(C_0) \Longrightarrow \mathbf{C}(\Omega_p, \tau_p, CS) = \mathbf{C}(\Omega_p, \tau_p^*)$.

Utilizing the foregoing results, Corollary 5.2 characterizes the relation between the core solutions of $\mathbf{G}$ and $\mathbf{G}^*$.

Corollary 5.2 *For the cooperative game under discussion, the core solution of the tri-opoly $\mathbf{G}(\Omega_p, \tau_p)$ is always equal to $\mathbf{C}(\Omega_p, \tau_p^*)$, corresponding with the coalition structure:*

1. $CS_{III} = \mathrm{I}_2|\mathrm{I}_1\mathrm{I}_3$, *if* $\Psi_p = \theta_p^{13}$.

2. $CS_{II} = \mathrm{I}_1|\mathrm{I}_2\mathrm{I}_3$, *if* $\Psi_p = \theta_p^{23}$.

3. $CS_V = \mathrm{I}_1\mathrm{I}_2\mathrm{I}_3|$, *if* $\Psi_p = \theta_p^{123}$.

To find the closed-form solution of (5.4), or equivalently $\mathbf{C}(\Omega_p, \tau_p^*)$, we define a new variable $\mathrm{Y}_q = \frac{\mathrm{X}_q \times \Psi_p}{\ell^0_{pkc}}$ for each $q \in \{1, 2, 3\}$, which simplifies the notation of the following theorem's proof.

Theorem 5.3 *If:*

1. $\Psi_p = \theta_p^{13}$, *then* $\mathbf{C}(\Omega_p, \tau_p^*) = \Big\{\Big(\frac{t}{\theta_p^{13}} \times \ell^0_{pkc}, 0, (1 - \frac{t}{\theta_p^{13}}) \times \ell^0_{pkc}\Big) \mid t \in [0, \theta_p^{13} - \theta_p^{23}]\Big\}$.

2. $\Psi_p = \theta_p^{23}$, *then* $\mathbf{C}(\Omega_p, \tau_p^*) = \Big\{\Big(0, \frac{t}{\theta_p^{23}} \times \ell^0_{pkc}, (1 - \frac{t}{\theta_p^{23}}) \times \ell^0_{pkc}\Big) \mid t \in [0, \theta_p^{23} - \theta_p^{13}]\Big\}$.

3. $\Psi_p = \theta_p^{123}$, *then* $\mathbf{C}(\Omega_p, \tau_p^*) = \Big\{\Big(\frac{t_1}{\theta_p^{123}} \times \ell^0_{pkc}, \frac{t_2}{\theta_p^{123}} \times \ell^0_{pkc}, (1 - \frac{t_1+t_2}{\theta_p^{123}}) \times \ell^0_{pkc}\Big) \mid t_1 \in [0, \theta_p^{123} - \theta_p^{23}]\ \&\ t_2 \in [0, \theta_p^{123} - \theta_p^{13}]\Big\}$.

For the first two supply chains introduced in Table 5.1, the closed-form expressions derived from Theorem 5.3 are as follows:

DMU	Ψ_p	Values of t	$\mathbf{C}(\Omega_p, \tau_p^*)$
SC_1	$\theta_p^{13} = \theta_p^{23} = \theta_p^{123}$	$T = \{0\}$	$\{(0, 0, \ell^0_{pkc})\}$
SC_2	$\theta_p^{13} = 0.28576$	$T = [0, 0.06745]$	$\Big\{\Big(\frac{t}{\theta_p^{13}} \times \ell^0_{pkc}, 0, (1 - \frac{t}{\theta_p^{13}}) \times \ell^0_{pkc}\Big)_{t \in T}\Big\}$

In this example, the core solution of the first supply chain is a single point, however that of the second supply chain is a line segment.

5.4 A Cournot Oligopoly Game for Inter Supply Chain Competitions

From now on, we cope with a non-cooperative setting where all the supply chains under discussion compete in their product/pollutant markets. Having developed their game-theoretic optimization problems, we introduce a systematic procedure that finds the equilibria of this game. To do so, we draw on the variational inequality literature and the modified projection method introduced by Korpelevich (1976). We also set out conditions under which this non-cooperative Cournot game has a unique Nash equilibrium.

5.4.1 Game Formation

We assume that there exist $\bar{n}$ sources of pollution in an ETS formation such that each typical source, SC_j, is composed of two suppliers and one manufacturer, as discussed earlier. We consider also $\bar{k}$ receptor points, where a typical point is denoted by k. Also, let there be $\bar{c}$ different classes of pollutants emitted by the supply chains and indexed by c. We assume that $\mathbf{E}_j \in \mathbb{R}_+^{\bar{c}}$ refers to the SC_j's emissions vector, with a typical element E_{jc} that represents the amount of the cth pollutant emitted by this supply chain. We assume as well an $\bar{n} \times \bar{k} \times \bar{c}$ matrix is given, with a typical component h_{jkc} denoting the contribution that one unit of emission by SC_j makes to average the cth pollutant's concentration at Point k. Hence, $h_{jkc} \times E_{jc}$ is equal to the actual amount of the cth pollutant emitted by SC_j at Point k.

Let $\mathbf{L}_j \in \mathbb{R}_+^{\bar{k}\times\bar{c}}$ denote the SC_j's license vector, with a typical element L_{jkc} that represents the number of licenses for emitting Pollutant c at Point k possessed by SC_j. We recall that the regulatory body determines a total ℓ_{kc}^0 units of the permits as the initial allocation of pollution for Pollutant c at Point k to ensure that environmental standards are met. As mentioned earlier, we can develop a rational process to allocate this value between the supply chains in a way that $\ell_{kc}^0 = \sum_{j=1}^{\bar{n}} \ell_{jkc}^0$, where for all $1 \le j \le \bar{n}$ the amount ℓ_{jkc}^0 denotes the initial allocation given to SC_j.

Since we have assumed that the permit market is perfectly competitive and the supply chains cannot affect the license price by themselves, let $\rho_{kc} > 0$ denotes the fixed purchasing price of the cth pollutant at Point k. We group these prices into the price vector $\vec{\rho} \in \mathbb{R}_+^{\bar{k}\times\bar{c}}$. To induce this supply chain to reduce pollution, it is also subjected to a per unit penalty $\nu_{kc} > \rho_{kc}$ for every additional emitted unit of Pollutant c at Point k, provided that $h_{jkc} \times E_{jc} > L_{jkc}$.

We assume that for each product d, the distributions D_{jd} are related to $\bar{n}$ independent random variables. However, the price of this product paid by the customers is affected by the total outputs of the oligopolistic supply chains through a Cournot price equation as $P_d \equiv P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d}) = A_d - B_d \times \sum_{j=1}^{\bar{n}} Q_{jd}$, where A_d and B_d are positive constant scalers. In this study, we assume that the function P_d takes positive values.

We assume that the goal of each supply chain in the non-cooperative oligopoly is to maximize its profit. Therefore, if a given SC_j is charged production cost $F_{jd}(Q_{jd})$ related to Product d as well as emissions cost $G_j(\mathbf{Q}_j, \mathbf{E}_j)$, the expected profit of SC_j ($j \in \{1, ..., \bar{n}\}$) can be characterized by

$$
\begin{aligned}
\Pi_j(\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j) \equiv\ & \Pi_j(\mathbf{Q}_j, \mathbf{Q}_{-j}, \mathbf{E}_j, \mathbf{L}_j) \\
&= \sum_{d=1}^{\bar{d}} \left(\int_0^{Q_{jd}} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})\xi - F_{jd}(Q_{jd}) \right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&+ \sum_{d=1}^{\bar{d}} \left(\int_{Q_{jd}}^{\infty} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd} - \hat{s}_{jd}(\xi - Q_{jd}) - F_{jd}(Q_{jd}) \right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&- G_j(\mathbf{Q}_j, \mathbf{E}_j) \\
&- \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} (\nu_{kc}[h_{jkc}E_{jc} - L_{jkc}]) \\
&- \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} (\rho_{kc}L_{jkc}) \\
&+ \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} \left(\rho_{kc}\ell^0_{jkc} \right),
\end{aligned} \tag{5.5}
$$

where the first two components represent the expected net payoffs obtained from overestimating/underestimating the product demand functions (Porteus 2002), the last two terms characterize the net profit lost/earned during the process of purchasing/allocating the licenses, and the remaining terms account for the emissions costs. Please note that the last term in the foregoing function relates the cooperative game and the non-cooperative game related to SC_j.

5.4.2 Demand Pattern: Certain vs. Uncertain

We remind that ℓ^0_{jkc} represents initial pollution allocation of Pollutant c at Point k for this supply chain. Drawn on the results of Corollary 5.2 and Theorem 5.3, the cooperation between all three partners of SC_j helps this player compete more effectively (by earning more profits) in the non-cooperative game only if $\max\{\theta_j^{13}, \theta_j^{23}, \theta_j^{123}\} = \theta_j^{123}$. Otherwise, a coalition of only one supplier and its manufacturer generates ℓ^0_{jkc} which implies that cooperation hurts the Cournot game. On the other hand, provided that there is no stochasticity, the profit function of SC_j can be simplified as

$$\begin{aligned}\widehat{\Pi}_j(\mathbf{Q}_j,\mathbf{Q}_{-j},\mathbf{E}_j,\mathbf{L}_j) = &\sum_{d=1}^{\bar{d}}\left[P_d(Q_{1d},...,Q_{jd},...,Q_{\bar{n}d})Q_{jd}\right] - \sum_{d=1}^{\bar{d}}\left[F_{jd}(Q_{jd})\right] - G_j(\mathbf{Q}_j,\mathbf{E}_j)\\ &-\sum_{k=1}^{\bar{k}}\sum_{c=1}^{\bar{c}}\left(\nu_{kc}[h_{jkc}E_{jc}-L_{jkc}]\right) - \sum_{k=1}^{\bar{k}}\sum_{c=1}^{\bar{c}}\left(\rho_{kc}L_{jkc}\right) + \sum_{k=1}^{\bar{k}}\sum_{c=1}^{\bar{c}}\left(\rho_{kc}\ell^0_{jkc}\right),\end{aligned} \tag{5.6}$$

and the following theorem demonstrates that why $\widehat{\Pi}_j > \Pi_j$, which intuitively is true since uncertainty may lead to overestimation or underestimation of demand that consequently increases direct costs.

Theorem 5.4 *For all $j \in \{1,...,\bar{n}\}$, we have that:*

1. $\widehat{\Pi}^*_j > \Pi^*_j$.
2. $\frac{\partial^2\widehat{\Pi}}{\partial Q^2_{jd}} > \frac{\partial^2\Pi}{\partial Q^2_{jd}}$, *where* $d \in \{1,...,\bar{d}\}$.
3. $\frac{\partial\widehat{\Pi}_j}{\partial E_{jc}} = \frac{\partial\Pi_j}{\partial E_{jc}}$, *where* $c \in \{1,...,\bar{c}\}$.
4. $\frac{\partial\widehat{\Pi}_j}{\partial L_{jkc}} = \frac{\partial\Pi_j}{\partial L_{jkc}}$, *where* $c \in \{1,...,\bar{c}\}$ *and* $k \in \{1,...,\bar{k}\}$.

We summarize below the SC_j's oligopolistic optimization problem (5.5) as

$$\max_{(\mathbf{Q},\mathbf{E}_j,\mathbf{L}_j)\in\mathbb{R}_+^{\bar{n}\bar{d}+\bar{c}+\bar{k}\bar{c}}} \Pi_j(\mathbf{Q},\mathbf{E}_j,\mathbf{L}_j), \tag{5.7}$$

where $j \in \{1,...,\bar{n}\}$.

5.4.3 Optimality Conditions

Since the oligopolistic firms compete in a non-cooperative manner in the product markets, we analyze (5.7) on the basis of the so-called Nash-Cournot equilibrium defined below.

Definition 5.1 (Peters 2008) *A Nash-Cournot equilibrium of the non-cooperative game defined by the payoff functions of type* (5.7) *is a strategy combination* $(\mathbf{Q}^*,\mathbf{E}^*_j,\mathbf{L}^*_j) \in \mathbb{R}_+^{\bar{n}\bar{d}+\bar{c}+\bar{k}\bar{c}}$*, such that*

$$\Pi_j(\mathbf{Q}_j^*, \mathbf{Q}_{-j}^*, \mathbf{E}_j^*, \mathbf{L}_j^*) \geq \Pi_j(\mathbf{Q}_j, \mathbf{Q}_{-j}^*, \mathbf{E}_j, \mathbf{L}_j) \quad \forall j \quad \forall \mathbf{Q}_j \quad \forall \mathbf{E}_j \quad \forall \mathbf{L}_j.$$

As stated earlier, in this study we benefit from the theory of variational inequalities to find the equilibria of the oligopoly established above. To build a relationship of this methodology to the optimization problem (5.7), we start with the following definition.

Definition 5.2 (Nagurney 1999) *The variational inequality problem* $\mathrm{VI}(\mathcal{F}, \mathcal{K})$ *is to determine a vector* $\mathcal{X}^* \in \mathcal{K} \subseteq \mathbb{R}^n$*, such that for all* $\mathcal{X} \in \mathcal{K}$ *we have that* $\langle \mathcal{F}(\mathcal{X}^*)^T, \mathcal{X} - \mathcal{X}^* \rangle \geq 0$*, where* $\mathcal{F}(\mathcal{X}) : \mathcal{K} \mapsto \mathbb{R}^n$ *is a continuous function over the closed convex set* $\mathcal{K}$ *and* $\langle \mathcal{X}_1^T, \mathcal{X}_2 \rangle$ *denotes the inner product of the vectors* $\mathcal{X}_1$ *and* $\mathcal{X}_2$*.*

Drawn on Definition 5.2, the subsequent theorem characterizes the relationship between an optimization problem and a variational inequality problem.

Theorem 5.5 *Let* $\mathcal{H}(\mathcal{X}) : \mathcal{K} \mapsto \mathbb{R}$ *be a convex function over the closed convex set* $\mathcal{K} \subseteq \mathbb{R}^n$*. Given that* $\mathcal{X}^* \in \mathcal{K}$*,* $\mathcal{X}^*$ *is a solution of the optimization problem* $\min_{\mathcal{X} \in \mathcal{K}} \mathcal{H}(\mathcal{X})$ *if and only if* $\mathcal{X}^*$ *is a solution of the variational inequality problem* $\mathrm{VI}(\nabla \mathcal{H}, \mathcal{K})$*.*

To take advantage of Theorem 5.5, the next step is specifying conditions under which the profit function (5.5) is concave. The following lemma and its consequent proposition investigate these conditions for a given SC_j.

Lemma 5.1 *Given that* $\mathcal{H}_1, \mathcal{H}_2 : \mathcal{K} \mapsto \mathbb{R}$ *are respectively convex (concave) and strictly convex (concave) functions over the closed convex set* $\mathcal{K} \subseteq \mathbb{R}^n$*, the function* $\mathcal{H} = \mathcal{H}_1 + \mathcal{H}_2$ *is strictly convex (concave).*

Proposition 5.2 *If the functions* $F_{jd}(Q_{jd})$*,* $G_j(\mathbf{Q}_j, \mathbf{E}_j)$ *with fixed values of* $\mathbf{E}_j$*, and* $G_j(\mathbf{Q}_j, \mathbf{E}_j)$ *with fixed values of* $\mathbf{Q}_j$ *are convex, then* Π_j *is concave with respect to its quantity–, emissions–, and license–oriented arguments. Particularly,* Π_j *is strictly concave with respect to* Q_{jd}*.*

We note that the forgoing results are valid for $\widehat{\Pi}_j$ as well. From now on, we assume that the functions $F_{jd}(Q_{jd})$, $G_j(\mathbf{Q}_j)$, and $G_j(\mathbf{E}_j)$ are convex. Consequently, the following corollary presents the necessary and sufficient optimality condition for a problem of type (5.7).

Corollary 5.3 *For a given SC_j, the necessary and sufficient condition for an equilibrium $(\mathbf{Q}_j^*, \mathbf{E}_j^*, \mathbf{L}_j^*) \in \mathbb{R}_+^{\bar{d}+\bar{c}+\bar{k}\bar{c}}$ for the problem*

$$\min_{(\mathbf{Q}_j, \mathbf{E}_j, \mathbf{L}_j) \in \mathbb{R}_+^{\bar{d}+\bar{c}+\bar{k}\bar{c}}} \Big\{ -\Pi_j(\mathbf{Q}_j, \mathbf{Q}_{-j}^*, \mathbf{E}_j, \mathbf{L}_j) \Big\},$$

given $\mathbf{Q}_{-j}^*$, is that

$$\begin{aligned}
&\sum_{d=1}^{\bar{d}} \Bigg(\Bigg[\frac{\partial F_{jd}(Q_{jd}^*)}{\partial Q_{jd}} + \frac{\partial G_j(\mathbf{Q}_j^*, \mathbf{E}_j^*)}{\partial Q_{jd}} + B_d \mu_{jd} - [P_d^* + \hat{s}_{jd}] \Big(1 - \varepsilon_{jd}(Q_{jd}^*)\Big) \\
&\qquad - B_d \bigg(\int_{Q_{jd}^*}^{\infty} \Big[\xi - Q_{jd}^*\Big] \epsilon_{jd}(\xi) \mathrm{d}\xi \bigg) \Bigg] \times \Big[Q_{jd} - Q_{jd}^* \Big] \Bigg) \\
&+ \sum_{c=1}^{\bar{c}} \Bigg(\Bigg[\frac{\partial G_j(\mathbf{Q}_j^*, \mathbf{E}_j^*)}{\partial E_{jc}} + \sum_{k=1}^{\bar{k}} \Big(\nu_{kc} h_{jkc} \Big) \Bigg] \times \Big[E_{jc} - E_{jc}^* \Big] \Bigg) \\
&+ \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} \Big(\Big[\rho_{kc} - \nu_{kc} \Big] \times \Big[L_{jkc} - L_{jkc}^* \Big] \Big) \geq 0 \qquad \forall Q_{jd} \;\; \forall E_{jc} \;\; \forall L_{jkc}. \qquad (5.8)
\end{aligned}$$

We note that Corollary 5.3 clarifies that an inequality of type (5.8) needs to meet for each supply chain in order to build a Nash-Cournot equilibrium. To deal with this complexity, Theorem 5.6 presents a more concise characterization of an equilibrium through a single inequality.

Theorem 5.6 *A vector $(\mathbf{Q}^*, \mathbf{E}^*, \mathbf{L}^*) \in \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$ is a Nash-Cournot equilibrium for the non-cooperative oligopoly under discussion if and only if it is a solution of the variational inequality problem*

$$\begin{aligned}
&\sum_{j=1}^{\bar{n}} \sum_{d=1}^{\bar{d}} \Bigg(\Bigg[\frac{\partial F_{jd}(Q_{jd}^*)}{\partial Q_{jd}} + \frac{\partial G_j(\mathbf{Q}_j^*, \mathbf{E}_j^*)}{\partial Q_{jd}} + B_d \mu_{jd} - [P_d^* + \hat{s}_{jd}] \Big(1 - \varepsilon_{jd}(Q_{jd}^*)\Big) \\
&\qquad - B_d \bigg(\int_{Q_{jd}^*}^{\infty} \Big[\xi - Q_{jd}^*\Big] \epsilon_{jd}(\xi) \mathrm{d}\xi \bigg) \Bigg] \times \Big[Q_{jd} - Q_{jd}^* \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{c=1}^{\bar{c}} \Bigg(\Bigg[\frac{\partial G_j(\mathbf{Q}_j^*, \mathbf{E}_j^*)}{\partial E_{jc}} + \sum_{k=1}^{\bar{k}} \Big(\nu_{kc} h_{jkc} \Big) \Bigg] \times \Big[E_{jc} - E_{jc}^* \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} \Big(\Big[\rho_{kc} - \nu_{kc} \Big] \times \Big[L_{jkc} - L_{jkc}^* \Big] \Big) \geq 0 \qquad \forall (\mathbf{Q}, \mathbf{E}, \mathbf{L}) \in \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}. \qquad (5.9)
\end{aligned}$$

The rest of this section investigates properties of the variational inequality problem (5.9) and presents an iterative procedure to calculate its solution(s).

5.4.4 Standard Form

To investigate properties of the solutions of the variational inequality problem (5.9), we put this problem into standard form (Nagurney 1999). Let $\mathcal{X} = (\mathbf{Q}, \mathbf{E}, \mathbf{L})$ denote a typical vector in $\mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$. We now define the function

$$\mathcal{P}(\mathcal{X}) \equiv (\mathcal{Q}(\mathcal{X}), \mathcal{E}(\mathcal{X}), \mathcal{L}(\mathcal{X})) : \mathcal{K} \equiv \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})} \mapsto \left(\mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}\right)^T, \tag{5.10}$$

where

$$\mathcal{Q}(\mathcal{X}) = \Big(\frac{-\partial\Pi_1(\mathcal{X}_1)}{\partial Q_{11}}, \frac{-\partial\Pi_1(\mathcal{X}_1)}{\partial Q_{12}}, ..., \frac{-\partial\Pi_1(\mathcal{X}_1)}{\partial Q_{1\bar{d}}}, \frac{-\partial\Pi_2(\mathcal{X}_2)}{\partial Q_{21}}, ..., \frac{-\partial\Pi_{\bar{n}}(\mathcal{X}_{\bar{n}})}{\partial Q_{\bar{n}\bar{d}}}\Big) : \mathcal{K} \mapsto \left(\mathbb{R}_+^{\bar{n}\bar{d}}\right)^T$$
$$\mathcal{E}(\mathcal{X}) = \Big(\frac{-\partial\Pi_1(\mathcal{X}_1)}{\partial E_{11}}, \frac{-\partial\Pi_1(\mathcal{X}_1)}{\partial E_{12}}, ..., \frac{-\partial\Pi_1(\mathcal{X}_1)}{\partial E_{1\bar{c}}}, \frac{-\partial\Pi_2(\mathcal{X}_2)}{\partial E_{21}}, ..., \frac{-\partial\Pi_{\bar{n}}(\mathcal{X}_{\bar{n}})}{\partial E_{\bar{n}\bar{c}}}\Big) : \mathcal{K} \mapsto \left(\mathbb{R}_+^{\bar{n}\bar{c}}\right)^T$$
$$\mathcal{L}(\mathcal{X}) = \left(\gamma_1, ..., \gamma_j, ...\gamma_{\bar{n}}\right) : \mathcal{K} \mapsto \left(\mathbb{R}_+^{\bar{n}\bar{k}\bar{c}}\right)^T,$$

for which we have $\gamma_j \equiv (\rho_{11} - \nu_{11}, \rho_{12} - \nu_{12}, ..., \rho_{1\bar{c}} - \nu_{1\bar{c}}, \rho_{21} - \nu_{21}, ..., \rho_{\bar{k}\bar{c}} - \nu_{\bar{k}\bar{c}}) \in \left(\mathbb{R}_+^{\bar{k}\bar{c}}\right)^T$ and $\mathcal{X}_j \equiv (\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j) \in \mathbb{R}_+^{\bar{n}\bar{d}+\bar{c}+\bar{k}\bar{c}}$ for each $1 \leq j \leq \bar{n}$.

On the basis of the new notation presented in (5.10), the statement of Theorem 5.6 can be simplified as follows:

$$\mathcal{X}^* \in \mathcal{K} \equiv \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})} \text{ is an equilibrium} \Leftrightarrow \forall \mathcal{X} \in \mathcal{K}\ \langle \mathcal{P}(\mathcal{X}^*), \mathcal{X} - \mathcal{X}^* \rangle \geq 0 \tag{5.11}$$

The following lemma and its consequent proposition investigate the monotonic behavior of $\mathcal{P}(\mathcal{X})$ defined in (5.10) for the oligopoly under discussion.

Lemma 5.2 *Given that $\mathcal{H} : \mathcal{K} \subseteq \mathbb{R}^n \mapsto \mathbb{R}$ is a (strictly) concave and continuously differentiable function over the closed convex set $\mathcal{K}$, the function $-\nabla\mathcal{H}$ is (strictly) monotone.*

Proposition 5.3 *The function $\mathcal{P}(\mathcal{X}) : \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})} \mapsto \left(\mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}\right)^T$ defined in* (5.10) *is strictly monotone.*

The following theorem and its consequent corollary investigate the uniqueness of solutions for the standard variational inequality problem presented in (5.11).

Theorem 5.7 *Given that $\mathcal{F} : \mathcal{K} \subseteq \mathbb{R}^n \mapsto \mathbb{R}^n$ is a strictly monotone function over the closed convex set $\mathcal{K}$, the solution of* $\mathrm{VI}(\mathcal{F}, \mathcal{K})$ *is unique.*

Corollary 5.4 *The standard variational inequality problem presented in* (5.11)*, or equivalently the variational inequality problem defined in* (5.9)*, has a unique solution in* $\mathcal{K} \equiv \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$.

So far, we have investigated conditions under which the uniqueness of the equilibria of the non-cooperative Cournot oligopoly characterized by the profit functions of type (5.5) is guaranteed. In the next section, we present a convergent algorithm for finding this unique equilibrium by the use of the standard form established above.

5.4.5 Solution Method

In this section, we focus on presenting a convergent algorithm that explores the unique solution of the variational inequality problem defined in (5.11), or equivalently in (5.9). Most of the variational inequality algorithms proceed to the equilibria progressively in the presence of strict monotonicity (Nagurney 1999).

In this work we adopt the modified projection method, known also as the extragradient method, proposed by Korpelevich (1976), which requires only monotonicity, but with the Lipschitz continuity condition. More interestingly, this approach splits the variational inequality problem into a number of simple subproblems, each of which can be solved in closed-form. To solve the general problem VI($\mathcal{F},\mathcal{K}$) introduced in Definition 5.2, where $\mathcal{F} : \emptyset \neq \mathcal{K} \subseteq \mathbb{R}^n \mapsto \mathbb{R}^n$ is monotone, that is,

$$\left\langle \Big(\mathcal{F}(\mathcal{X}) - \mathcal{F}(\mathcal{X}')\Big)^T, \mathcal{X} - \mathcal{X}' \right\rangle \geq 0, \quad \forall \mathcal{X}, \mathcal{X}' \in \mathcal{K}, \tag{5.12}$$

and also Lipschitz continuous, that is, there exists a constant $L_{\mathcal{F}} > 0$ such that

$$\|\mathcal{F}(\mathcal{X}) - \mathcal{F}(\mathcal{X}')\| \leq L_{\mathcal{F}} \times \|\mathcal{X} - \mathcal{X}'\|, \quad \forall \mathcal{X}, \mathcal{X}' \in \mathcal{K}, \tag{5.13}$$

the statement of the modified projection method is as follows:

Step 0: Initialization

MaxIter $\in \mathbb{Z}_+$ and $\varphi_1 > 0$ are given; Select $\mathcal{X}^{(0)} \in \mathcal{K}$; $i \leftarrow 1$

Select φ_2, such that $0 < \varphi_2 < \dfrac{1}{L_{\mathcal{F}}}$, where $L_{\mathcal{F}}$ is the Lipschitz constant for $\mathcal{F}$

Step 1: Construction and Computation

Compute $\tilde{\mathcal{X}}^{(i-1)}$ by solving the variational inequality subproblem:

$$\left\langle \left(\tilde{\mathcal{X}}^{(i-1)} + (\varphi_2 \mathcal{F}(\mathcal{X}^{(i-1)}) - \mathcal{X}^{(i-1)})\right)^T, \mathcal{X} - \tilde{\mathcal{X}}^{(i-1)} \right\rangle \geq 0, \quad \forall \mathcal{X} \in \mathcal{K} \tag{5.14}$$

Step 2: Adaptation

Compute $\mathcal{X}^{(i)}$ by solving the variational inequality subproblem:

$$\left\langle \left(\mathcal{X}^{(i)} + (\varphi_2 \mathcal{F}(\tilde{\mathcal{X}}^{(i-1)}) - \mathcal{X}^{(i-1)})\right)^T, \mathcal{X} - \mathcal{X}^{(i)} \right\rangle \geq 0, \quad \forall \mathcal{X} \in \mathcal{K} \tag{5.15}$$

Step 3: Convergence Verification

If $i =$ MaxIter or $\max_{1 \leq t \leq n}\{|\mathcal{X}_t^{(i)} - \mathcal{X}_t^{(i-1)}|\} \leq \varphi_1$, having the solution $\mathcal{X}^{(i)}$ terminate

$i \leftarrow i + 1$; Return to **Step 1**

The following theorem summarizes conditions under which the aforementioned algorithm converges to a solution of VI$(\mathcal{F}, \mathcal{K})$.

Theorem 5.8 *Given that $\mathcal{F} : \mathcal{K} \subseteq \mathbb{R}^n \mapsto \mathbb{R}^n$ is a monotone and Lipschitz continuous function over the closed convex set $\mathcal{K}$, the modified projection method converges to a solution of* VI$(\mathcal{F}, \mathcal{K})$ *introduced in Definition 5.2.*

The following lemma and its consequent proposition and theorem explain under which conditions applying the modified projection method to the problem defined in (5.11), or equivalently in (5.9), results in finding its unique solution (cf. Corollary 5.4).

Lemma 5.3 *Under the assumptions that for a given SC_j all the functions ϵ_{jd} are bounded and also $F_{jd}(Q_{jd})$ and $G_j(\mathbf{Q}_j, \mathbf{E}_j)$ have bounded second order derivatives, the profit function $\Pi_j(\mathbf{Q}_j, \mathbf{Q}_{-j}, \mathbf{E}_j, \mathbf{L}_j)$ has bounded second order derivatives as well.*

Proposition 5.4 *Under the assumptions that all the functions ϵ_{jd} are bounded and also $F_{jd}(Q_{jd})$ and $G_j(\mathbf{Q}_j, \mathbf{E}_j)$ have bounded second order derivatives, where $j \in \{1, ..., \bar{n}\}$, the function $\mathcal{P}(\mathcal{X})$ is Lipschitz continuous.*

Theorem 5.9 *Under the assumptions that all the functions ϵ_{jd} are bounded, $F_{jd}(Q_{jd})$ and $G_j(\mathbf{Q}_j, \mathbf{E}_j)$ have bounded second order derivatives, and also $F_{jd}(Q_{jd})$, $G_j(\mathbf{Q}_j)$, and $G_j(\mathbf{E}_j)$ are convex, where $j \in \{1, ..., \bar{n}\}$, the modified projection method converges to the unique solution of the problem defined in* (5.11)*, or equivalently in* (5.9)*.*

For completeness, we now restate (5.14) and (5.15) in which $\mathcal{F}(\mathcal{X}) \equiv \mathcal{P}(\mathcal{X})$ is in expanded form for our particular setting introduced in (5.10). In this regard, for each vector $\mathcal{X} = (\mathbf{Q}, \mathbf{E}, \mathbf{L}) \in \mathcal{K} \equiv \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$, the problem in (5.14) can be written as

$$
\begin{aligned}
&\sum_{j=1}^{\bar{n}} \sum_{d=1}^{\bar{d}} \Bigg(\Bigg[\tilde{Q}_{jd}^{(i-1)} + \varphi_2 \Bigg\{ \frac{\partial F_{jd}(Q_{jd}^{(i-1)})}{\partial Q_{jd}} + \frac{\partial G_j(\mathbf{Q}_j^{(i-1)}, \mathbf{E}_j^{(i-1)})}{\partial Q_{jd}} \\
&\qquad + B_d \mu_{jd} - \Big[P_d^{(i-1)} + \hat{s}_{jd} \Big] \Big(1 - \varepsilon_{jd}(Q_{jd}^{(i-1)}) \Big) \\
&\qquad - B_d \Bigg(\int_{Q_{jd}^{(i-1)}}^{\infty} \Big[\xi - Q_{jd}^{(i-1)} \Big] \epsilon_{jd}(\xi) \mathrm{d}\xi \Bigg) \Bigg\} - Q_{jd}^{(i-1)} \Bigg] \times \Big[Q_{jd} - \tilde{Q}_{jd}^{(i-1)} \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{c=1}^{\bar{c}} \Bigg(\Bigg[\tilde{E}_{jc}^{(i-1)} + \varphi_2 \Bigg\{ \frac{\partial G_j(\mathbf{Q}_j^{(i-1)}, \mathbf{E}_j^{(i-1)})}{\partial E_{jc}} + \sum_{k=1}^{\bar{k}} \Big(\nu_{kc} h_{jkc} \Big) \Bigg\} - E_{jc}^{(i-1)} \Bigg] \times \Big[E_{jc} - \tilde{E}_{jc}^{(i-1)} \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} \Big(\Big[\tilde{L}_{jkc}^{(i-1)} + \varphi_2 \{ \rho_{kc} - \nu_{kc} \} - L_{jkc}^{(i-1)} \Big] \times \Big[L_{jkc} - \tilde{L}_{jkc}^{(i-1)} \Big] \Big) \geq 0,
\end{aligned} \tag{5.16}
$$

which has the following closed-form solution, as discussed in Nagurney and Dhanda (1996) on the basis of Theorem 5.5:

$$
\begin{aligned}
\tilde{Q}_{jd}^{(i-1)} = \max \Bigg\{ 0, -\varphi_2 \Bigg\{ & \frac{\partial F_{jd}(Q_{jd}^{(i-1)})}{\partial Q_{jd}} + \frac{\partial G_j(\mathbf{Q}_j^{(i-1)}, \mathbf{E}_j^{(i-1)})}{\partial Q_{jd}} \\
& + B_d \mu_{jd} - \Big[P_d^{(i-1)} + \hat{s}_{jd} \Big] \Big(1 - \varepsilon_{jd}(Q_{jd}^{(i-1)}) \Big) \\
& - B_d \Bigg(\int_{Q_{jd}^{(i-1)}}^{\infty} \Big[\xi - Q_{jd}^{(i-1)} \Big] \epsilon_{jd}(\xi) \mathrm{d}\xi \Bigg) \Bigg\} + Q_{jd}^{(i-1)} \Bigg\}
\end{aligned} \tag{5.17}
$$

$$
\tilde{E}_{jc}^{(i-1)} = \max \Bigg\{ 0, -\varphi_2 \Bigg\{ \frac{\partial G_j(\mathbf{Q}_j^{(i-1)}, \mathbf{E}_j^{(i-1)})}{\partial E_{jc}} + \sum_{k=1}^{\bar{k}} \Big(\nu_{kc} h_{jkc} \Big) \Bigg\} + E_{jc}^{(i-1)} \Bigg\} \tag{5.18}
$$

$$
\tilde{L}_{jkc}^{(i-1)} = \max \Big\{ 0, -\varphi_2 \{ \rho_{kc} - \nu_{kc} \} + L_{jkc}^{(i-1)} \Big\}. \tag{5.19}
$$

In the same vein, the problem in (5.15) can be written as

$$\begin{aligned}
&\sum_{j=1}^{\bar{n}}\sum_{d=1}^{\bar{d}}\Bigg(\Bigg[Q_{jd}^{(i)}+\varphi_2\Bigg\{\frac{\partial F_{jd}(\tilde{Q}_{jd}^{(i-1)})}{\partial Q_{jd}}+\frac{\partial G_j(\tilde{\mathbf{Q}}_j^{(i-1)},\tilde{\mathbf{E}}_j^{(i-1)})}{\partial Q_{jd}}\\
&\quad+B_d\mu_{jd}-\Big[\tilde{P}_d^{(i-1)}+\hat{s}_{jd}\Big]\Big(1-\varepsilon_{jd}(\tilde{Q}_{jd}^{(i-1)})\Big)\\
&\quad-B_d\bigg(\int_{\tilde{Q}_{jd}^{(i-1)}}^{\infty}\Big[\xi-\tilde{Q}_{jd}^{(i-1)}\Big]\epsilon_{jd}(\xi)\mathrm{d}\xi\bigg)\Bigg\}-Q_{jd}^{(i-1)}\Bigg]\times\Big[Q_{jd}-Q_{jd}^{(i)}\Big]\Bigg)\\
&+\sum_{j=1}^{\bar{n}}\sum_{c=1}^{\bar{c}}\Bigg(\Bigg[E_{jc}^{(i)}+\varphi_2\Bigg\{\frac{\partial G_j(\tilde{\mathbf{Q}}_j^{(i-1)},\tilde{\mathbf{E}}_j^{(i-1)})}{\partial E_{jc}}+\sum_{k=1}^{\bar{k}}\Big(\nu_{kc}h_{jkc}\Big)\Bigg\}-E_{jc}^{(i-1)}\Bigg]\times\Big[E_{jc}-E_{jc}^{(i)}\Big]\Bigg)\\
&+\sum_{j=1}^{\bar{n}}\sum_{k=1}^{\bar{k}}\sum_{c=1}^{\bar{c}}\Big(\Big[L_{jkc}^{(i)}+\varphi_2\{\rho_{kc}-\nu_{kc}\}-L_{jkc}^{(i-1)}\Big]\times\Big[L_{jkc}-L_{jkc}^{(i)}\Big]\Big)\geq 0,
\end{aligned}\tag{5.20}$$

which has the following closed-form solution:

$$\begin{aligned}
Q_{jd}^{(i)}&=\max\Bigg\{0,-\varphi_2\Bigg\{\frac{\partial F_{jd}(\tilde{Q}_{jd}^{(i-1)})}{\partial Q_{jd}}+\frac{\partial G_j(\tilde{\mathbf{Q}}_j^{(i-1)},\tilde{\mathbf{E}}_j^{(i-1)})}{\partial Q_{jd}}\\
&\quad+B_d\mu_{jd}-\Big[\tilde{P}_d^{(i-1)}+\hat{s}_{jd}\Big]\Big(1-\varepsilon_{jd}(\tilde{Q}_{jd}^{(i-1)})\Big)\\
&\quad-B_d\bigg(\int_{\tilde{Q}_{jd}^{(i-1)}}^{\infty}\Big[\xi-\tilde{Q}_{jd}^{(i-1)}\Big]\epsilon_{jd}(\xi)\mathrm{d}\xi\bigg)\Bigg\}+Q_{jd}^{(i-1)}\Bigg\}
\end{aligned}\tag{5.21}$$

$$E_{jc}^{(i)}=\max\Bigg\{0,-\varphi_2\Bigg\{\frac{\partial G_j(\tilde{\mathbf{Q}}_j^{(i-1)},\tilde{\mathbf{E}}_j^{(i-1)})}{\partial E_{jc}}+\sum_{k=1}^{\bar{k}}\Big(\nu_{kc}h_{jkc}\Big)\Bigg\}+E_{jc}^{(i-1)}\Bigg\}\tag{5.22}$$

$$L_{jkc}^{(i)}=\max\Big\{0,-\varphi_2\{\rho_{kc}-\nu_{kc}\}+L_{jkc}^{(i-1)}\Big\}.\tag{5.23}$$

As a result, to solve the subproblems (5.14) and (5.15) and find the unique solution of the problem defined in (5.11), or equivalently in (5.9) (cf. Theorem 5.9), it is sufficient to benefit from the closed-form equations (5.17)–(5.19) and (5.21)–(5.23). We also remind that in order to implement the modified projection method where $\mathcal{F}\equiv\mathcal{P}$, the Lipschitz constant can be defined as:

$$
\begin{aligned}
L_{\mathcal{P}} = &\sqrt{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})} \times (\bar{n}\bar{d}+\bar{c}+\bar{k}\bar{c})\times \\
&\times \Bigg[\left(\max_{j,d}\left\{\left|\frac{\partial^2 F_{jd}(Q_{jd})}{\partial Q_{jd}^2}\right|+\left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd}^2}\right|+(A_d+\hat{s}_{jd})\times|\epsilon_{jd}(Q_{jd})|+2B_d\right\}\right)^2 \\
&+\left(\max_{j,d\neq d'}\left\{\left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd'}\partial Q_{jd}}\right|\right\}\right)^2+\left(\max_{d}\left\{B_d\right\}\right)^2+\left(\max_{j,c,d}\left\{\left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc}\partial Q_{jd}}\right|\right\}\right)^2 \\
&+\left(\max_{j,c}\left\{\left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc}^2}\right|\right\}\right)^2+\left(\max_{j,c\neq c'}\left\{\left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc'}\partial E_{jc}}\right|\right\}\right)^2 \\
&+\left(\max_{j,c,d}\left\{\left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd}\partial E_{jc}}\right|\right\}\right)^2\Bigg]. \qquad (5.24)
\end{aligned}
$$

5.4.6 Numerical Examples

For completeness, four examples are presented in this section to illustrate the application of the modified projection method in solving Equation (5.9). Our purpose is to highlight the theoretical and practical merits of the proposed market-based setting. The following examples are solved on a 8 GB RAM, 4.3 GHz desktop computer, where the convergence tolerance φ_1 is set to 10^{-5}.

We start with a simple example which includes two homogeneous supply chains that compete in a single-product market. We assume that the demand distributions of this duopoly are identical. Under such simple conditions, we are able to analytically explore the unique Nash equilibrium of the proposed non-cooperative Cournot game and computationally investigate the developed solution procedure using standard functions in Microsoft Excel. As shown in the following example, both approaches lead to the same results.

Example 5.1 [A Single-Product Single-Pollutant Duopoly]: Our first example consists of a simple duopoly where the two supply chains are assigned no initial permits (i.e., $\ell^0_{jkc} = 0$) and face a single-product single-pollutant local market (i.e., $\bar{d} = \bar{c} = \bar{k} = 1$). We assume that the price of the product follows the functional form of $P(Q_1, Q_2) = A - B(Q_1 + Q_2) = 10 - 2(Q_1 + Q_2)$. Other market parameters (e.g., product lost opportunity cost, pollutant penalty cost, pollutant purchasing price, and emissions contribution) are set equal to 1.

We also let each supply chain face a production cost function of the form $F_j \equiv {Q_j}^2$ and an emission cost function of the form $G_j \equiv Q_j - E_j$. Both supply chains' demand is assumed to be distributed using the probability density function $\epsilon_j(x) = \varepsilon'_j(x) = \frac{2}{\sqrt{2\pi}}\, e^{-\frac{x^2}{2}}$, $x \geq 0$, as illustrated in Figure 5.2. This resembles a truncated normal density for $x \geq 0$ where the mean is approximately $\mu = 0.798$. Given that PDF and CDF of the standard normal distribution are denoted by $\mathrm{PDF}_S(x)$ and $\mathrm{CDF}_S(x)$, respectively, it turns out that $\epsilon_j(x) = 2\mathrm{PDF}_S(x)$ and $\varepsilon_j(x) = 2\mathrm{CDF}_S(x) - 1$.

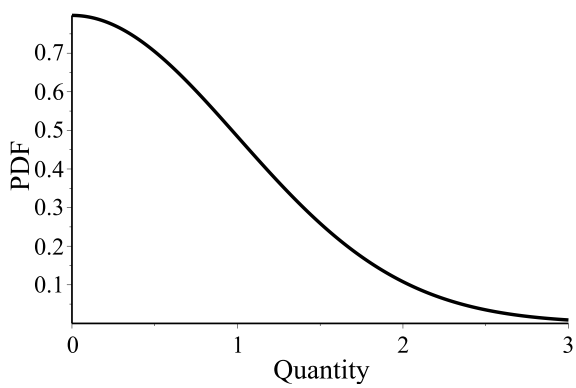


Figure 5.2: The probability density function of demand in Example 5.1

The functions in this example satisfy the conditions stated in Theorem 5.9. The unique equilibrium of the Cournot game can be characterized analytically. Using (5.5) we can write

$$\begin{aligned}\Pi_1(Q_1, Q_2, E_1, L_1) = &\int_0^{Q_1} \left[(A - B(Q_1 + Q_2))\xi - Q_1^2\right] \epsilon(\xi)\mathrm{d}\xi \\ &+ \int_{Q_1}^{\infty} \left[(A - B(Q_1 + Q_2))Q_1 - (\xi - Q_1) - Q_1^2\right] \epsilon(\xi)\mathrm{d}\xi \\ &- (Q_1 - E_1) - (E_1 - L_1) - L_1,\end{aligned}$$

and $\int_0^a x\epsilon(x)\mathrm{d}x = -\epsilon(a) + \sqrt{\frac{2}{\pi}}$ results in

$$\begin{aligned}
\Pi_1 \equiv \Pi_1(Q_1, Q_2) &= -(Q_1^2 + Q_1) + \left[-BQ_1^2 + (A - BQ_2 + 1)Q_1\right](1 - \varepsilon(Q_1)) \\
&+ \left[-BQ_1 + (A - BQ_2 + 1)\right]\left(\frac{-2(e^{-\frac{Q_1^2}{2}} - 1)}{\sqrt{2\pi}}\right) - \mu \\
&\Longrightarrow \frac{\partial \Pi_1}{\partial Q_1} = -(2Q_1 + 1) + B\left(\epsilon(Q_1) - \sqrt{\frac{2}{\pi}}\right) + \left[-2BQ_1 + (A - BQ_2 + 1)\right](1 - \varepsilon(Q_1)).
\end{aligned}$$

In a similar vein, $\frac{\partial \Pi_2}{\partial Q_2}$ is determined. To find the equilibrium, it is now sufficient to solve the system $\frac{\partial \Pi_1}{\partial Q_1} = \frac{\partial \Pi_2}{\partial Q_2} = 0$. Considering the homogeneity of the players, it turns out that $Q_1^* = Q_2^*$, which simplifies the above equation as follows

$$-(2Q_1^* + 1) + B\left(\epsilon(Q_1^*) - \sqrt{\tfrac{2}{\pi}}\right) + (-3BQ_1^* + A + 1)(1 - \varepsilon(Q_1^*)) = 0.$$

This univariate equation can be solved numerically by the use of the Microsoft Excel features (e.g., $\mathrm{PDF}_S(x)$, $\mathrm{CDF}_S(x)$, and Goal Seek) that result in $Q_1^* = Q_2^* = 0.7557767$. Furthermore, equations (5.17) and (5.21) can solve this instance through the following equations:

$$\begin{aligned}
\tilde{Q}_1^{(i-1)} &= \max\Bigg\{0, -\varphi_2\Big\{2Q_1^{(i-1)} + 1 + B\mu - \left[A - B(Q_1^{(i-1)} + Q_2^{(i-1)}) + 1\right](1 - \varepsilon(Q_1^{(i-1)})) \\
&\qquad - B\left(\int_{Q_1^{(i-1)}}^{\infty}\left[\xi - Q_1^{(i-1)}\right]\epsilon(\xi)\mathrm{d}\xi\right)\Big\} + Q_1^{(i-1)}\Bigg\} \\
\Longrightarrow \tilde{Q}_1^{(i-1)} &= \tilde{Q}_2^{(i-1)} = \max\Bigg\{0, -\varphi_2\Big\{2Q_1^{(i-1)} + 1 + B\left(-2\mathrm{PDF}_S(Q_1^{(i-1)}) + \sqrt{\frac{2}{\pi}}\right) \\
&\qquad + 2\left[3BQ_1^{(i-1)} - A - 1\right] \times \left[1 - \mathrm{CDF}_S(Q_1^{(i-1)})\right]\Big\} + Q_1^{(i-1)}\Bigg\}
\end{aligned} \tag{5.25}$$

$$
\begin{aligned}
Q_1^{(i)} =& \max\Bigg\{0, -\varphi_2\Big\{2\tilde{Q}_1^{(i-1)} + 1 + B\mu - \Big[A - B(\tilde{Q}_1^{(i-1)} + \tilde{Q}_2^{(i-1)}) + 1\Big]\left(1 - \varepsilon(\tilde{Q}_1^{(i-1)})\right) \\
&- B\left(\int_{\tilde{Q}_1^{(i-1)}}^{\infty}\left[\xi - \tilde{Q}_1^{(i-1)}\right]\epsilon(\xi)\mathrm{d}\xi\right)\Big\} + Q_1^{(i-1)}\Bigg\} \\
\Longrightarrow Q_1^{(i)} =& Q_2^{(i)} = \max\Bigg\{0, -\varphi_2\Big\{2\tilde{Q}_1^{(i-1)} + 1 + B\left(-2\mathrm{PDF}_S(\tilde{Q}_1^{(i-1)}) + \sqrt{\frac{2}{\pi}}\right) \\
&+ 2\left[3B\tilde{Q}_1^{(i-1)} - A - 1\right] \times \left[1 - \mathrm{CDF}_S(\tilde{Q}_1^{(i-1)})\right]\Big\} + Q_1^{(i-1)}\Bigg\}.
\end{aligned}
\tag{5.26}
$$

Assuming $\mathcal{X}^{(0)} = (Q_1^0, Q_2^0) = (\mu, \mu)$, one can code (5.25) and (5.26) in Microsoft Excel to determine the unique equilibrium $(Q_1^*, Q_2^*) = (0.7557767, 0.7557767)$. The convergence of the solution procedure to this equilibrium is depicted in Figure 5.3.

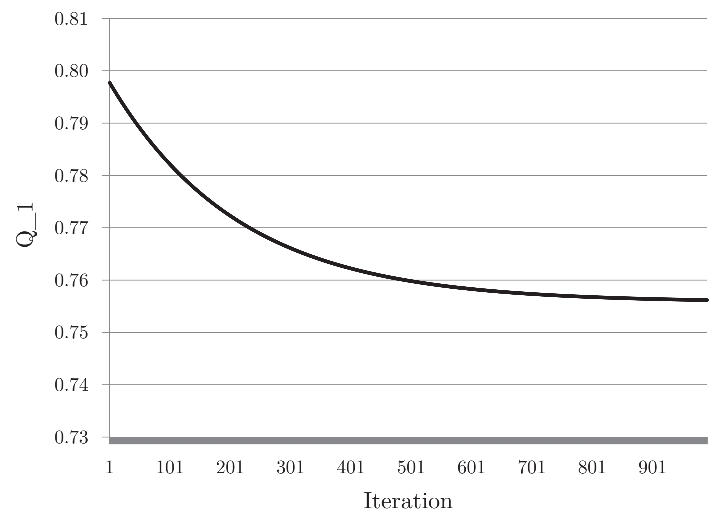


Figure 5.3: Solving Example 5.1 in Microsoft Excel through equations (5.25) and (5.26)

For the remaining examples, we use Maple software features in calculating definite integrals in order to solve the proposed non-cooperative game. This approach allows us to investigate more realistic scenarios, such as the oligopolistic games in the next examples where multiple products/pollutants are traded. Each of these examples consists of three players which are assigned some random initial permits and face a market that satisfies $\bar{d} = \bar{c} = \bar{k} = 3$. We assume that the market parameters for demand distribution, product lost opportunity cost, pollutant penalty cost, pollutant purchasing price, and emissions contribution are randomly generated as presented for each example. We let each supply chain face a production cost function of the form $F_{jd} \equiv \lambda_{jd}Q_{jd} + \alpha_{jd}{Q_{jd}}^{\beta_{jd}}$ and an emission cost function of the form $G_j \equiv \sum_d \left(a^{\mathrm{q}}_{jd}Q^2_{jd} + b^{\mathrm{q}}_{jd}Q_{jd}\right) + \sum_c \left(a^{\mathrm{e}}_{jc}E^2_{jc} + b^{\mathrm{e}}_{jc}E_{jc}\right) -$

$M_j \left(\sum_d Q_{jd}\right) \left(\sum_c E_{jc}\right) + N_j$.

Example 5.2 conducts a sensitivity analysis on initial assignments of the matrices $\mathbf{Q}^0$, $\mathbf{E}^0$, and $\mathbf{L}^0$. Moreover, Example 5.3 investigates the impact of the parameters ν and ρ on the equilibrium as the values determined by the regulatory decision maker. Finally, Example 5.4 takes into account the impact of demand stochasticity on outputs and production levels of the entities. We assume that other parameters are determined exogenously as they are characterized by market dynamics, customers, and/or production technologies.

Example 5.2 [A Three-Product Three-Pollutant Triopoly – Changes in $\mathbf{Q}^0$, $\mathbf{E}^0$, and $\mathbf{L}^0$]: The demand distributions in all three supply chains are assumed to be distributed using Log-normal distributions with randomly generated parameters, as illustrated in Figure 5.4.

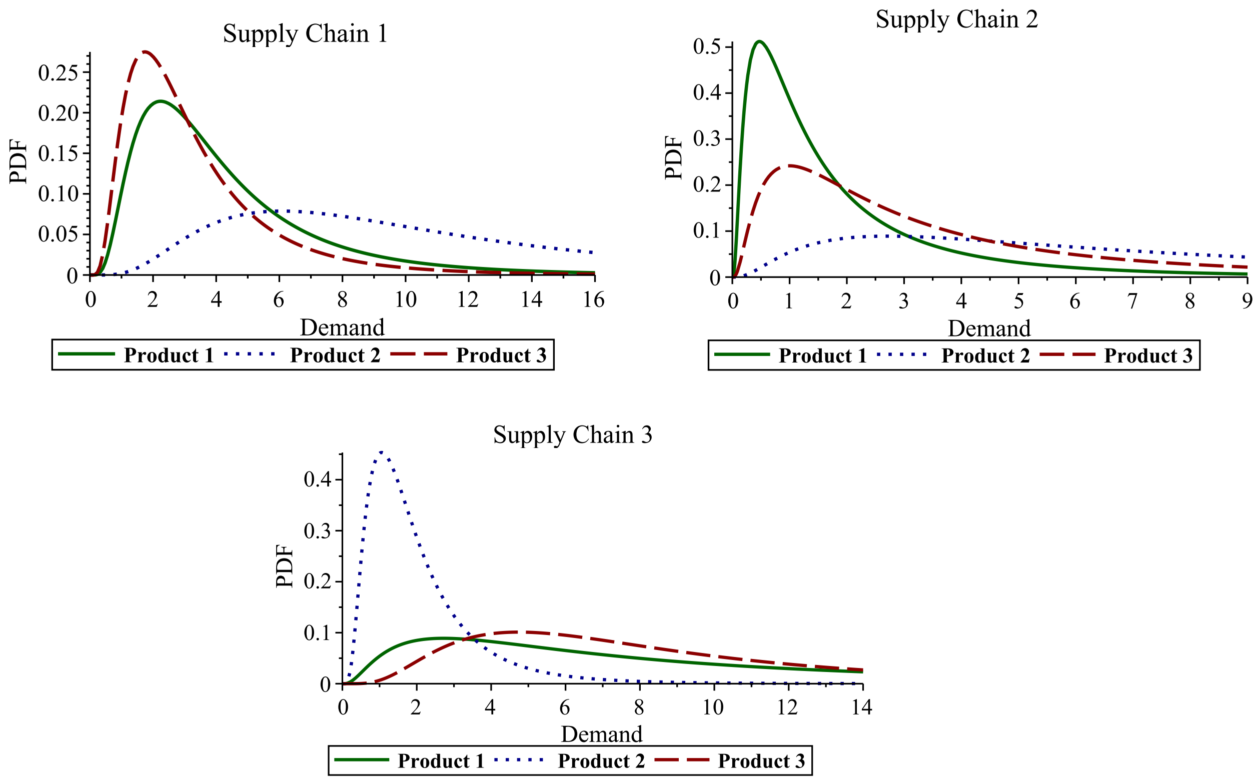


Figure 5.4: The probability density functions of demand in Example 5.2

Parameters used in this example are as follows:

$$\hat{s}_{\bar{n}\times\bar{d}} = \begin{bmatrix} 3 & 1 & 12 \\ 6 & 9 & 12 \\ 3 & 13 & 14 \end{bmatrix} \qquad A_{1\times\bar{d}} = \begin{bmatrix} 189 & 168 & 189 \end{bmatrix} \qquad B_{1\times\bar{d}} = \begin{bmatrix} 6 & 3 & 1 \end{bmatrix}$$

$$h_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 1 & 10 & 16 \\ 16 & 13 & 18 \\ 11 & 2 & 7 \end{bmatrix} \qquad h_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 4 & 7 & 10 \\ 3 & 18 & 1 \\ 9 & 10 & 9 \end{bmatrix} \qquad h_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 8 & 13 & 16 \\ 3 & 17 & 19 \\ 16 & 5 & 2 \end{bmatrix}$$

$$\text{Demand: Parameter 1} = \begin{bmatrix} 5/4 & 9/4 & 1 \\ 1/4 & 2 & 1 \\ 2 & 1/2 & 2 \end{bmatrix} \qquad \text{Parameter 2} = \begin{bmatrix} 2/3 & 2/3 & 2/3 \\ 1 & 1 & 1 \\ 1 & 2/3 & 2/3 \end{bmatrix}$$

$$\rho_{\bar{k}\times\bar{c}} = \begin{bmatrix} 6 & 7 & 7 \\ 2 & 8 & 4 \\ 8 & 6 & 3 \end{bmatrix} \quad \nu_{\bar{k}\times\bar{c}} = \begin{bmatrix} 8 & 9 & 11 \\ 11 & 8 & 9 \\ 8 & 9 & 9 \end{bmatrix}$$

The functions in this example are given by $F_{jd} \equiv {Q_{jd}}^2$ and $G_j \equiv \sum_d \left(Q_{jd}\right) + \sum_c \left(E_{jc}^2\right)$ which satisfy the conditions stated in Theorem 5.9. Given that the first scenario is carried out based on the initial production quantities $Q_{jd}^0 = \frac{1}{2}\mu_{jd}$ and the following parameters

$$\mathbf{E}^0_{\bar{n}\times\bar{c}} = \begin{bmatrix} 6 & 7 & 9 \\ 7 & 2 & 7 \\ 5 & 9 & 2 \end{bmatrix} \quad \mathbf{L}^0_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 1 & 2 & 4 \\ 2 & 2 & 1 \\ 1 & 1 & 3 \end{bmatrix} \quad \mathbf{L}^0_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 4 & 1 & 3 \\ 1 & 2 & 3 \\ 3 & 1 & 1 \end{bmatrix} \quad \mathbf{L}^0_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 1 & 3 & 3 \\ 1 & 2 & 1 \\ 4 & 4 & 2 \end{bmatrix}$$

and the second scenario assumes the initial production quantities $Q_{jd}^0 = \frac{2}{3}\mu_{jd}$ and the following parameters

$$\mathbf{E}^0_{\bar{n}\times\bar{c}} = \begin{bmatrix} 5 & 6 & 3 \\ 3 & 7 & 4 \\ 2 & 5 & 2 \end{bmatrix} \quad \mathbf{L}^0_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 1 & 5 & 2 \\ 4 & 3 & 4 \\ 5 & 2 & 3 \end{bmatrix} \quad \mathbf{L}^0_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 4 & 3 & 1 \\ 2 & 4 & 5 \\ 4 & 3 & 2 \end{bmatrix} \quad \mathbf{L}^0_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 3 & 3 & 2 \\ 2 & 4 & 5 \\ 4 & 4 & 5 \end{bmatrix},$$

we can find the unique equilibrium using (5.17)–(5.19) and (5.21)–(5.23):

$$\mathbf{Q}^*_{\bar{n}\times\bar{d}} = \begin{bmatrix} 3.675 & 7.489 & 3.945 \\ 2.206 & 7.287 & 4.301 \\ 6.799 & 2.479 & 7.508 \end{bmatrix} \quad \mathbf{E}^*_{\bar{n}\times\bar{c}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \mathbf{L}^*_{j,\bar{k}\times\bar{c}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

We observe that the foregoing scenario pair produces the same Nash equilibria for the ETS mechanism and that the developed solution procedure converges to this solution. This result is expected on the basis of Theorem 5.9, as the mentioned cases only differ in $\mathbf{Q}^0$, $\mathbf{E}^0$, and $\mathbf{L}^0$. We also note that finding zero values for $\mathbf{E}^*$, and $\mathbf{L}^*$ is due to the definition of G_j in this example. In the next cases, we study more realistic functions where the entities will be penalized for their emissions.

Example 5.3 [A Three-Product Three-Pollutant Triopoly – Changes in ν and ρ]: The demand distributions in all three supply chains are assumed to follow Gamma distributions with randomly generated parameters, as illustrated in Figure 5.5.

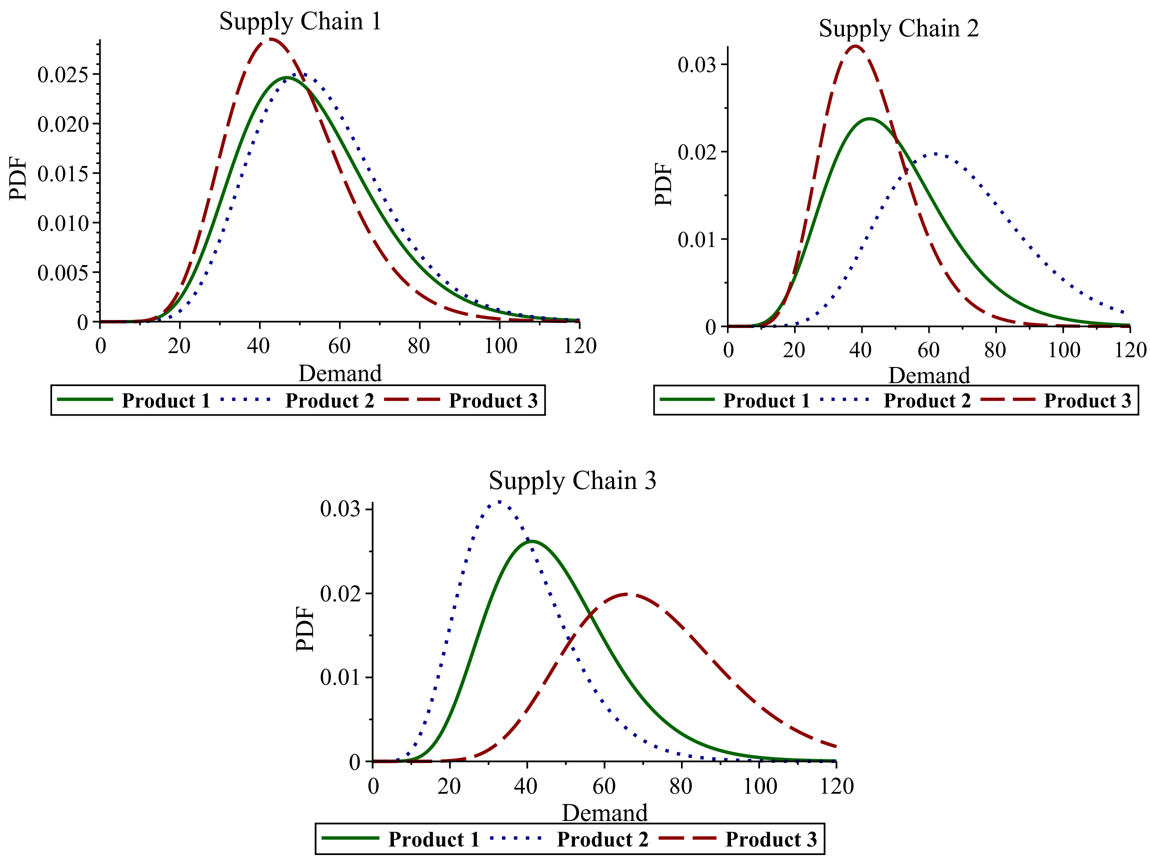


Figure 5.5: The probability density functions of demand in Example 5.3

Parameters used in this example are as follows:

$$\hat{s}_{\bar{n}\times\bar{d}} = \begin{bmatrix} 43 & 23 & 30 \\ 34 & 46 & 48 \\ 41 & 20 & 34 \end{bmatrix} \qquad A_{1\times\bar{d}} = \begin{bmatrix} 823 & 906 & 979 \end{bmatrix} \qquad B_{1\times\bar{d}} = \begin{bmatrix} 5 & 3 & 1 \end{bmatrix}$$

$$h_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 18 & 4 & 12 \\ 15 & 1 & 10 \\ 15 & 13 & 2 \end{bmatrix} \qquad h_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 12 & 6 & 5 \\ 6 & 17 & 12 \\ 2 & 12 & 13 \end{bmatrix} \qquad h_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 6 & 4 & 17 \\ 19 & 19 & 8 \\ 3 & 18 & 7 \end{bmatrix}$$

$$\text{Demand: Parameter 1} = \begin{bmatrix} 11/2 & 5 & 9/2 \\ 13/2 & 13/2 & 4 \\ 11/2 & 5 & 6 \end{bmatrix} \quad \text{Parameter 2} = \begin{bmatrix} 19/2 & 11/2 & 21/2 \\ 15/2 & 21/2 & 21/2 \\ 17/2 & 15/2 & 12 \end{bmatrix}$$

$$\mathbf{E}^0_{\bar{n}\times\bar{c}} = \begin{bmatrix} 10 & 5 & 1 \\ 2 & 10 & 1 \\ 2 & 9 & 10 \end{bmatrix} \quad \mathbf{L}^0_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 1 & 3 & 1 \\ 3 & 1 & 1 \\ 1 & 3 & 1 \end{bmatrix} \quad \mathbf{L}^0_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 3 & 3 & 2 \\ 1 & 1 & 3 \\ 2 & 3 & 2 \end{bmatrix} \quad \mathbf{L}^0_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 2 & 2 & 2 \\ 3 & 2 & 1 \\ 3 & 3 & 3 \end{bmatrix}$$

This example's functions, $G_j \equiv \sum_d \left(Q^2_{jd}\right) + \sum_c \left(1.2jE^2_{jc} - 300jE_{jc}\right) + 3j$ and $F_{jd} \equiv Q_{jd}{}^{\frac{1}{2}}$, satisfy the conditions of Theorem 5.9. Setting the initial production quantities $Q^0_{jd} = \mu_{jd}$, the distributions' means, we can find the unique equilibrium using (5.17)–(5.19) and (5.21)–(5.23). The parameters in the first scenario are set equal to

$$\rho_{\bar{k}\times\bar{c}} = \begin{bmatrix} 6 & 6 & 5 \\ 6 & 6 & 3 \\ 6 & 7 & 5 \end{bmatrix} \quad \nu_{\bar{k}\times\bar{c}} = \begin{bmatrix} 9 & 10 & 8 \\ 11 & 9 & 9 \\ 8 & 8 & 7 \end{bmatrix},$$

and the second scenario assumes the following parameters

$$\rho_{\bar{k}\times\bar{c}} = \begin{bmatrix} 10 & 9 & 7 \\ 10 & 8 & 10 \\ 7 & 9 & 8 \end{bmatrix} \quad \nu_{\bar{k}\times\bar{c}} = \begin{bmatrix} 12 & 10 & 10 \\ 11 & 10 & 12 \\ 12 & 12 & 11 \end{bmatrix}.$$

Our Maple code provides the following solutions for the Cournot game in a negligible amount of CPU time, as each iteration of the algorithm is computationally efficient:

Scenario 1:

$$\mathbf{\Pi}^*_{\bar{n}\times 1} = \begin{bmatrix} 59,288 \\ 68,939 \\ 92,970 \end{bmatrix} \quad \mathbf{Q}^*_{\bar{n}\times\bar{d}} = \begin{bmatrix} 35.858 & 42.064 & 42.035 \\ 33.497 & 50.446 & 38.625 \\ 32.534 & 30.621 & 58.709 \end{bmatrix} \quad \mathbf{E}^*_{\bar{n}\times\bar{c}} = \begin{bmatrix} 6.66 & 7.64 & 2.91 \\ 9.63 & 14.63 & 7.79 \\ 13.15 & 17.94 & 20.63 \end{bmatrix}$$

$$\mathbf{L}^*_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} TT & TT & TT \\ TT & TT & TT \\ TT & TT & TT \end{bmatrix} \quad \mathbf{L}^*_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} TT & TT & TT \\ TT & TT & TT \\ TT & TT & TT \end{bmatrix} \quad \mathbf{L}^*_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} TT & TT & TT \\ TT & TT & TT \\ TT & TT & TT \end{bmatrix}$$

Scenario 2:

$$\mathbf{\Pi}^*_{\bar{n}\times 1} = \begin{bmatrix} 52,848 \\ 60,122 \\ 85,088 \end{bmatrix} \quad \mathbf{Q}^*_{\bar{n}\times\bar{d}} = \begin{bmatrix} 47.516 & 54.159 & 51.203 \\ 44.384 & 66.495 & 46.202 \\ 42.671 & 38.021 & 75.053 \end{bmatrix} \quad \mathbf{E}^*_{\bar{n}\times\bar{c}} = \begin{bmatrix} 4.44 & 6.60 & 1.70 \\ 8.80 & 13.40 & 5.92 \\ 12.59 & 16.25 & 19.03 \end{bmatrix}$$

$$\mathbf{L}^*_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} TT & TT & TT \\ TT & TT & TT \\ TT & TT & TT \end{bmatrix} \quad \mathbf{L}^*_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} TT & TT & TT \\ TT & TT & TT \\ TT & TT & TT \end{bmatrix} \quad \mathbf{L}^*_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} TT & TT & TT \\ TT & TT & TT \\ TT & TT & TT \end{bmatrix}$$

Comparing the foregoing cases, we are able to discuss three main observations. Firstly, each element of the matrix $\mathbf{Q}^*$ in the first scenario is smaller than the corresponding value in the second case. This result implies that the increases in the values ρ and ν lead to a more intense competition in the product markets. More precisely, although enlarging production quantities will decrease per unit purchasing prices in the product markets and increase emissions cost, the supply chains endeavor to compensate their higher environmental taxation through larger product market-shares. These changes, however, do not result in greater profitability performance in this example, as presented by the vector $\mathbf{\Pi}^*$. This finding can be beneficial in policy making where the regulator seriously accounts for economic sustainability of the businesses under control or carefully considers customer satisfaction by less expensive products as a result of mass production.

Secondly, comparing both scenarios for all $j \in \{1, 2, 3\}$ we observe that the element L_{jkc} increases if and only if $\nu_{kc} - \rho_{kc}$ increases. This is intuitive, as taking into consideration the variables L_{jkc} in (5.5). If any increase (decrease) of the elements $\nu_{kc} - \rho_{kc}$ from the first scenario to the second case is denoted by $\uparrow$ ($\downarrow$), we have the following result:

$$\text{Changes in } \{[\nu] - [\rho]\} \equiv \begin{bmatrix} \downarrow & \downarrow & - \\ \downarrow & \downarrow & \downarrow \\ \uparrow & \uparrow & \uparrow \end{bmatrix}$$

This matrix clearly explains why there exists a decrease in $L^*[1, 1]$, an increase in $L^*[3, 2]$, and no change in $L^*[1, 3]$ from the first scenario to the second case for all supply chains. This analysis reveals important results, as the supply chain managers can take advantage of the information obtained form sustainability-oriented regulations and incorporate it into their profit maximizing decisions. We remind that purchasing fewer permits from the pollutant markets, which is characterized by reducing the optimal variables L^*_{jkc}, will bring about more profitability for the supply chain j. It is worth mentioning that slower convergence of the variables L_{jkc} to the optimal values L^*_{jkc} is embedded in the linearity of the function Π_j over these variables.

Finally, we observe that raising the parameters ν and ρ from the first scenario to the second case results in less pollution in the second ETS setting. More precisely, comparing both scenarios (5.5) intuitively implies that the element E^*_{jc} increases if and only if $\sum_{k=1}^{\bar{k}} \nu_{kc}$ decreases, given that the matrices h_j do not alter. This result shows that the regulatory policy maker having a main focus on curbing pollution needs only to determine the parameters ν_{kc} such that the total amount of emissions in the framework is desirable. On the other hand, monitoring the parameters ρ_{kc} can be prominent provided that the policy maker has also interests in its own financial income. We recall that $\sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} (\rho_{kc} L_{jkc})$ is a stream of revenue for the regulatory body, as explained in (5.5). Since increasing the variables L^*_{jkc} may lead to decreasing in the variables E^*_{jc}, a profit-sensitive regulator that is simultaneously concerned in environmental pollution requires to analyze both ν and ρ.

Example 5.4 [A Three-Product Three-Pollutant Triopoly – Certain vs. Uncertain]: In this example, we study the impact of demand stochasticity on model outputs and production levels of the entities. The demand distributions in all three supply chains are assumed to be normally distributed with randomly generated parameters. In all cases, we choose the variance and mean of the normal distributions in a way that the probability of a negative draw for the demand is almost zero. In the first scenario we assume the following parameters ($\cong N(100, 1)$)

$$\text{Demand: Parameter 1} = \begin{bmatrix} 104 & 100 & 98 \\ 104 & 102 & 101 \\ 96 & 99 & 99 \end{bmatrix} \quad \text{Parameter 2} = \begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 2 & 2 & 2 \end{bmatrix},$$

as illustrated in Figure 5.6.

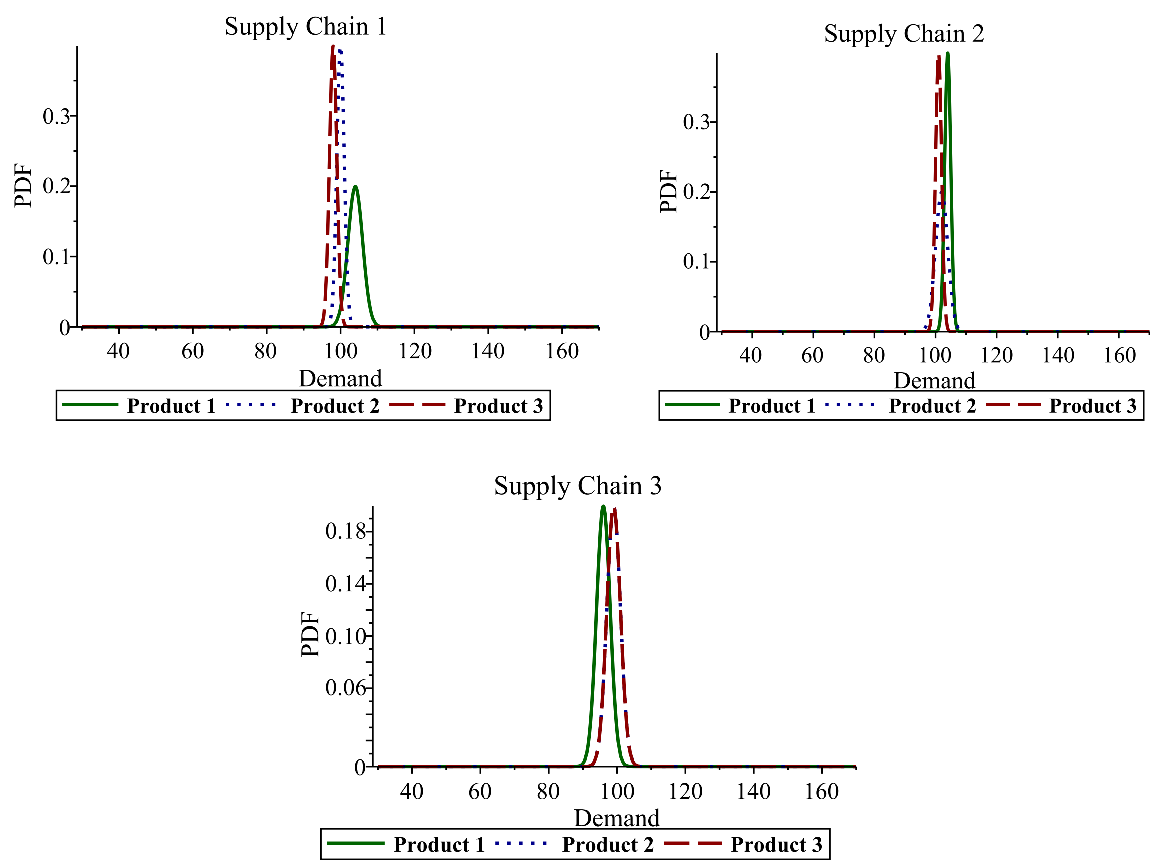


Figure 5.6: The probability density functions of demand in Example 5.4, Scenario 1

In addition, the second scenario is analyzed based on the following parameters ($\cong N(100, 18)$)

$$\text{Demand: Parameter 1} = \begin{bmatrix} 104 & 100 & 98 \\ 104 & 102 & 101 \\ 96 & 99 & 99 \end{bmatrix} \quad \text{Parameter 2} = \begin{bmatrix} 18 & 19 & 15 \\ 15 & 18 & 15 \\ 18 & 20 & 18 \end{bmatrix},$$

as illustrated in Figure 5.7.

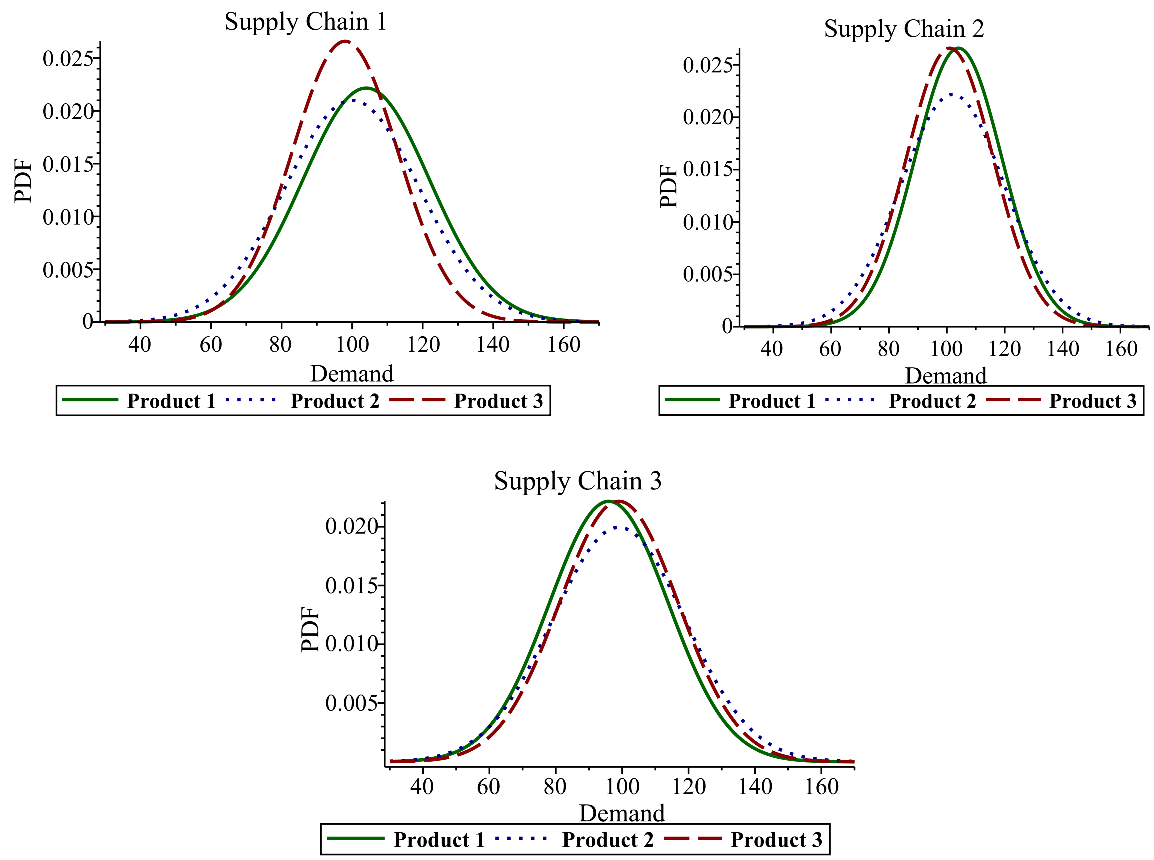


Figure 5.7: The probability density functions of demand in Example 5.4, Scenario 2

We note that selecting relatively small values for the standard deviation of demand in the first scenario allows us to examine an approximately certain case. While generated distributions in both scenarios meet $\mu_{jd} \simeq 100$, the adequately less dispersed observations in Scenario 1 can resemble an ETS without stochasticity in demand versus the very uncertain behaviors in Scenario 2. Other parameters used in this example are as follows:

$$\hat{s}_{\bar{n}\times\bar{d}} = \begin{bmatrix} 59 & 73 & 55 \\ 75 & 57 & 85 \\ 87 & 94 & 94 \end{bmatrix} \qquad A_{1\times\bar{d}} = \begin{bmatrix} 2383 & 2781 & 2584 \end{bmatrix} \qquad B_{1\times\bar{d}} = \begin{bmatrix} 2 & 3 & 1 \end{bmatrix}$$

$$h_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 8 & 15 & 14 \\ 11 & 6 & 15 \\ 12 & 11 & 13 \end{bmatrix} \quad h_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 12 & 12 & 6 \\ 5 & 11 & 12 \\ 5 & 11 & 11 \end{bmatrix} \quad h_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 9 & 5 & 15 \\ 13 & 13 & 12 \\ 8 & 9 & 5 \end{bmatrix}$$

$$\rho_{\bar{k}\times\bar{c}} = \begin{bmatrix} 6 & 5 & 7 \\ 10 & 8 & 6 \\ 5 & 9 & 7 \end{bmatrix} \quad \nu_{\bar{k}\times\bar{c}} = \begin{bmatrix} 10 & 10 & 12 \\ 11 & 14 & 14 \\ 12 & 14 & 13 \end{bmatrix}$$

$$\mathbf{E}^0_{\bar{n}\times\bar{c}} = \begin{bmatrix} 5 & 1 & 2 \\ 1 & 2 & 9 \\ 1 & 9 & 7 \end{bmatrix} \quad \mathbf{L}^0_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 5 & 4 & 1 \\ 5 & 7 & 9 \\ 2 & 9 & 5 \end{bmatrix} \quad \mathbf{L}^0_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 2 & 4 & 7 \\ 6 & 4 & 7 \\ 2 & 5 & 3 \end{bmatrix} \quad \mathbf{L}^0_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 7 & 8 & 9 \\ 9 & 3 & 1 \\ 7 & 8 & 9 \end{bmatrix}$$

As the functions $G_j \equiv \sum_d \left(5Q_{jd}^2 - 100Q_{jd}\right) + \sum_c \left(\frac{1}{2}E_{jc}^2 - 500E_{jc}\right) - \left(\sum_d Q_{jd}\right)\left(\sum_c E_{jc}\right)$ and $F_{jd} \equiv \frac{2}{3}{Q_{jd}}^{\frac{3}{2}}$ satisfy the conditions stated in Theorem 5.9. Setting the initial production quantities $Q^0_{jd} = \mu_{jd}$, the distributions' means, we can find the unique equilibrium using (5.17)–(5.19) and (5.21)–(5.23). Our Maple code provides the following solutions for the Cournot game in a negligible amount of CPU time, as each iteration of the algorithm is computationally efficient:

Scenario 1:

$$\mathbf{\Pi}^*_{\bar{n}\times 1} = \begin{bmatrix} 517,776 \\ 521,066 \\ 492,012 \end{bmatrix} \quad \mathbf{Q}^*_{\bar{n}\times\bar{d}} = \begin{bmatrix} 103.32 & 99.87 & 98.24 \\ 103.83 & 97.04 & 101.28 \\ 95.97 & 95.09 & 99.50 \end{bmatrix} \quad \mathbf{E}^*_{\bar{n}\times\bar{c}} = \begin{bmatrix} 44.99 & 31.55 & 41.98 \\ 34.95 & 40.94 & 23.88 \\ 25.49 & 16.19 & 25.22 \end{bmatrix}$$

$$\mathbf{L}^*_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 90 & 86 & 66 \\ 86 & 97 & 61 \\ 74 & 93 & 83 \end{bmatrix} \quad \mathbf{L}^*_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 58 & 86 & 64 \\ 99 & 63 & 55 \\ 63 & 75 & 63 \end{bmatrix} \quad \mathbf{L}^*_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 78 & 72 & 80 \\ 80 & 75 & 62 \\ 51 & 81 & 86 \end{bmatrix}$$

Scenario 2:

$$\mathbf{\Pi}^*_{\bar{n}\times 1} = \begin{bmatrix} 465,144 \\ 494,767 \\ 457,019 \end{bmatrix} \quad \mathbf{Q}^*_{\bar{n}\times\bar{d}} = \begin{bmatrix} 109.27 & 86.99 & 95.21 \\ 97.43 & 95.13 & 102.98 \\ 84.07 & 104.37 & 90.19 \end{bmatrix} \quad \mathbf{E}^*_{\bar{n}\times\bar{c}} = \begin{bmatrix} 30.14 & 26.75 & 33.08 \\ 43.16 & 30.35 & 32.78 \\ 24.21 & 40.75 & 35.36 \end{bmatrix}$$

$$\mathbf{L}^*_{1,\bar{k}\times\bar{c}} = \begin{bmatrix} 63 & 59 & 65 \\ 79 & 84 & 68 \\ 64 & 88 & 79 \end{bmatrix} \quad \mathbf{L}^*_{2,\bar{k}\times\bar{c}} = \begin{bmatrix} 59 & 54 & 57 \\ 92 & 91 & 76 \\ 52 & 88 & 59 \end{bmatrix} \quad \mathbf{L}^*_{3,\bar{k}\times\bar{c}} = \begin{bmatrix} 87 & 96 & 67 \\ 93 & 65 & 78 \\ 77 & 93 & 72 \end{bmatrix}$$

The first result of comparing the forgoing cases is reduction in profitability, as expected from 5.4. As the second scenario includes greater uncertainty in demand forecasting, the supply chains face loss in consequence of overestimating/underestimating demand. This worse profitability performance is not necessarily a result of higher production quantities.

We note that the literature of the newsvendor problem provides evidence to show that more demand stochasticity results in larger quantity sizes. However, we observe a different pattern in this example by tracking changes in the matrix $\mathbf{Q}^*$ in both scenarios. Reviewing Figure 5.8, we note that a supply chain may need to produce fewer items at optimality even in the presence of significant uncertainty. For example, this production reduction takes place for the second product type produced by the first two supply chains in this example. On the other hand, we observe instances where growing uncertainty ends in more production, such as the optimal quantity of the third supply chain associated with Product 2.

It is also worth pointing out that the matrix $\mathbf{Q}^*$ in the first case is nearly identical to the mean matrix that presents the first parameter values of the generated distributions. This is intuitive, as the first scenario provides less uncertainty and there is not mush flexibility in macro-level production plans.

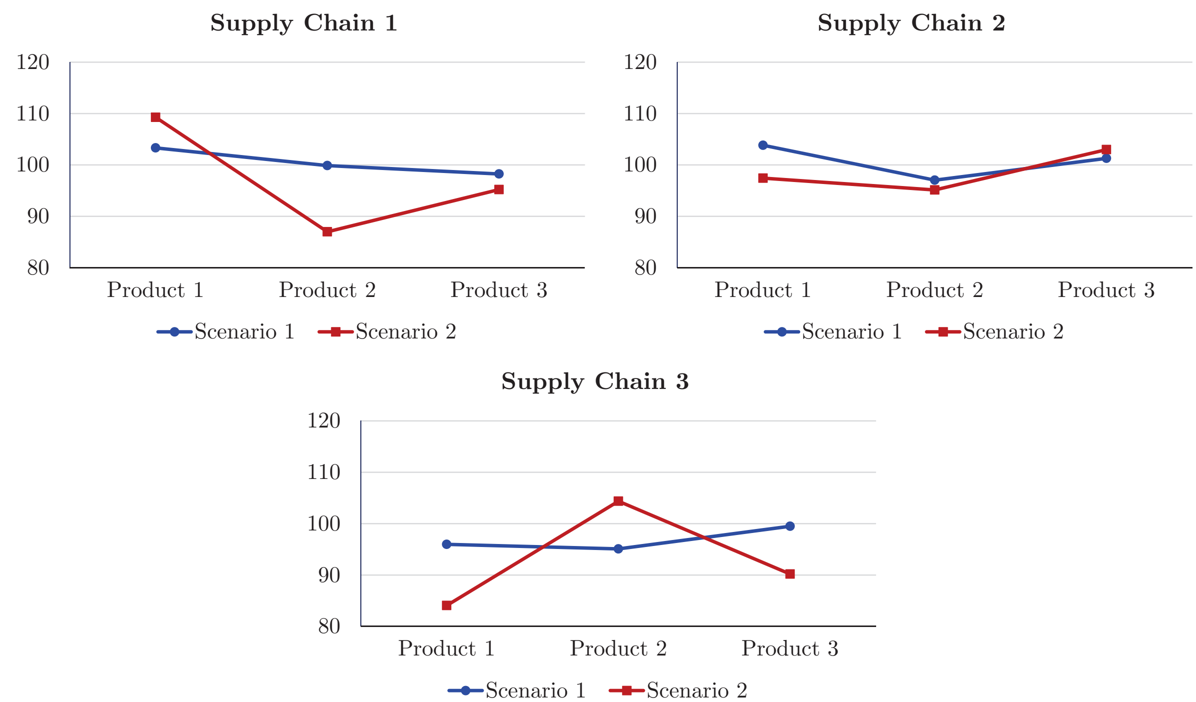


Figure 5.8: The optimal production quantities, Q^*_{jd}, in Example 5.4

In a similar vein, we observe that the elements of the matrices $\mathbf{E}^*$ in both cases may present increases or decreases in the presence of a higher level of uncertainty. As illustrated in Figure 5.9, the first supply chain puts in a better environmental performance for all pollutant types. The third player, however, almost shows an antithetical pattern, in particular with regard to emissions of the last two pollutant types. Moreover, the overall pollution emitted in the second scenario is 5% more than the associated amount in the other case. This result demonstrates that overlooking uncertainty in demand analysis may cause the underestimation of environmental pollution in the mechanism under examination.

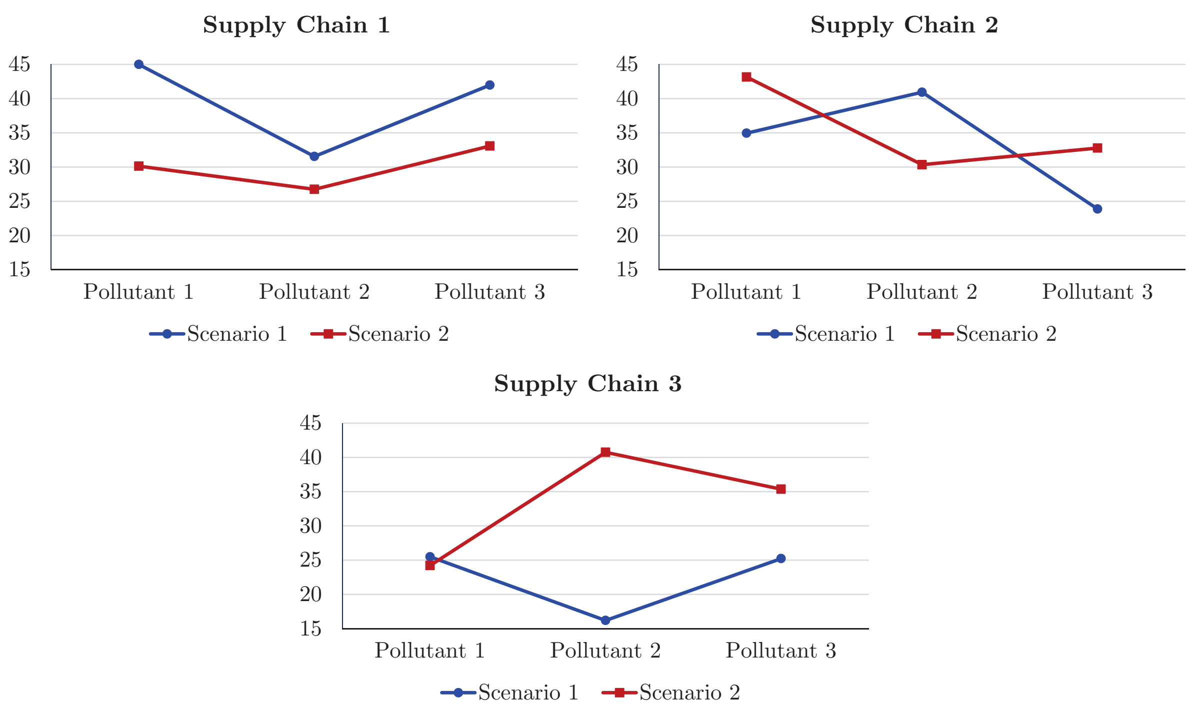


Figure 5.9: The optimal emissions values, E^*_{jc}, in Example 5.4

5.5 Conclusion and Future Extensions

In addition to reviewing pollution control mechanisms and their implementations in the developed countries, a multi-level emissions trading system is developed in this work. This game-theoretic setting monitors several supply chains competing in two market types, the product markets and the pollutant markets.

We assume that the dynamics of the first market category is characterized by a non-cooperative competition with a major objective of meeting customer expectations, where product demand follows non-negative probability density functions. In addition, a central regulator determines the parameters of the second market class with a focus on curbing pollution level in the entire system. The model extends those that have been presented in the literature to date through incorporating the sustainability performance of the supply chains under control into their optimal production/emissions policies.

The methodology we have developed in this chapter to solve the obtained oligopoly relies on the theory of variational inequality problems. More specifically, we establish the formulation, qualitative analysis, and computation of equilibria in multi-product multi-pollutant oligopolistic markets in the presence of stochastic demand of customers. In this regard, first an optimization problem is introduced for each of the profit-sensitive supply chains competing in a non-cooperative Cournot setting, and then all the problems are integrated in order to develop a single optimization problem which can be solved easily. This transformation plays an important role from the computational perspective, as it helps us calculate optimal policies by considering a single inequality instead of solving simultaneously a system of optimization problems. For the mechanism developed in this study, we provide sufficient and necessary conditions for the uniqueness of the Cournot game's Nash equilibria as well as sufficient conditions for the convergence of an efficient solution method to this unique equilibrium.

In addition, a cooperative game is introduced for each of the entities where a supply chain decision maker aims to distribute awards obtained from the regulatory body among its triple partners. Although such a cooperative game is not superadditive, we develop a simplified closed-form solution using the concept of the superadditivity cover.

Despite the fact that a static single-period perspective has been introduced in this study, more complicated approaches of games can be investigated in future studies. Especially in the presence of leader-follower relationships between the supply chains, a

Stackelberg framework can be established. In addition, we have assumed that all demand distributions follow continuous random variables, however, this assumption can be relaxed for the investigation of cases that face discrete demand behaviors. Furthermore, all demand distributions are assumed to be stochastically independent in the current setup, while they can be considered dependent for a set of products for practical cases where there is elasticity among substitute goods in the product markets. Another extension to this study is to allow the product price function to be nonlinear over the order quantity variables. For example, multiplicative pricing functions can be studied for the proposed ETS. Finally, investigating the impact of having shared partners between the supply chains and/or examining heterogeneous multi-echelon networks on the optimal policies can be analyzed in the future.

Chapter 6

Conclusions and Future Research

The topic of sustainability development has been of great interest for the last decade. There is now serious debate about incorporating sustainability practices in business operations. In recent years, many governments also have taken actions to incentivize firms that employ disruptive technologies to reduce their perilous environmental and social impacts. On the other hand, business managers strive to direct their organizational operations towards maximal long-run efficacy. In this regard, understanding different aspects of sustainability and business operations, as well as relating them to performance measurement, has been well investigated over the last decade. In this dissertation, the main focus is on performance assessment frameworks and sustainable supply chain management (SSCM), defined as "the management of supply chain operations, information, and funds in order to maximize the profitability while minimizing the environmental impacts and maximizing the social well-being."

Drawing on Chapter 2 that reviews the literature on performance evaluation in SSCM, we focus on the following areas for further research:

1. We observe that social measures have not received the attention they deserve. However, one may hypothesize that social sustainability metrics can serve as a realistic indicator for dangers caused by business operations and threatening labors and societies. The question one faces is how global supply chains can develop performance measures that incorporate social measures, as well as other indicators.

2. Production units may discharge pollutants irresponsibly when there is neither any attached cost to such behavior nor any incentive for reducing such emissions. This

review indicates that many researchers have proposed levers for motivating decision makers to develop sustainability-oriented policies. Examples of these mechanisms include marketable pollution permits and environmental taxes.

This dissertation contributes to the literature by connecting the social standpoint to the more investigated environmental and economic perspectives. Thus far, we have sought to answer the aforementioned research questions. In Chapters 3-4, we have developed settings for evaluating supply chain operations from a sustainable perspective. Moreover, we have explored the second question in Chapter 5 and investigated market-based pollution control schemes. In this regard, we concentrate on game-theoretic formulations by which we are able to characterize the sustainable operations of a set of competitive supply chains facing an uncertain demand for their products.

In Chapter 4, we review the literature of supply chains' performance evaluation by using data envelopment analysis (DEA) as an analytical formulation to measure the relative efficiency of comparable decision making units. The proposed DEA-oriented model examines a supply chain which includes all partner types (i.e., suppliers, manufacturers, distributers, and retailers). This study also inspects various cases addressing sustainability efficiency evaluation of supply chains. The methodology we have developed in Chapter 4 can be applied to measure efficiency of operations within the supply chains as long as such the entire network is assumed to be impacted by the action of more than one partner. Although a centralized perspective has been introduced in Chapter 4, more complicated approaches of game theory could be integrated with the DEA technique in future studies. Furthermore, all indicators are assumed independent in the current chapter, while they could be generalized for practical cases that deal with correlated and non-separable direct/intermediate measures. In addition, investigating the impact of the missed data of some DMUs on the overall score and also beneficiating the privileges of super efficiency models to overcome the infeasibility and multi-efficiency appearance could be analyzed in the future.

In parallel, we have investigated another quantitative framework in Chapter 3, motivated by two-stage DEA models and concentrating on environmental and social dangers of the energy sector. Unlike the previous literature we allow for the realistic scenario where any intermediate indicator's weight in the first stage may not be equal to that in the second stage. This novel formulation introduced a nonlinear optimization problem, for which we develop an efficient algorithm. To document the practicability of the proposed framework, we seek an application of the fossil-based electricity generation industry. None of prior research has explained the impact of such plants on the society and people. This study, however, bridges the gap between network assessment frameworks and the case study from a twofold environmental-social perspective. From this work we can conclude that unless social measures are explicitly incorporated in an aggregate measure, economic and environmental measures may not accurately reflect sustainability performance. This result confirms the current trend that large corporations are making by being more transparent on reporting social metrics related to their business practices. Despite the fact that a centralized perspective has been discussed in this study, other approaches could be integrated with the DEA technique in future studies. In this respect, a possible drawback to the two-stage model is that the individual efficiency of any of the stages may not be unique at the optimality of the network efficiency. Hence, decentralized versions of this model can open up future avenues of research. Another possible extension is to consider multi-stage and multi-partner networks. This is particularly significant in light of the fact that the supply chain operations are performed in a multi-dimensional and multi-disciplinary manner in practice.

In Chapter 5, the ample literature on regional, nationwide, and international programs in establishing mechanisms that aim to curb pollution are reviewed. Many countries agree to form an international treaty to cooperatively consider measures as to how to slow the pace of global warming. The Kyoto Protocol particularly defined the industrialized countries' contractual obligations to reduce their greenhouse gas emissions in 1997, by proposing the concept of "carbon markets". We have explored such pollution control systems and focused on generalizing the standard emissions trading system (ETS). It is shown in the literature why regulatory bodies should choose such schemes in practice. The underlying logic behind any ETS is that permits put a cost on the right to pollute, due to the imposed central authority limits. From the economic perspective, business foundations and industrial sectors can determine whether it is worth to continue polluting or to reduce their pollution on the basis of market signals. We have generalized the single-product ETS by allowing the supply chains to compete in a non-cooperative manner in their multi-product markets. In addition, each supply chain as a source of pollution purchases the permits to pollute at a certain receptor point at a predetermined per unit price regulated by an upstream decision maker. In Chapter 5, we develop a Cournot competition that represents a multi-product multi-pollutant formation, where all the supply chains compete individually in their product markets and focus on maximizing profit. Having developed the supply chains' optimization problems, we introduce a systematic procedure that calculates the equilibria of the game at which no player has an incentive to deviate from its chosen strategy. More narrowly, we provide conditions under which an efficient algorithm converges to the game's unique equilibrium. Such information can be critical to the long-term future of the centralized policy maker that regulates such mechanisms. By using of the obtained solution the regulatory body is able to achieve its sustainability objectives by inspiring the firms to operate in an environmentally friendly manner, while protecting them from bankruptcy. Although a static single-period perspective has been introduced in this study, more complicated approaches of games can be investigated in future studies. Especially in the presence of leader-follower relationships between the supply chains, a Stackelberg framework can be established. In addition, we have assumed that all demand distributions follow continuous random variables, however, this assumption can be relaxed for the investigation of cases that face discrete demand behaviors. Furthermore, all demand distributions are assumed to be stochastically independent in the current setup, while they can be considered dependent for a set of products for practical cases where there is elasticity among substitute goods in the product markets. Another extension to this study is to allow the product price function to be nonlinear over the order quantity variables. For example, multiplicative pricing functions can be studied for the proposed ETS. Finally, investigating the impact of having shared partners between the supply chains and/or examining heterogeneous multi-echelon networks on the optimal policies can be analyzed in the future.

In Chapter 1, we review the relevant literature from fourteen influential journals in the operations research field in order to identify the major directions and problems that have been studied in the context of SSCM. We employ a selection of sustainability keywords in the Abstract field of these journals to search publications from 2000 to 2014. After carefully examining the results of the initial search and removing references that do not explicitly investigate supply chain applications, we end up with a list of relevant publications in the SSCM context. Within this refinement, we restrict our attention by excluding work that investigates sustainability development descriptively, marketing and human resource questions, strategic importance of SSCM, green technology innovation and product design, waste and disposal management, as well as forest management. On the basis of this review, we are able to classify the existing SSCM literature into seven broad categories: Performance Measurement in SSCM; Upstream Environmental Regulations; Carbon-constrained Inventory Problems; Closed-Loop Supply Chains (CLSCs); Green Transportation and Facility Location; Humanitarian Logistics (HL); Green Supplier Selection. Since we dig out the first two categories in this dissertation, my next research projects particularly examine the other topics. For example, in pursuing emissions reduction efforts, many businesses have focused on the physical processes involved. They, however, may neglect a significant source of emissions that can be lessened through momentous lot sizing decision makings, drawn on generalizations of the economic order quantity (EOQ) models which take into account carbon emissions. Furthermore, CLSCs combine forward and backward flows into a single system in order to improve economic and environmental performance. Given the scrupulous attention of policy makers around the world to recycling procedures, remanufacturing practices, and green disposing options, this topic will open several future research avenues. Finally, the literature of HL looks at the economic and social implications as there is ample evidence that negative impacts of natural disasters are increasing. The term HL encompasses a wide range of managerial decisions (including the distribution of medical supplies for routine disease prevention, food supplies to fight hunger, and critical supplies in the aftermath of a disaster) which provide me with an excellent line of research in future.

Appendix A

Proofs and Data of Chapter 3

A.1 Proofs

Proof of Theorem 3.1: Given the facts that $e_o^{\mathrm{HT}} = e_o^{1,\mathrm{HT}} \times e_o^{2,\mathrm{HT}}$ is obtained from (M0-A) by separating this model into two standard DEA formulations, that (M0-B) is created by adding the constraint set "$w_d = \tilde{w}_d, \forall d \in \Delta_{\mathrm{HM}}$" to (M0-A) in order to calculate e_o^{Mixed}, and that e_o^{HM} is the optimal solution of a more constrained version of (M0-B) where "$w_d = \tilde{w}_d, \forall d \in \Delta$" is satisfied, one can easily justify the results of Parts (i) and (iii). Part (ii) follows from Theorems 1 and 3 in Liang et al. (2008). ■

Proof of Theorem 3.2: For a given $o \in \{1, ..., n\}$, it is sufficient to show that the bilinear numerator and denominator of the objective function are indefinite functions. Within this proof, we always assume that $d \in \Delta = \{1, ..., D\}$. First of all consider the Hessian matrix of the numerator, which can be written as follows:

$$\mathbf{H} = \left(\begin{array}{c:c} \mathbf{0}_{D\times D} & \mathbf{F}_{D\times s} \\ \hdashline \mathbf{G}_{s\times D} & \mathbf{0}_{s\times s} \end{array}\right), \text{ where: } \mathbf{G}^t = \mathbf{F} = \begin{bmatrix} z_{1o}y_{1o} & z_{1o}y_{2o} & \cdots & z_{1o}y_{ro} & \cdots & z_{1o}y_{so} \\ \vdots & & & & & \\ z_{do}y_{1o} & z_{do}y_{2o} & \cdots & z_{do}y_{ro} & \cdots & z_{do}y_{so} \\ \vdots & & & & & \\ z_{Do}y_{1o} & z_{Do}y_{2o} & \cdots & z_{Do}y_{ro} & \cdots & z_{Do}y_{so} \end{bmatrix}$$

Now we show that $\mathbf{H}$ is an indefinite matrix. For any given vector of dimension

$(D+s)$ such as $S_H = (k_1, \dots, k_d, \dots, k_D, l_1, \dots, l_r, \dots, l_s)$ we can obtain:

$$
\begin{aligned}
Q_{\mathbf{H}} =& S_H \mathbf{H} S_H^t \\
=& \Bigg(0 + \sum_r l_r z_{1o} y_{ro}, \dots, 0 + \sum_r l_r z_{do} y_{ro}, \dots, 0 + \sum_r l_r z_{Do} y_{ro}, \\
& \sum_d k_d z_{do} y_{1o} + 0, \dots, \sum_d k_d z_{do} y_{ro} + 0, \dots, \sum_d k_d z_{do} y_{so} + 0\Bigg) S_H^t \\
=& k_1 z_{1o} \sum_r l_r y_{ro} + \ldots + k_d z_{do} \sum_r l_r y_{ro} + \ldots + k_D z_{Do} \sum_r l_r y_{ro} \\
+& l_1 y_{1o} \sum_d k_d z_{do} + \ldots + l_r y_{ro} \sum_d k_d z_{do} + \ldots + l_s y_{so} \sum_d k_d z_{do} \\
=& \left(\sum_r l_r y_{ro}\right) \times \left(\sum_d k_d z_{do}\right) + \left(\sum_d k_d z_{do}\right) \times \left(\sum_r l_r y_{ro}\right) = 2 \times \left(\sum_d k_d z_{do}\right) \times \left(\sum_r l_r y_{ro}\right)
\end{aligned}
$$

Since z_{do} and y_{ro} are nonnegative values, and on the other hand k_d and l_r can take any value, the last equation implies that $S_H \mathbf{H} S_H^t$ is not a sign-definite value, which consequently makes $\mathbf{H}$ be an indefinite matrix. Likewise, we can show that the Hessian matrix of the denominator is an indefinite matrix. ■

Proof of Theorem 3.3: Parts (I) and (II) of this theorem follow from Theorems 4.1 and 4.2, respectively, in Shen et al. (2009), with the cuts and bounds adapted to the special functions in model (M3). ■

Proof of Theorem 3.4: For a given $o \in \{1, ..., n\}$, it is sufficient to show that red$[a, b]$ and UB$(X_{a,b})$ are computed by solving several single-variable linear equations. The relevant equations for red$[a, b]$ and UB$(X_{a,b})$ are described in Theorem 3.3. Since in our problem $g(x) = Z$, from Theorem 3.3 we find that $\theta^* = \sup\{\theta \mid g(a + \theta(b - a)) < V - \varepsilon\}$ that results in $\theta^* = \frac{V - \varepsilon - a_N}{b_N - a_N}$ which completes the proof for UB$(X_{a,b})$. Likewise, we can obtain a similar formulation for computing τ. On the other hand, the following formula sets represent the analytical solutions of all equations needed to be solved in terms of variables α or β, when we compute red$[a, b]$ for (M) and its components, the variables α_k^I and β_k^I:

For all $k \in \{1, \dots, n\}$:

$$\varphi_k^I(\alpha) = \begin{cases} \left(\sum_{d=1}^{\tilde{d}} b_{d+m+D} z_{dk} + \sum_{d=\tilde{d}+1}^{D} b_{d+m} z_{dk}\right) - \alpha(b_I - a_I) z_{(I-m)k}, I = m+\tilde{d}+1, \dots, m+D \\ \left(\sum_{d=1}^{\tilde{d}} b_{d+m+D} z_{dk} + \sum_{d=\tilde{d}+1}^{D} b_{d+m} z_{dk}\right) - \alpha(b_I - a_I) z_{(I-m-D)k}, I = m+D+1, \dots, m+D+\tilde{d} \\ \sum_{d=1}^{\tilde{d}} b_{d+m+D} z_{dk} + \sum_{d=\tilde{d}+1}^{D} b_{d+m} z_{dk}, \text{otherwise} \end{cases}$$

$$\psi_k^I(\beta) = \begin{cases} \left(\sum_{r=1}^{s} a'_{r+m+2D} y_{rk}\right) + \beta(b_I - a'_I) y_{(I-m-2D)k}, I = m+2D+1, \dots, m+2D+s \\ \sum_{r=1}^{s} a'_{r+m+2D} y_{rk}, \text{otherwise} \end{cases}$$

For all $k \in \{n+1, \dots, 2n\}$:

$$\varphi_k^I(\alpha) = \begin{cases} \left(\sum_{i=1}^{m} b_i x_{i(k-n)}\right) - \alpha(b_I - a_I) x_{I(k-n)}, I = 1, \dots, m \\ \sum_{i=1}^{m} b_i x_{i(k-n)}, \text{otherwise} \end{cases}$$

$$\psi_k^I(\beta) = \begin{cases} \left(\sum_{d=1}^{D} a'_{d+m} z_{d(k-n)}\right) + \beta(b_I - a'_I) z_{(I-m)(k-n)}, I = m+1, \dots, m+D \\ \sum_{d=1}^{D} a'_{d+m} z_{d(k-n)}, \text{otherwise} \end{cases}$$

For all $k = 2n+1$:

$$\varphi_k^I(\alpha) = \nu_{2n+1}^{+}(b - \alpha(b_I - a_I)e^I) = H^{+}(b - \alpha(b_I - a_I)e^I) = 1$$

$$\psi_k^I(\beta) = \nu_{2n+1}^{-}(a' + \beta(b_I - a'_I)e^I) = H^{-}(a' + \beta(b_I - a'_I)e^I)$$

$$= \begin{cases} a'_{N_0+1} \cdot \left(\left(\sum_{i=1}^{m} a'_i x_{io}\right) + \beta(b_I - a'_I) x_{Io}\right) \cdot \left(\sum_{d=1}^{\tilde{d}} a'_{d+m+D} z_{do} + \sum_{d=\tilde{d}+1}^{D} a'_{d+m} z_{do}\right), I = 1, \dots, m \\ a'_{N_0+1} \cdot \sum_{i=1}^{m} a'_i x_{io} \cdot \left(\left(\sum_{d=1}^{\tilde{d}} a'_{d+m+D} z_{do} + \sum_{d=\tilde{d}+1}^{D} a'_{d+m} z_{do}\right) + \beta(b_I - a'_I) z_{(I-m)o}\right), I = m+\tilde{d}+1, \dots, m+\tilde{d} \\ a'_{N_0+1} \cdot \sum_{i=1}^{m} a'_i x_{io} \cdot \left(\left(\sum_{d=1}^{\tilde{d}} a'_{d+m+D} z_{do} + \sum_{d=\tilde{d}+1}^{D} a'_{d+m} z_{do}\right) + \beta(b_I - a'_I) z_{(I-m-D)o}\right), I = m+D+1, \dots, m+D+\tilde{d} \\ \left(a'_{N_0+1} + \beta(b_{N_0+1} - a'_{N_0+1})\right) \cdot \sum_{i=1}^{m} a'_i x_{io} \cdot \left(\sum_{d=1}^{\tilde{d}} a'_{d+m+D} z_{do} + \sum_{d=\tilde{d}+1}^{D} a'_{d+m} z_{do}\right), I = m+D+\tilde{d}+s+1 = N_0+1 \\ a'_{N_0+1} \cdot \sum_{i=1}^{m} a'_i x_{io} \cdot \left(\sum_{d=1}^{\tilde{d}} a'_{d+m+D} z_{do} + \sum_{d=\tilde{d}+1}^{D} a'_{d+m} z_{do}\right), \text{otherwise} \end{cases}$$

For all $k = 2n+2 = K_0$:

$$\varphi_k^I(\alpha) = \nu_{2n+2}^{+}(b - \alpha(b_I - a_I)e^I) = G^{-}(b - \alpha(b_I - a_I)e^I)$$

$$= \begin{cases} b_{N_0+1} \cdot \left(\left(\sum_{d=1}^{D} b_{d+m} z_{do}\right) - \alpha(b_I - a_I) z_{(I-m)o}\right) \cdot \sum_{r=1}^{s} b_{r+m+2D} y_{ro} + b_{N_0+2}, I = m+1, \dots, m+D \\ b_{N_0+1} \cdot \sum_{d=1}^{D} b_{d+m} z_{do} \cdot \left(\left(\sum_{r=1}^{s} b_{r+m+2D} y_{ro}\right) - \alpha(b_I - a_I) y_{(I-m-2D)o}\right) + b_{N_0+2}, I = m+2D+1, \dots, m+2D+s \\ (b_{N_0+1} - \alpha(b_{N_0+1} - a_{N_0+1})) \cdot \sum_{d=1}^{D} b_{d+m} z_{do} \cdot \sum_{r=1}^{s} b_{r+m+2D} y_{ro} + b_{N_0+2}, I = m+2D+s+1 = N_0+1 \\ b_{N_0+1} \cdot \sum_{d=1}^{D} b_{d+m} z_{do} \cdot \sum_{r=1}^{s} b_{r+m+2D} y_{ro} + (b_{N_0+2} - \alpha(b_{N_0+2} - a_{N_0+2})), I = m+2D+s+2 = N_0+2 \\ b_{N_0+1} \cdot \sum_{d=1}^{D} b_{d+m} z_{do} \cdot \sum_{r=1}^{s} b_{r+m+2D} y_{ro} + b_{N_0+2}, \text{otherwise} \end{cases}$$

$$\psi_k^I(\beta) = \nu_{2n+2}^{-}(a' + \beta(b_I - a'_I)e^I) = 0$$

For all $k = 2n + 2 + 1 = K_0 + 1$:

$$\gamma_k^I(\beta) = g(a' + \beta(b_I - a'_I)e^I) = \begin{cases} a'_{N_0+2} + \beta(b_{N_0+2} - a'_{N_0+2}), I = N_0 + 2 \\ a'_{N_0+2}, \text{otherwise.} \end{cases}$$

■

A.2 Branch-Reduce-Bound Algorithm for (P)

Step 0: Initialization

Iter $\leftarrow 0$; UsedColumnsOfQ $\leftarrow 0$; UsedColumnsOfF $\leftarrow 0$; UsedColumnsOfF$'$ $\leftarrow 0$

$\varepsilon > 0$ is given; $X_0 = [x^l, x^u] \subseteq \mathbb{R}^N$ is given; MaxIteration is given

$[a, b] \leftarrow X_0$; $V \leftarrow g(x^u) + \varepsilon$; $Q \leftarrow \{X_0\}$; UsedColumnsOfQ $\leftarrow$ UsedColumnsOfQ $+ 1$; $F \leftarrow \emptyset$

Step 1: Reduction Cut

Iter $\leftarrow$ Iter $+ 1$; If Iter $>$ MaxIteration, terminate

$\bar{Q} \leftarrow \emptyset$; Counter $\leftarrow 0$; WhileCounter $\leftarrow 0$

While $\bar{Q} \neq \emptyset$ ($\equiv$ "UsedColumnsOfQ $>$ WhileCounter")

  WhileCounter $\leftarrow$ WhileCounter $+ 1$

  Select $\widetilde{X} \in Q$; Assume $\widetilde{X} = [\widetilde{a}, \widetilde{b}] \subseteq \mathbb{R}^N$

  $[a, b] \leftarrow [\widetilde{a}, \widetilde{b}]$

  Compute red$\widetilde{X}$ = red$[a, b]$; Assume red$\widetilde{X} = [a', b'] \subseteq \mathbb{R}^N$

  If red$\widetilde{X} = \emptyset$

    $Q \leftarrow Q \setminus \{\widetilde{X}\}$

   Else

    $Q \leftarrow Q \setminus \{\widetilde{X}\}$

    $[a, b] \leftarrow$ red$\widetilde{X} = [a', b']$

    Compute UB(red$\widetilde{X}$) = UB($X_{a,b}$)

    If UB(red$\widetilde{X}$) ≥ 0

      $\bar{Q} \leftarrow \bar{Q} \cup \{red\widetilde{X}\}$; Counter $\leftarrow$ Counter $+ 1$

UsedColumnsOfQ $\leftarrow$ Counter & $Q \leftarrow \bar{Q}$

Step 2: Fathoming

$Q' \leftarrow Q$; $F' \leftarrow Q' \cup F$; UsedColumnsOfF$'$ $\leftarrow$ UsedColumnsOfQ + UsedColumnsOfF

If $F' = \emptyset$

  If $V = g(x^u) + \varepsilon$, then (P) is a nonisolated infeasible problem

   Else $\hat{x}$ is a nonisolated ε-optimal solution of (P) with $g(\hat{x}) = V$

  Terminate

 Else

  Since $\{\text{UB}(X_1) | X_1 \in F'\} \neq \emptyset$, select $\widetilde{\widetilde{X}} \in F'$ such that $\widetilde{\widetilde{X}} \in \text{argmax}\{\text{UB}(X_1) | X_1 \in F'\}$

$[a, b] \leftarrow \tilde{\tilde{X}}$; $\tilde{\tilde{\mathrm{UB}}} \leftarrow \mathrm{UB}(\tilde{\tilde{X}}) = \mathrm{UB}(X_{a,b})$

Step 3: Optimality Check

If $\tilde{\tilde{\mathrm{UB}}} < \varepsilon$

If $V = g(x^u) + \varepsilon$, then (P) is a nonisolated infeasible problem

Else $\hat{x}$ is a nonisolated ε-optimal solution of (P) with $g(\hat{x}) = V$

Terminate

Step 4: Updating the Best Feasible Solution (so far)

If $g(b) > V - \varepsilon$

$\tau \leftarrow \sup\{\tau \mid g(a + \tau(b - a)) < V - \varepsilon\} \in \mathbb{R}^1$; $\hat{\hat{x}} \leftarrow a + \tau(b - a) \in \mathbb{R}^N$

Else

$\hat{\hat{x}} \leftarrow a$

If $h(\hat{\hat{x}}) \geq 0$

$\hat{\hat{x}}$ is a new better feasible solution of (M) with $g(\hat{\hat{x}}) \leq V - \varepsilon$

$\hat{x} \leftarrow \hat{\hat{x}}$; $V \leftarrow g(\hat{x})$

Step 5: Partitioning

Divide $\tilde{\tilde{X}}$ into two sub-rectangles, say $\tilde{\tilde{X}}_{[1]}$ and $\tilde{\tilde{X}}_{[2]}$

$Q \leftarrow \{\tilde{\tilde{X}}_{[1]}, \tilde{\tilde{X}}_{[2]}\}$; UsedColumnsOfQ $\leftarrow 2$

$F \leftarrow F' \setminus \{\tilde{\tilde{X}}\}$; UsedColumnsOfF $\leftarrow$ UsedColumnsOfF$' - 1$

Return to **Step 1**

A.3 Real Data of the Power Plant Case Study

Appendix A.3: Real Data relating to the Power Plant case study

Plant	Performance Indicators																
	x_1	x_2	x_3	x_4	z_1	z_2	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
1	26751918	720728479	103256497	706.8	2369865	107	17	26	290	12	10	18	2518045	13303	6199	7091	2121
2	127139462	3269038117	489700658	2932.6	12969046	333	19	30	300	14	11	15	11850123	61771	28768	3133	3240
3	9821651	115786047	32726699	152.5	792166	46	3	5	60	2	2	3	1027389	5086	227	2449	2232
4	14066065	108895412	59095375	551.3	1931407	21	1	1	8	1	1	1	652495	375	254	4	58
5	51580001	663775666	315280842	1475.8	6858053	146	13	18	140	9	7	8	2789007	1608	1087	20	748
6	3442319	61652321	14099918	67.2	192411	34	1	1	8	1	1	1	22972	4331	2222	68	255
7	28604435	597604826	114877152	559.0	3998496	26	1	1	12	1	1	1	1541615	886	600	9	106
8	128456949	1805748482	582043937	2160.2	13990125	168	23	35	380	17	14	20	12047697	29897	64196	4075	4955
9	77177866	1660890317	230741415	1664.4	7437274	189	55	89	860	41	33	45	7560202	37685	17556	24869	8446
10	10270553	72150049	40500477	330.0	1199452	18	10	11	150	6	5	9	560859	315	213	3	147
11	100180048	1923182895	448670789	1884.5	9556350	384	11	15	160	8	6	9	10300110	49525	23059	9158	4779
12	27146927	551473236	118078520	1096.8	2661344	124	46	71	720	34	27	38	2479256	12876	5991	19699	2067
13	30900957	200716784	66614906	457.0	2830363	143	13	20	210	9	8	13	2876940	14989	6980	12290	10579
14	14569568	179109771	49177464	601.6	1390349	46	9	14	150	6	6	9	1433087	7051	328	2796	6056
15	26587206	736575539	87942357	642.2	2640259	110	4	5	65	2	2	1	2491386	12967	6038	11463	2704
16	31912972	214166607	109065347	499.5	3090433	97	4	6	73	3	2	3	3006529	15612	7270	1357	6871
17	76283955	1082468220	158080329	1073.3	7260677	209	16	24	260	11	10	16	7743024	40285	1710	4645	4625
18	95288891	2761061261	647944820	3540.4	9565786	390	16	22	270	11	10	16	9558661	50867	23684	3119	4651

Indicators. x_1: Annual Fuel Consumed (MMBTU); x_2: Book Value of Plant and Land ($); x_3: Annual Production Expenses ($); x_4: Plant Nameplate Capacity (MW); z_1: Annual Electricity Net Generation (MWH); z_2: Annual Number of Employees; y_1: Annual Incidence of Deaths; y_2: Annual Incidence of Heart Attacks; y_3: Annual Incidence of Asthma Attacks; y_4: Annual Incidence of Hospital Admissions; y_5: Annual Incidence of Chronic Bronchitis; y_6: Annual Incidence of Asthma ER Visits; y_7: Carbon Dioxide (CO_2) Emission (TON); y_8: Nitrous Oxide (N_2O) Emission (TON); y_9: Methane (CH_4) Emission (TON); y_{10}: Sulfur Dioxide (SO_2) Emission (TON); y_{11}: Nitrogen Oxides (NO_x) Emission (TON)

Appendix A.3: Real Data relating to the Power Plant case study

Plant	Performance Indicators																
	x_1	x_2	x_3	x_4	z_1	z_2	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
19	13121280	110729445	24746896	290.8	1164975	39	11	17	180	8	7	11	1330947	6924	3225	4697	1035
20	29175004	360311377	112948018	660.9	2666614	122	18	27	290	13	11	17	2657469	15042	7193	6127	4737
21	14520863	132570769	38540031	188.6	1287240	66	5	8	120	4	4	5	1391161	7410	3451	8307	3615
22	73673164	1983731164	240285849	1880.4	7372305	320	48	79	750	36	28	37	6852969	35579	16553	8144	2270
23	74092129	673231413	112105022	1128.8	6984860	52	10	16	190	7	7	9	7682732	40940	19067	6174	9300
24	64215828	681118185	247763167	1303.8	5945617	394	140	220	2300	100	86	140	5689399	29658	13812	52839	13816
25	44134339	1222185401	178495642	848.0	4400124	139	9	14	150	7	6	8	3958722	21870	10184	1875	6694
26	56056543	1241116895	159377705	1005.4	5060276	158	3	4	46	2	2	3	5153913	26865	12512	103	1974
27	62821348	1438413933	280015777	1890.8	5789044	300	48	78	740	36	28	39	6130469	31954	14882	12881	8463
28	18728833	527870674	106457769	417.3	1988813	66	5	7	83	4	3	5	1676354	8914	4150	1322	1061
29	31349240	1499929858	207200482	1135.1	2770727	225	6	9	110	5	4	6	3193221	14910	6973	942	2605
30	11155632	65555524	37380390	519.2	1040784	49	1	1	5	1	1	1	603016	347	235	3	769
31	16026833	373369290	121190921	566.9	2132523	19	1	1	1	1	1	1	867628	498	337	5	70
32	35404738	648591048	123607362	669.3	3184661	92	8	13	140	6	5	8	3019155	16089	7493	1497	2939
33	35191334	475088556	93681759	716.2	3074438	170	30	63	430	28	24	16	2131431	1250	836	39	855
34	18658087	439008695	67821146	368.9	1693312	90	7	10	110	5	4	7	1960561	10553	4915	2116	1384
35	55549402	1066618718	219411991	1152.0	5554695	161	36	59	550	28	21	27	5070717	26410	1125	3422	7962
36	68462304	567979147	335375181	2827.5	9189309	43	5	7	52	4	2	3	4279338	2466	1668	31	935

Indicators. x_1: Annual Fuel Consumed (MMBTU); x_2: Book Value of Plant and Land ($); x_3: Annual Production Expenses ($); x_4: Plant Nameplate Capacity (MW); z_1: Annual Electricity Net Generation (MWH); z_2: Annual Number of Employees; y_1: Annual Incidence of Deaths; y_2: Annual Incidence of Heart Attacks; y_3: Annual Incidence of Asthma Attacks; y_4: Annual Incidence of Hospital Admissions; y_5: Annual Incidence of Chronic Bronchitis; y_6: Annual Incidence of Asthma ER Visits; y_7: Carbon Dioxide (CO_2) Emission (TON); y_8: Nitrous Oxide (N_2O) Emission (TON); y_9: Methane (CH_4) Emission (TON); y_{10}: Sulfur Dioxide (SO_2) Emission (TON); y_{11}: Nitrogen Oxides (NO_x) Emission (TON)

Appendix A.3: Real Data relating to the Power Plant case study

Plant	Performance Indicators																
	x_1	x_2	x_3	x_4	z_1	z_2	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
37	15323643	152775059	47517126	781.4	1398918	37	2	2	30	1	1	2	825919	475	322	5	1520
38	32040852	1018530493	200821502	1416.7	3052678	289	10	13	160	7	6	10	2938697	15660	7293	3220	3260
39	11214031	82915582	39001902	188.6	906273	47	43	64	700	31	26	42	914309	6699	2888	18990	2066
40	39549759	548509384	121578010	1197.5	3784659	154	79	120	1300	58	48	81	3848857	20220	9424	21542	3109
41	27008395	249418329	41417464	438.6	2477127	70	4	6	72	3	3	4	2628300	13992	594	1819	5129
42	13350444	383831198	63763651	644.0	1853376	28	3	5	50	2	2	3	730419	420	285	4	90
43	92952250	1102795750	557025132	2262.5	12998510	68	4	6	64	3	2	4	4902017	2820	1910	28	674
44	67865197	824779006	129043419	996.0	6744160	161	4	6	83	3	3	3	6170602	32873	15309	2300	7391
45	183324192	3350771050	546251084	2822.0	17625767	346	8	11	130	6	5	8	18411481	95980	44700	737	6934
46	140442620	1596370879	388371470	2317.7	13625135	341	23	35	440	16	15	20	13603271	70887	33012	9975	13762
47	20209519	188709405	74292930	677.7	1868376	32	2	3	45	2	2	3	1090383	629	425	6	1008
48	7893668	156896824	42490537	352.4	622885	85	2	3	40	2	1	2	467522	489	256	1190	920
49	47318495	1217022377	185480232	1086.5	4688606	450	18	28	280	13	11	14	5133053	26759	12462	4989	4579
50	157051781	1183121575	332835148	2389.4	15350931	278	78	120	1300	56	48	85	14074467	73370	34170	42235	7306
51	20786764	356733564	154981555	591.3	2890938	25	5	7	160	3	4	3	1142784	657	445	6	84
52	13668993	377053536	40436442	314.0	1136806	50	11	17	180	8	6	11	1260818	6558	3053	4477	949
53	4911122	86197773	17318723	116.0	368366	41	1	2	16	1	1	1	466508	2409	103	262	431
54	3229846	40241734	10075992	50.0	254009	27	1	1	14	1	1	1	303650	1526	65	600	598

Indicators. x_1: Annual Fuel Consumed (MMBTU); x_2: Book Value of Plant and Land (\$); x_3: Annual Production Expenses (\$); x_4: Plant Nameplate Capacity (MW); z_1: Annual Electricity Net Generation (MWH); z_2: Annual Number of Employees; y_1: Annual Incidence of Deaths; y_2: Annual Incidence of Heart Attacks; y_3: Annual Incidence of Asthma Attacks; y_4: Annual Incidence of Hospital Admissions; y_5: Annual Incidence of Chronic Bronchitis; y_6: Annual Incidence of Asthma ER Visits; y_7: Carbon Dioxide (CO_2) Emission (TON); y_8: Nitrous Oxide (N_2O) Emission (TON); y_9: Methane (CH_4) Emission (TON); y_{10}: Sulfur Dioxide (SO_2) Emission (TON); y_{11}: Nitrogen Oxides (NO_x) Emission (TON)

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55	92254154	1333848127	431585744	1996.0	9614619	143	28	42	470	21	17	26	8947306	47679	22205	4599	11027
56	26355730	286593117	66561218	468.5	2421770	30	4	6	79	3	3	5	1252667	807	547	8	409
57	82749048	1912257008	356458321	2603.6	11980556	75	27	38	460	19	17	28	4687805	2935	1931	424	308
58	12933647	663549076	80801019	496.4	1186281	109	2	4	32	2	1	1	1266512	5941	2767	1004	1834
59	84973104	1058233226	270478380	1344.0	8307828	181	81	120	1300	59	49	78	7531325	40132	18691	26407	6853
60	26838455	157067880	99210854	959.2	2346145	41	2	2	29	1	1	2	1446676	832	564	8	2000
61	88893163	1129744918	271120132	1717.2	8361161	228	74	110	1200	54	45	72	7978346	45172	21600	30499	7219
62	8054895	98072742	56907163	319.0	1107026	17	1	1	2	1	1	1	433435	249	169	5	33
63	19882496	267640707	66677399	564.0	1801535	125	13	20	220	10	8	14	1974646	10294	436	6445	2530
64	82694563	1553184938	274005472	1300.0	8292574	200	12	18	180	9	7	9	7915140	41242	19205	1151	2264
65	48849533	656847913	186303387	1036.8	6586447	50	1	1	11	1	1	1	2541543	1461	990	14	125
66	27789093	396117937	118477750	913.0	2761614	70	2	4	76	2	2	4	1572489	888	602	9	1731
67	58650018	796096203	172159946	1234.8	5521461	157	33	51	560	24	20	35	5330573	27788	12942	16519	3004
68	7057937	237494598	28635757	328.0	820513	24	8	16	270	8	8	19	349609	102	69	2	55
69	19596178	547968427	98366002	559.0	2793674	29	2	3	38	1	1	1	1061560	610	413	6	53
70	34211852	562640945	68751183	552.3	3264261	79	12	19	230	9	8	12	3376422	17554	745	13510	3474
71	103834954	1741917518	310327731	2154.8	9640905	279	41	62	680	29	25	42	9282181	49463	23036	15463	9293
72	7182068	239726671	21937781	213.4	558877	59	6	10	110	5	4	7	1161616	5692	2034	2615	1400

Indicators. x_1: Annual Fuel Consumed (MMBTU); x_2: Book Value of Plant and Land (\$); x_3: Annual Production Expenses (\$); x_4: Plant Nameplate Capacity (MW); z_1: Annual Electricity Net Generation (MWH); z_2: Annual Number of Employees; y_1: Annual Incidence of Deaths; y_2: Annual Incidence of Heart Attacks; y_3: Annual Incidence of Asthma Attacks; y_4: Annual Incidence of Hospital Admissions; y_5: Annual Incidence of Chronic Bronchitis; y_6: Annual Incidence of Asthma ER Visits; y_7: Carbon Dioxide (CO_2) Emission (TON); y_8: Nitrous Oxide (N_2O) Emission (TON); y_9: Methane (CH_4) Emission (TON); y_{10}: Sulfur Dioxide (SO_2) Emission (TON); y_{11}: Nitrogen Oxides (NO_x) Emission (TON)

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Plant	**Performance Indicators**																
	x_1	x_2	x_3	x_4	z_1	z_2	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
73	22760332	368745293	89495335	450.0	1900500	155	14	22	220	10	8	13	2235867	11654	494	6028	3695
74	6383713	88661839	18898344	115.0	476956	48	4	6	68	3	2	4	616752	3098	136	1868	967
75	8725598	56821580	40353645	266.5	753874	47	1	1	6	1	1	1	470857	271	183	3	746
76	18414155	375987803	92163541	685.1	2451436	29	1	1	30	1	1	1	1015516	584	395	6	63
77	145709649	1791535277	585023592	2558.2	13962988	246	47	73	780	36	29	41	13204371	70371	35279	13373	13068
78	72674153	810464068	386864752	2377.8	9692848	62	4	6	80	3	3	5	3939755	2267	1536	22	1089
79	6822308	218248642	36671097	171.2	433209	80	1	2	17	1	1	1	118779	7464	7464	736	345
80	88028875	1270899864	266029612	2469.3	8234518	292	48	78	840	36	31	55	8417116	43860	1860	10376	8344
81	23065380	420188163	78228202	524.0	2210495	121	4	7	75	3	3	5	2110480	11002	466	6095	1945
82	50619261	1225394483	146880654	1099.4	4905611	183	19	29	320	14	12	21	4494488	23417	10904	2658	5878
83	2588904	140277795	11629930	119.1	222604	22	2	2	25	1	1	2	294591	1000	463	1769	467
84	10194734	156873649	32356447	252.0	872319	42	6	10	100	5	4	6	1054878	5494	234	2656	1198
85	11449304	49818571	40162051	411.8	975145	24	1	1	11	1	1	1	605487	348	236	3	1030
86	36222417	341389115	130969134	775.5	3454942	145	58	93	920	43	34	50	3539061	18098	8427	22426	4487
87	8534786	62348387	31010103	122.5	734454	15	5	7	82	4	3	5	479355	268	181	2	194
88	1110963770	639497340	244781964	1674.0	10280099	132	26	39	450	19	16	28	10331936	53860	25084	23212	10074
89	36195556	680528177	174750171	686.5	3723042	85	5	8	88	4	3	5	3163778	16828	7862	1032	1747
90	7083441	184554669	13970847	95.0	587832	40	1	1	6	1	1	1	676276	3525	149	165	222

Indicators. x_1: Annual Fuel Consumed (MMBTU); x_2: Book Value of Plant and Land ($); x_3: Annual Production Expenses ($); x_4: Plant Nameplate Capacity (MW); z_1: Annual Electricity Net Generation (MWH); z_2: Annual Number of Employees; y_1: Annual Incidence of Deaths; y_2: Annual Incidence of Heart Attacks; y_3: Annual Incidence of Asthma Attacks; y_4: Annual Incidence of Hospital Admissions; y_5: Annual Incidence of Chronic Bronchitis; y_6: Annual Incidence of Asthma ER Visits; y_7: Carbon Dioxide (CO_2) Emission (TON); y_8: Nitrous Oxide (N_2O) Emission (TON); y_9: Methane (CH_4) Emission (TON); y_{10}: Sulfur Dioxide (SO_2) Emission (TON); y_{11}: Nitrogen Oxides (NO_x) Emission (TON)

Appendix B

Proofs and Data of Chapter 4

B.1 Proofs

Proof of Proposition 4.1: For a given $p \in \mathbb{J} = \{1, ..., \bar{n}\}$, let vectors $(\lambda^*, \beta^*, \delta^*, \gamma^*)$, $(\mathbf{s}^{-*}, \mathbf{s}^{+*})$, and $(\theta_p^{*S(\alpha)}, \theta_p^{*M(\pi)}, \theta_p^{*D(\eta)}, \theta_p^{*R(\varphi)})$ denote the optimal solution of (4.6), which is consequently feasible for this model. Provided that the vector $(\mathbf{s}^{-*}, \mathbf{s}^{+*})$ is appropriately partitioned into $(s_{i\alpha}^{-*}, s_{r\alpha}^{+*}, s_{m\alpha\pi}^{-}, \ldots, s_{i\pi}^{-*}, \ldots, s_{i\eta}^{-*}, \ldots, s_{i\varphi}^{-*}, \ldots)$, based on the slacks of all models of type (4.4), we can form $(\theta_p^{*S(\alpha)}, \lambda_j, s_{i\alpha}^{-*}, \ldots)$, $(\theta_p^{*M(\pi)}, \beta_j, s_{i\pi}^{-*}, \ldots)$, $(\theta_p^{*D(\eta)}, \delta_j, s_{i\eta}^{-*}, \ldots)$, and $(\theta_p^{*R(\varphi)}, \gamma_j, s_{i\varphi}^{-*}, \ldots)$. These four vectors construct a feasible solution (not necessarily optimal) of the models obtained by (4.4). As a result we have:

$$\begin{aligned}
\theta_p^* =& \frac{\sum_\alpha w^{S(\alpha)}\theta_p^{*S(\alpha)} + \sum_\pi w^{M(\pi)}\theta_p^{*M(\pi)} + \sum_\eta w^{D(\eta)}\theta_p^{*D(\eta)} + \sum_\varphi w^{R(\varphi)}\theta_p^{*R(\varphi)}}{\sum_\alpha w^{S(\alpha)} + \sum_\pi w^{M(\pi)} + \sum_\eta w^{D(\eta)} + \sum_\varphi w^{R(\varphi)}} \\
\geq& \frac{\sum_\alpha w^{S(\alpha)}\mu_p^{*S(\alpha)} + \sum_\pi w^{M(\pi)}\mu_p^{*M(\pi)} + \sum_\eta w^{D(\eta)}\mu_p^{*D(\eta)} + \sum_\varphi w^{R(\varphi)}\mu_p^{*R(\varphi)}}{\sum_\alpha w^{S(\alpha)} + \sum_\pi w^{M(\pi)} + \sum_\eta w^{D(\eta)} + \sum_\varphi w^{R(\varphi)}} = \mu_p^* \qquad \blacksquare
\end{aligned}$$

Proof of Proposition 4.2: For a given $p \in \mathbb{J} = \{1, ..., \bar{n}\}$, assume each of the models of the type (4.4) has been solved and the optimal solutions have been noted by the vectors $(\lambda^*, \beta^*, \delta^*, \gamma^*)$, $(\mathbf{s}^{-*}, \mathbf{s}^{+*})$, and $(\mu_p^{*S(\alpha)}, \mu_p^{*M(\pi)}, \mu_p^{*D(\eta)}, \mu_p^{*R(\varphi)})$. Since there is only one partner in each stage, viz $|\mathrm{A}| = |\Pi| = |\mathrm{H}| = |\Phi| = 1$, vectors $(\mu_p^{*S(\alpha)}, \lambda_j, s_{i\alpha}^{-*}, \ldots)$, $(\mu_p^{*M(\pi)}, \beta_j, s_{i\pi}^{-*}, \ldots)$, $(\mu_p^{*D(\eta)}, \delta_j, s_{i\eta}^{-*}, \ldots)$, and $(\mu_p^{*R(\varphi)}, \gamma_j, s_{i\varphi}^{-*}, \ldots)$ provide a feasible solution of (4.6), which correspond to the supplier, manufacturer, distributer, and retailer segments of this model, respectively. Analogous to the rationale used in Proposition 4.1, we get $\mu_p^* \geq \theta_p^*$. Together with the previous result, we conclude that $\mu_p^* = \theta_p^*$. $\blacksquare$

B.2 Real Data of the Bank Case Study

B.2: Real data of the Bank case adopted from Liang et al. (2008)

DMU	Performance Indicators					
	x_1^1	x_2^1	x_3^1	z_1	y_1^2	y_2^2
1	0.713	0.150	13.300	14.478	0.232	0.986
2	1.071	0.170	16.900	19.502	0.340	0.986
3	1.224	0.235	24.000	20.952	0.363	0.986
4	0.363	0.211	15.600	13.902	0.211	0.982
5	0.409	0.133	18.485	15.206	0.237	0.984
6	5.846	0.497	56.420	81.186	1.103	0.955
7	0.918	0.060	56.420	81.186	1.103	0.986
8	1.235	0.071	12.000	11.441	0.199	0.985
9	18.120	1.500	89.510	124.072	1.858	0.972
10	1.821	0.120	19.800	17.425	0.274	0.983
11	1.915	0.120	19.800	17.425	0.274	0.983
12	0.874	0.050	13.100	14.342	0.177	0.985
13	6.918	0.370	12.500	32.491	0.648	0.945
14	4.432	0.440	41.900	47.653	0.639	0.979
15	4.504	0.431	41.100	52.630	0.741	0.981
16	1.241	0.110	14.400	17.493	0.243	0.988
17	0.450	0.053	7.600	9.512	0.067	0.980
18	5.892	0.345	15.500	42.469	1.002	0.948
19	0.973	0.128	12.600	18.987	0.243	0.985
20	0.444	0.055	5.900	7.546	0.153	0.987
21	0.508	0.057	5.700	7.595	0.123	0.987
22	0.370	0.098	14.100	16.906	0.233	0.981
23	0.395	0.104	14.600	17.264	0.263	0.983
24	2.680	0.206	19.600	36.430	0.601	0.982
25	0.781	0.067	10.500	11.581	0.120	0.987
26	0.872	0.100	12.100	22.207	0.248	0.972
27	1.757	0.011	12.700	20.670	0.253	0.988

Indicators. x_1^1: Fixed Assets (B$); x_2^1: IT Budget (B$); x_3^1: Numbers of Employees (1000); z_1: Deposits Generated (B$); y_1^2: Profit (B$); y_2^2: Fraction of Loans Recovered

B.3 Real Data of the Beverage Case Study

B.3: Real data of the Beverage case adopted from Mirhedayatian et al. (2014)

DMU	Name	Performance Indicators							
		$x_1^{Sup.}$	$x_2^{Sup.}$	$y_1^{Sup.}$	$z_{t.1}^{Sup\text{-}Man}$	$x_1^{Man.}$	$x_2^{Man.}$	$x_3^{Man.}$	$1/y_1^{Man.}$
1	Behnoush	290.0	220.0	1,250.0	999,961.0	104.0	139.0	394.0	0.00645
2	Abali	300.0	345.0	1,295.0	999,966.0	125.0	125.0	452.0	0.00599
3	Kafir	288.0	350.0	1,320.0	999,954.0	110.0	155.0	329.0	0.00654
4	Zam	320.0	330.0	1,259.0	999,968.0	105.0	132.0	442.0	0.00556
5	Khazar	290.0	275.0	1,320.0	999,947.0	135.0	149.0	526.0	0.00599
6	Damdaran	340.0	210.0	1,349.0	999,938.0	142.0	176.0	349.0	0.00641
7	Sara	325.0	370.0	1,329.0	999,961.0	159.0	125.0	527.0	0.00562
8	Ramak	330.0	250.0	1,276.0	999,955.0	130.0	192.0	397.0	0.00549
9	Pegah	349.0	320.0	1,293.0	999,928.0	115.0	156.0	309.0	0.00599
10	Varna	295.0	335.0	1,302.0	999,958.0	100.0	145.0	403.0	0.00575

B.3: Real data of the Beverage case adopted from Mirhedayatian et al. (2014)

DMU	Name	**Performance Indicators**							
		$y_2^{Man.}$	$z_{f.1}^{Man\text{-}Dis}$	$x_1^{Dis.}$	$x_2^{Dis.}$	$y_1^{Dis.}$	$z_{e.1}^{Dis\text{-}Ret}$	$x_1^{Ret.}$	$y_1^{Ret.}$
1	Behnoush	3.0	490.0	127.0	29.0	170.0	9,590.0	102.0	4.0
2	Abali	2.0	523.0	147.0	32.0	189.0	9,721.0	112.0	2.0
3	Kafir	3.0	539.0	247.0	28.0	172.0	10,372.0	130.0	3.0
4	Zam	3.0	597.0	147.0	35.0	193.0	10,333.0	100.0	4.0
5	Khazar	2.0	479.0	184.0	32.0	219.0	9,742.0	139.0	4.0
6	Damdaran	3.0	623.0	194.0	35.0	189.0	11,036.0	149.0	3.0
7	Sara	3.0	589.0	204.0	29.0	190.0	11,553.0	147.0	4.0
8	Ramak	2.0	532.0	215.0	26.0	153.0	10,846.0	125.0	2.0
9	Pegah	3.0	508.0	167.0	37.0	189.0	10,423.0	130.0	3.0
10	Varna	3.0	639.0	156.0	30.0	210.0	10,467.0	104.0	2.0

B.4 Data Set of the Two-Supplier Case Study

B.4: Data set of the Beverage case's two suppliers including their new randomly-generated intermediate

DMU	Name	**Supplier 1's Performance Indicators**					**Supplier 2's Performance Indicators**				
		x_1^{Sup1}	x_2^{Sup1}	y_1^{Sup1}	$z_{t.1}^{Sup1\text{-}Man}$	$z_{t.2}^{Sup1\text{-}Man}$	x_1^{Sup2}	x_2^{Sup2}	y_1^{Sup2}	$z_{t.1}^{Sup2\text{-}Man}$	$z_{t.2}^{Sup2\text{-}Man}$
1	Behnoush	290.0	220.0	1,250.0	999,961.0	483,342.7	25,920.3	3,790.3	14,322.8	143,477.3	584.2
2	Abali	300.0	345.0	1,295.0	999,966.0	65,421.0	32,671.9	5,779.0	46,371.3	184,987.1	407.7
3	Kafir	288.0	350.0	1,320.0	999,954.0	486,457.8	807.9	15,821.9	21,464.1	215,020.8	656.9
4	Zam	320.0	330.0	1,259.0	999,968.0	986,359.8	80,655.3	16,174.3	43,863.5	209,565.9	58.8
5	Khazar	290.0	275.0	1,320.0	999,947.0	928,035.4	339.8	14,959.3	38,837.2	162,750.0	314.8
6	Damdaran	340.0	210.0	1,349.0	999,938.0	642,430.8	78,325.0	5,895.1	56,071.7	189,519.4	151.1
7	Sara	325.0	370.0	1,329.0	999,961.0	697,244.8	28,612.0	5,124.5	54,115.9	57,393.4	171.4
8	Ramak	330.0	250.0	1,276.0	999,955.0	989,770.9	24,062.6	839.4	49,800.0	127,003.5	711.1
9	Pegah	349.0	320.0	1,293.0	999,928.0	624,045.2	15,776.0	7,736.7	38,404.8	243,092.0	340.5
10	Varna	295.0	335.0	1,302.0	999,958.0	207,894.1	20,031.1	10,708.2	41,645.2	102,310.6	133.3

Appendix C

Proofs and Data of Chapter 5

C.1 Proofs

Proof of Theorem 5.1: The reader is referred to Theorem 17.79 in Maschler et al. (2013). ■

Proof of Theorem 5.2: The reader is referred to Theorem 3.8.4 in Peleg and Sudhölter (2007). ■

Proof of Proposition 5.1: It is easy to see that $\mathbf{X} = (0, 0, \ell^0_{pkc})$ satisfies all the inequalities in (5.4). ■

Proof of Corollary 5.1: Theorem 5.2 and Proposition 5.1 immediately complete the proof. ■

Proof of Corollary 5.2: Since $\Psi_p \in \{\theta^{13}_p, \theta^{23}_p, \theta^{123}_p\}$, (5.2) implies that there exists some CS in the set $\{CS_{\mathrm{III}}, CS_{\mathrm{II}}, CS_{\mathrm{V}}\}$ that satisfies $\sum_{C_0 \in CS} \tau_p(C_0) = \ell^0_{pkc}$. Therefore, with this CS we have that $\sum_{C_0 \in CS} \tau_p(C_0) = \tau^*_p(\Omega_p)$. Consequently, Corollary 5.1 completes the proof. ■

Proof of Theorem 5.3: First we note that (5.4) can be written as follows:

$$\begin{cases} \mathrm{Y}_1 + \mathrm{Y}_2 + \mathrm{Y}_3 = \Psi_p & \text{(C.1a)} \\ \mathrm{Y}_1 + \mathrm{Y}_3 \geq \theta_p^{13} & \text{(C.1b)} \\ \mathrm{Y}_2 + \mathrm{Y}_3 \geq \theta_p^{23} & \text{(C.1c)} \\ \mathrm{Y}_1, \mathrm{Y}_2, \mathrm{Y}_3 \geq 0 & \text{(C.1d)} \end{cases}$$

If $\Psi_p = \theta_p^{13}$, then (C.1) implies that $\mathrm{Y}_2 = 0$:

$$\text{(C.1a), (C.1b)} \Rightarrow \begin{cases} \mathrm{Y}_2 = \theta_p^{13} - (\mathrm{Y}_1 + \mathrm{Y}_3) \\ \theta_p^{13} - (\mathrm{Y}_1 + \mathrm{Y}_3) \leq 0 \end{cases} \Rightarrow \mathrm{Y}_2 \leq 0 \xrightarrow{\mathrm{Y}_2 \geq 0} \mathrm{Y}_2 = 0$$

Thus (C.1) can be reduced to the following system:

$$\begin{cases} \mathrm{Y}_1 + \mathrm{Y}_3 = \theta_p^{13} \\ \mathrm{Y}_3 \geq \theta_p^{23} \\ \mathrm{Y}_1, \mathrm{Y}_3 \geq 0 \ \ \& \ \ \mathrm{Y}_2 = 0 \end{cases} \tag{C.2}$$

which has the solution set $\{(t, 0, \theta_p^{13} - t) \mid t \in [0, \theta_p^{13} - \theta_p^{23}]\}$. That is, given that $\Psi_p = \theta_p^{13}$, we can write:

$$\mathrm{X}_q = \frac{\mathrm{Y}_q \times \ell_{pkc}^0}{\Psi_p} \Rightarrow \mathbf{C}(\Omega_p, \tau_p^*) = \left\{ \left(\frac{t}{\theta_p^{13}} \times \ell_{pkc}^0, 0, (1 - \frac{t}{\theta_p^{13}}) \times \ell_{pkc}^0 \right) \mid t \in [0, \theta_p^{13} - \theta_p^{23}] \right\}$$

Similar to arguments made by above, one can solve (5.4) for two other cases $\Psi_p = \theta_p^{23}$ and $\Psi_p = \theta_p^{123}$. ■

Proof of Theorem 5.4: We start with showing that $\widehat{\Pi}_j^* > \Pi_j^*$. Let $(\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j)$ be an arbitrary solution. Given that $\hat{s}_{jd} > 0$, we can write:

$$
\begin{aligned}
\hat{\text{A}} &= \sum_{d=1}^{\bar{d}} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd}\right] - \sum_{d=1}^{\bar{d}} \left[F_{jd}(Q_{jd})\right] \\
&= \sum_{d=1}^{\bar{d}} \left(\int_0^{\infty} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd} - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&= \sum_{d=1}^{\bar{d}} \left(\int_0^{Q_{jd}} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd} - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&+ \sum_{d=1}^{\bar{d}} \left(\int_{Q_{jd}}^{\infty} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd} - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&\geq \sum_{d=1}^{\bar{d}} \left(\int_0^{Q_{jd}} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})\xi - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&+ \sum_{d=1}^{\bar{d}} \left(\int_{Q_{jd}}^{\infty} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd} - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&> \sum_{d=1}^{\bar{d}} \left(\int_0^{Q_{jd}} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})\xi - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&+ \sum_{d=1}^{\bar{d}} \left(\int_{Q_{jd}}^{\infty} \left[P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})Q_{jd} - \hat{s}_{jd}(\xi - Q_{jd}) - F_{jd}(Q_{jd})\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) = \text{A}.
\end{aligned}
$$

Now that $\hat{\text{A}} > \text{A}$ for all vectors $(\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j)$, comparing (5.5) and (5.6) completes the proof of the first statement. As $\frac{\partial \widehat{\Pi}_j}{\partial E_{jc}} = \frac{\partial \Pi_j}{\partial E_{jc}}$ and $\frac{\partial \widehat{\Pi}_j}{\partial L_{jkc}} = \frac{\partial \Pi_j}{\partial L_{jkc}}$ can be proved easily, it is sufficient to show that $\frac{\partial^2 \widehat{\Pi}}{\partial Q_{jd}^2} > \frac{\partial^2 \Pi}{\partial Q_{jd}^2}$. As explained in detail in Proposition 5.2, we can conclude that

$$
\frac{\partial \Pi_{jd}}{\partial Q_{jd}} = -B_d \mu_{jd} - \frac{\partial F_{jd}}{\partial Q_{jd}} + \left[P_d + \hat{s}_{jd}\right] \left(1 - \varepsilon_{jd}(Q_{jd})\right) + B_d \left(\int_{Q_{jd}}^{\infty} \left[\xi - Q_{jd}\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) - \frac{\partial G_j}{\partial Q_{jd}}
$$

and

$$
\frac{\partial \widehat{\Pi}_{jd}}{\partial Q_{jd}} = -B_d Q_{jd} + P_d - \frac{\partial F_{jd}}{\partial Q_{jd}} - \frac{\partial G_j}{\partial Q_{jd}},
$$

which implies that:

$$
\begin{aligned}
&\frac{\partial \Pi_{jd}}{\partial Q_{jd}} - \frac{\partial \widehat{\Pi}_{jd}}{\partial Q_{jd}} = -B_d(\mu_{jd} - Q_{jd}) - P_d + \left[P_d + \hat{s}_{jd}\right] \left(1 - \varepsilon_{jd}(Q_{jd})\right) + B_d \left(\int_{Q_{jd}}^{\infty} \left[\xi - Q_{jd}\right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
\Rightarrow &\frac{\partial^2 \Pi_{jd}}{\partial Q_{jd}^2} - \frac{\partial^2 \widehat{\Pi}_{jd}}{\partial Q_{jd}^2} = -B_d \times (0 - 1) - B_d - \left[P_d + \hat{s}_{jd}\right] \epsilon_{jd}(Q_{jd}) - B_d \left(1 - \varepsilon_{jd}(Q_{jd})\right) - B_d \left(1 - \varepsilon_{jd}(Q_{jd})\right).
\end{aligned}
$$

Hence, $\frac{\partial^2 \Pi_{jd}}{\partial Q_{jd}^2} - \frac{\partial^2 \widehat{\Pi}_{jd}}{\partial Q_{jd}^2} \leq -2B_d \left(1 - \varepsilon_{jd}(Q_{jd})\right) < 0$ is held. This inequality completes the proof of the second statement. ■

Proof of Theorem 5.5: Provided that $\mathcal{X}^*$ is a minimizer of $\mathcal{H}$ over $\mathcal{K}$, the function $\mathcal{M}(t) = \mathcal{H}(\mathcal{X}^* + t(\mathcal{X} - \mathcal{X}^*))$, where $t \in [0, 1]$, achieves its minimum at $t^* = 0$. On the other hand, the domain of $\mathcal{M}(t)$ is $[0, 1]$ which along with $t^* = 0$ results in $\mathcal{M}'(t^*) \geq 0$. Based on the chain rule we can write:

$$\begin{aligned}
\mathcal{M}'(t^*) \geq 0 &\Rightarrow \forall\ \mathcal{X} \in \mathcal{K} \ \ \langle \nabla \mathcal{H}(\mathcal{X}^* + t^*(\mathcal{X} - \mathcal{X}^*))^T, \mathcal{X} - \mathcal{X}^* \rangle \geq 0 \\
&\Rightarrow \forall\ \mathcal{X} \in \mathcal{K} \ \ \langle \nabla \mathcal{H}(\mathcal{X}^*)^T, \mathcal{X} - \mathcal{X}^* \rangle \geq 0 \\
&\Rightarrow \mathcal{X}^* \text{ is a solution of VI}(\nabla \mathcal{H}, \mathcal{K})
\end{aligned}$$

Now we assume that $\mathcal{X}^*$ is a solution of VI$(\nabla \mathcal{H}, \mathcal{K})$. Borrowing from the convexity theory, we can write

$$\begin{aligned}
\mathcal{H} \text{ is a convex function} &\Rightarrow \forall\ \mathcal{X} \in \mathcal{K} \ \ \mathcal{H}(\mathcal{X}) \geq \mathcal{H}(\mathcal{X}^*) + \langle \nabla \mathcal{H}(\mathcal{X}^*)^T, \mathcal{X} - \mathcal{X}^* \rangle \\
&\Rightarrow \forall\ \mathcal{X} \in \mathcal{K} \ \ \mathcal{H}(\mathcal{X}) \geq \mathcal{H}(\mathcal{X}^*) + 0 = \mathcal{H}(\mathcal{X}^*) \\
&\Rightarrow \mathcal{X}^* \text{ is a solution of } \min_{\mathcal{X} \in \mathcal{K}} \mathcal{H}(\mathcal{X}),
\end{aligned}$$

and all these arguments complete the proof. ■

Proof of Lemma 5.1: Based on the definitions of strictly convex/concave functions, one can easily complete the proof. ■

Proof of Proposition 5.2: Based on Lemma 5.1 and considering that linear functions are both convex and concave, it is sufficient to show that the following function

$$\begin{aligned}
\alpha_{jd}(Q_{jd}) = &\left(\int_0^{Q_{jd}} \left[P_d \xi - F_{jd}(Q_{jd}) \right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \\
&+ \left(\int_{Q_{jd}}^{\infty} \left[P_d Q_{jd} - \hat{s}_{jd}(\xi - Q_{jd}) - F_{jd}(Q_{jd}) \right] \epsilon_{jd}(\xi) \mathrm{d}\xi \right) \qquad \text{(C.3)}
\end{aligned}$$

is strictly concave with respect to Q_{jd}, where j and d are given arbitrarily. This function can be simplified as

$$\begin{aligned}\alpha_{jd}(Q_{jd}) &= \left(\int_0^{Q_{jd}} P_d\xi\epsilon_{jd}(\xi)\mathrm{d}\xi + \int_{Q_{jd}}^{\infty} P_d\xi\epsilon_{jd}(\xi)\mathrm{d}\xi\right) \\ &\quad + \left(\int_{Q_{jd}}^{\infty} \left[-P_d\xi + P_dQ_{jd} - \hat{s}_{jd}(\xi - Q_{jd})\right]\epsilon_{jd}(\xi)\mathrm{d}\xi\right) - F_{jd}(Q_{jd}) \\ &= P_d\mu_{jd} - F_{jd}(Q_{jd}) - [P_d + \hat{s}_{jd}] \times \left(\int_{Q_{jd}}^{\infty} [\xi - Q_{jd}]\,\epsilon_{jd}(\xi)\mathrm{d}\xi\right),\end{aligned}$$

which along with $P_d \equiv P_d(Q_{1d}, ..., Q_{jd}, ..., Q_{\bar{n}d})$ and $\epsilon_{jd} = \varepsilon'_{jd}$ results in

$$\begin{aligned}&\frac{\partial\alpha_{jd}}{\partial Q_{jd}} = -B_d\mu_{jd} - \frac{\partial F_{jd}}{\partial Q_{jd}} + [P_d + \hat{s}_{jd}]\left(1 - \varepsilon_{jd}(Q_{jd})\right) + B_d\left(\int_{Q_{jd}}^{\infty} [\xi - Q_{jd}]\,\epsilon_{jd}(\xi)\mathrm{d}\xi\right) \\ \Rightarrow &\frac{\partial^2\alpha_{jd}}{\partial Q_{jd}^2} = 0 - \frac{\partial^2 F_{jd}}{\partial Q_{jd}^2} - [P_d + \hat{s}_{jd}]\,\epsilon_{jd}(Q_{jd}) - B_d\left(1 - \varepsilon_{jd}(Q_{jd})\right) - B_d\left(1 - \varepsilon_{jd}(Q_{jd})\right),\end{aligned}$$

and given that $F_{jd}(Q_{jd})$ is convex, we conclude that $\frac{\partial^2 F_{jd}}{\partial Q_{jd}^2} \geq 0$. Hence

$$\frac{\partial^2\alpha_{jd}}{\partial Q_{jd}^2} \leq -2B_d\left(1 - \varepsilon_{jd}(Q_{jd})\right) < 0$$

is held. This inequality completes the proof. ■

Proof of Corollary 5.3: Theorem 5.5 and Proposition 5.2 immediately complete the proof. ■

Proof of Theorem 5.6: If $(\mathbf{Q}^*, \mathbf{E}^*, \mathbf{L}^*) \in \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$ is a Nash-Cournot equilibrium, then Corollary 5.3 and Definition 5.1 immediately imply that (5.9) is held. Reversely, we now assume that (5.9) is satisfied for $(\mathbf{Q}^*, \mathbf{E}^*, \mathbf{L}^*) \in \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$. Let us consider a given $j_0 \in \{1, ..., \bar{n}\}$. It is sufficient to define the vector $(\mathbf{Q}, \mathbf{E}, \mathbf{L}) \in \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$, such that for each $j \in \{1, ..., \bar{n}\} - \{j_0\}$ we have that $Q_{jd} = Q^*_{jd}$, $E_{jc} = E^*_{jc}$, and $L_{jkc} = L^*_{jkc}$, where

d, k, and c are arbitrary. Hence, for this specific vector (5.9) implies that

$$\sum_{j=1}^{\bar{n}}\sum_{d=1}^{\bar{d}}\Bigg(\Bigg[\frac{\partial F_{jd}(Q^*_{jd})}{\partial Q_{jd}}+\frac{\partial G_j(\mathbf{Q}^*_j,\mathbf{E}^*_j)}{\partial Q_{jd}}+B_d\mu_{jd}-[P^*_d+\hat{s}_{jd}]\Big(1-\varepsilon_{jd}(Q^*_{jd})\Big)$$
$$-B_d\Bigg(\int_{Q^*_{jd}}^{\infty}\Big[\xi-Q^*_{jd}\Big]\epsilon_{jd}(\xi)\mathrm{d}\xi\Bigg)\Bigg]\times\Big[Q_{jd}-Q^*_{jd}\Big]\Bigg)$$
$$+\sum_{j=1}^{\bar{n}}\sum_{c=1}^{\bar{c}}\Bigg(\Bigg[\frac{\partial G_j(\mathbf{Q}^*_j,\mathbf{E}^*_j)}{\partial E_{jc}}+\sum_{k=1}^{\bar{k}}\Big(\nu_{kc}h_{jkc}\Big)\Bigg]\times\Big[E_{jc}-E^*_{jc}\Big]\Bigg)$$
$$+\sum_{j=1}^{\bar{n}}\sum_{k=1}^{\bar{k}}\sum_{c=1}^{\bar{c}}\Big(\Big[\rho_{kc}-\nu_{kc}\Big]\times\Big[L_{jkc}-L^*_{jkc}\Big]\Big)\geq 0,$$

for which $Q_{jd}=Q^*_{jd}$, $E_{jc}=E^*_{jc}$, and $L_{jkc}=L^*_{jkc}$, where $j\in\{1,...,\bar{n}\}-\{j_0\}$, explicitly imply that

$$\sum_{d=1}^{\bar{d}}\Bigg(\Bigg[\frac{\partial F_{j_0d}(Q^*_{j_0d})}{\partial Q_{j_0d}}+\frac{\partial G_{j_0}(\mathbf{Q}^*_{j_0},\mathbf{E}^*_{j_0})}{\partial Q_{j_0d}}+B_d\mu_{j_0d}-[P^*_d+\hat{s}_{j_0d}]\Big(1-\varepsilon_{j_0d}(Q^*_{j_0d})\Big)$$
$$-B_d\Bigg(\int_{Q^*_{j_0d}}^{\infty}\Big[\xi-Q^*_{j_0d}\Big]\epsilon_{j_0d}(\xi)\mathrm{d}\xi\Bigg)\Bigg]\times\Big[Q_{j_0d}-Q^*_{j_0d}\Big]\Bigg)+\sum_{j\neq j_0}0$$
$$+\sum_{c=1}^{\bar{c}}\Bigg(\Bigg[\frac{\partial G_{j_0}(\mathbf{Q}^*_{j_0},\mathbf{E}^*_{j_0})}{\partial E_{j_0c}}+\sum_{k=1}^{\bar{k}}\Big(\nu_{kc}h_{j_0kc}\Big)\Bigg]\times\Big[E_{j_0c}-E^*_{j_0c}\Big]\Bigg)+\sum_{j\neq j_0}0$$
$$+\sum_{k=1}^{\bar{k}}\sum_{c=1}^{\bar{c}}\Big(\Big[\rho_{kc}-\nu_{kc}\Big]\times\Big[L_{j_0kc}-L^*_{j_0kc}\Big]\Big)+\sum_{j\neq j_0}0\geq 0,$$

and we conclude that (5.8) is met for SC_{j_0}. All these arguments along with Corollary 5.3 and Definition 5.1 show that $(\mathbf{Q}^*,\mathbf{E}^*,\mathbf{L}^*)\in\mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$ is a Nash-Cournot equilibrium, which completes the proof. ■

Proof of Lemma 5.2: Since $\mathcal{H}$ is (strictly) concave, for any pair of distinct vectors $\mathcal{X}$ and $\mathcal{Y}$ in $\mathcal{K}$ we can write:

$$\mathcal{H}(\mathcal{Y})(<)\leq\mathcal{H}(\mathcal{X})+\langle\nabla\mathcal{H}(\mathcal{X})^T,\mathcal{Y}-\mathcal{X}\rangle$$
$$\mathcal{H}(\mathcal{X})(<)\leq\mathcal{H}(\mathcal{Y})+\langle\nabla\mathcal{H}(\mathcal{Y})^T,\mathcal{X}-\mathcal{Y}\rangle$$

which together imply that:

$$\begin{aligned}
&\mathcal{H}(\mathcal{Y}) + \mathcal{H}(\mathcal{X})(<) \leq \mathcal{H}(\mathcal{X}) + \mathcal{H}(\mathcal{Y}) + \langle \nabla\mathcal{H}(\mathcal{X})^T - \nabla\mathcal{H}(\mathcal{Y})^T, \mathcal{Y} - \mathcal{X}\rangle \\
\Rightarrow &\Big\langle \Big((- \nabla\mathcal{H}(\mathcal{Y})) - (- \nabla\mathcal{H}(\mathcal{X})) \Big)^T, \mathcal{Y} - \mathcal{X} \Big\rangle (>) \geq 0
\end{aligned}$$

Since $\mathcal{X}$ and $\mathcal{Y}$ are two arbitrary vectors in $\mathcal{K}$, $-\nabla\mathcal{H}$ is (strictly) monotone. ■

Proof of Proposition 5.3: For any pair of distinct vectors $\mathcal{X}$ and $\mathcal{X}'$ in $\mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})}$ we can write

$$\begin{aligned}
\langle \mathcal{P}(\mathcal{X}) - \mathcal{P}(\mathcal{X}'), \mathcal{X} - \mathcal{X}' \rangle = &\sum_{j=1}^{\bar{n}} \sum_{d=1}^{\bar{d}} \Bigg(\Bigg[\Big(-\frac{\partial \Pi_j(\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j)}{\partial Q_{jd}} \Big) - \Big(-\frac{\partial \Pi_j(\mathbf{Q}', \mathbf{E}'_j, \mathbf{L}'_j)}{\partial Q'_{jd}} \Big) \Bigg] \\
&\quad \times \Big[Q_{jd} - Q'_{jd} \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{c=1}^{\bar{c}} \Bigg(\Bigg[\Big(\frac{\partial G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial E_{jc}} + \sum_{k=1}^{\bar{k}} \Big(\nu_{kc} h_{jkc} \Big) \Big) \\
&\quad - \Big(\frac{\partial G_j(\mathbf{Q}'_j, \mathbf{E}'_j)}{\partial E'_{jc}} + \sum_{k=1}^{\bar{k}} \Big(\nu_{kc} h_{jkc} \Big) \Big) \Bigg] \times \Big[E_{jc} - E'_{jc} \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{k=1}^{\bar{k}} \sum_{c=1}^{\bar{c}} \Bigg(\Big[(\rho_{kc} - \nu_{kc}) - (\rho_{kc} - \nu_{kc}) \Big] \times \Big[L_{jkc} - L'_{jkc} \Big] \Bigg) \\
= &\sum_{j=1}^{\bar{n}} \sum_{d=1}^{\bar{d}} \Bigg(\Bigg[\Big(-\frac{\partial \Pi_j(\mathbf{Q}, \mathbf{E}_j, \mathbf{L}_j)}{\partial Q_{jd}} \Big) - \Big(-\frac{\partial \Pi_j(\mathbf{Q}', \mathbf{E}'_j, \mathbf{L}'_j)}{\partial Q'_{jd}} \Big) \Bigg] \\
&\quad \times \Big[Q_{jd} - Q'_{jd} \Big] \Bigg) \\
&+ \sum_{j=1}^{\bar{n}} \sum_{c=1}^{\bar{c}} \Bigg(\Bigg[\Big(\frac{\partial G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial E_{jc}} \Big) - \Big(\frac{\partial G_j(\mathbf{Q}'_j, \mathbf{E}'_j)}{\partial E'_{jc}} \Big) \Bigg] \times \Big[E_{jc} - E'_{jc} \Big] \Bigg) \\
> &\ 0 + 0,
\end{aligned}$$

where the last strict inequality is justified by the use of Lemma 5.2, Proposition 5.2, and convexity of $G_j(E_{jc})$. Therefore, we have that $\langle \mathcal{P}(\mathcal{X}) - \mathcal{P}(\mathcal{X}'), \mathcal{X} - \mathcal{X}' \rangle > 0$. Since $\mathcal{X}$ and $\mathcal{X}'$ are two arbitrary vectors, $\mathcal{P}$ is strictly monotone. ■

Proof of Theorem 5.7: The reader is referred to Theorem 1.6 in Nagurney (1999). ■

Proof of Corollary 5.4: Theorem 5.7 and Proposition 5.3 immediately complete the proof. ■

Proof of Theorem 5.8: The reader is referred to Theorem 2 in Korpelevich (1976). ■

Proof of Lemma 5.3: Based on the above assumptions and also the triangle inequality, the following qualities/inequalities

$$
\begin{aligned}
\frac{\partial \Pi_j}{\partial Q_{jd}} &= -\frac{\partial F_{jd}(Q_{jd})}{\partial Q_{jd}} - \frac{\partial G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd}} - B_d\mu_{jd} + [P_d + \hat{s}_{jd}]\left(1-\varepsilon_{jd}(Q_{jd})\right) \\
&\quad + B_d\left(\int_{Q_{jd}}^{\infty}[\xi - Q_{jd}]\,\epsilon_{jd}(\xi)\mathrm{d}\xi\right) \\
\left|\frac{\partial^2 \Pi_j}{\partial Q_{jd}^2}\right| &\le \left|\frac{\partial^2 F_{jd}(Q_{jd})}{\partial Q_{jd}^2}\right| + \left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd}^2}\right| + (A_d + \hat{s}_{jd}) \times |\epsilon_{jd}(Q_{jd})| + 2B_d \\
\left|\frac{\partial^2 \Pi_j}{\partial Q_{jd'}\partial Q_{jd}}\right| &\le \left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd'}\partial Q_{jd}}\right| \\
\left|\frac{\partial^2 \Pi_j}{\partial Q_{j'd}\partial Q_{jd}}\right| &\le B_d \\
\left|\frac{\partial^2 \Pi_j}{\partial Q_{j'd'}\partial Q_{jd}}\right| &= 0 \\
\left|\frac{\partial^2 \Pi_j}{\partial E_{jc}\partial Q_{jd}}\right| &\le \left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc}\partial Q_{jd}}\right| \\
\left|\frac{\partial^2 \Pi_j}{\partial E_{j'c}\partial Q_{jd}}\right| &= \left|\frac{\partial^2 \Pi_j}{\partial L_{jkc}\partial Q_{jd}}\right| = \left|\frac{\partial^2 \Pi_j}{\partial L_{j'kc}\partial Q_{jd}}\right| = 0 \\
\frac{\partial \Pi_j}{\partial E_{jc}} &= -\frac{\partial G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc}} - \sum_{k=1}^{\bar{k}}\left(\nu_{kc}h_{jkc}\right) \\
\left|\frac{\partial^2 \Pi_j}{\partial E_{jc}^2}\right| &\le \left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc}^2}\right| \\
\left|\frac{\partial^2 \Pi_j}{\partial E_{jc'}\partial E_{jc}}\right| &\le \left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial E_{jc'}\partial E_{jc}}\right| \\
\left|\frac{\partial^2 \Pi_j}{\partial E_{j'c}\partial E_{jc}}\right| &= \left|\frac{\partial^2 \Pi_j}{\partial E_{j'c'}\partial E_{jc}}\right| = 0 \\
\left|\frac{\partial^2 \Pi_j}{\partial Q_{jd}\partial E_{jc}}\right| &\le \left|\frac{\partial^2 G_j(\mathbf{Q}_j,\mathbf{E}_j)}{\partial Q_{jd}\partial E_{jc}}\right| \\
\left|\frac{\partial^2 \Pi_j}{\partial Q_{j'd}\partial E_{jc}}\right| &= \left|\frac{\partial^2 \Pi_j}{\partial L_{jkc}\partial E_{jc}}\right| = \left|\frac{\partial^2 \Pi_j}{\partial L_{jkc'}\partial E_{jc}}\right| = \left|\frac{\partial^2 \Pi_j}{\partial L_{j'kc}\partial E_{jc}}\right| = \left|\frac{\partial^2 \Pi_j}{\partial L_{j'kc'}\partial E_{jc}}\right| = 0 \\
\frac{\partial \Pi_j}{\partial L_{jkc}} &= (-\rho_{kc} + \nu_{kc}) \\
\left|\frac{\partial^2 \Pi_j}{\partial \ldots \partial L_{jkc}}\right| &= 0,
\end{aligned}
\tag{C.4}
$$

obtained directly from (5.5), complete the proof, where $j \neq j' \in \{1, ..., \bar{n}\}$, $k \in \{1, ..., \bar{k}\}$, $c \neq c' \in \{1, ..., \bar{c}\}$, and $d \neq d' \in \{1, ..., \bar{d}\}$. ■

Proof of Proposition 5.4: We first note that (5.10), (C.4), Lemma 5.3, and

$$
\begin{aligned}
U^{(\mathcal{P})} &= (\bar{n}\bar{d} + \bar{c} + \bar{k}\bar{c}) \\
&\times \Bigg[\left(\max_{j,d} \left\{ \left| \frac{\partial^2 F_{jd}(Q_{jd})}{\partial Q_{jd}^2} \right| + \left| \frac{\partial^2 G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial Q_{jd}^2} \right| + (A_d + \hat{s}_{jd}) \times |\epsilon_{jd}(Q_{jd})| + 2B_d \right\} \right)^2 \\
&+ \left(\max_{j,d \neq d'} \left\{ \left| \frac{\partial^2 G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial Q_{jd'} \partial Q_{jd}} \right| \right\} \right)^2 + \left(\max_{d} \left\{ B_d \right\} \right)^2 + \left(\max_{j,c,d} \left\{ \left| \frac{\partial^2 G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial E_{jc} \partial Q_{jd}} \right| \right\} \right)^2 \\
&+ \left(\max_{j,c} \left\{ \left| \frac{\partial^2 G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial E_{jc}^2} \right| \right\} \right)^2 + \left(\max_{j,c \neq c'} \left\{ \left| \frac{\partial^2 G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial E_{jc'} \partial E_{jc}} \right| \right\} \right)^2 \\
&+ \left(\max_{j,c,d} \left\{ \left| \frac{\partial^2 G_j(\mathbf{Q}_j, \mathbf{E}_j)}{\partial Q_{jd} \partial E_{jc}} \right| \right\} \right)^2 \Bigg]
\end{aligned}
$$

imply that

$$
\forall\ \mathcal{X} \in \mathcal{K} \equiv \mathbb{R}_+^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})} \quad \forall\ t \in \{1, ..., \bar{n}(\bar{d} + \bar{c} + \bar{k}\bar{c})\} \quad \|\nabla \mathcal{P}_t(\mathcal{X})\| \leq U^{(\mathcal{P})} < \infty, \tag{C.5}
$$

where $\nabla \mathcal{P}_t(\mathcal{X})$ denotes the gradient of the t-th element of $\mathcal{P}(\mathcal{X})$. Since the parameters B_d are positive, it is easy to see that $U^{(\mathcal{P})} > 0$. Let $\mathcal{X}$ and $\mathcal{X}'$ be in the set $\mathcal{K}$. Since $\mathcal{P}$ is differentiable, the mean value theorem ensures that for each $t \in \{1, ..., \bar{n}(\bar{d} + \bar{c} + \bar{k}\bar{c})\}$ there exists $\beta_t \in (0, 1)$ such that $\mathcal{P}_t(\mathcal{X}) - \mathcal{P}_t(\mathcal{X}') = \langle \nabla \mathcal{P}_t(\mathcal{X}^t), \mathcal{X} - \mathcal{X}' \rangle$, where $\mathcal{X}^t = \beta_t \mathcal{X} + (1 - \beta_t)\mathcal{X}'$. Therefore:

$$
\begin{aligned}
\|\mathcal{P}(\mathcal{X}) - \mathcal{P}(\mathcal{X}')\|^2 &= \sum_t (\mathcal{P}_t(\mathcal{X}) - \mathcal{P}_t(\mathcal{X}'))^2 \\
&= \sum_t \left(\langle \nabla \mathcal{P}_t(\mathcal{X}^t), \mathcal{X} - \mathcal{X}' \rangle \right)^2 \\
&= \sum_t \left| \langle \nabla \mathcal{P}_t(\mathcal{X}^t), \mathcal{X} - \mathcal{X}' \rangle \right|^2 \\
&\overset{\text{Schwarz}}{\leq} \left(\sum_t \|\nabla \mathcal{P}_t(\mathcal{X}^t)\|^2 \right) \times \|\mathcal{X} - \mathcal{X}'\|^2 \\
&\overset{\text{(C.5)}}{\leq} \left(\sum_{t=1}^{\bar{n}(\bar{d}+\bar{c}+\bar{k}\bar{c})} \left(U^{(\mathcal{P})} \right)^2 \right) \times \|\mathcal{X} - \mathcal{X}'\|^2 \\
&= \bar{n}(\bar{d} + \bar{c} + \bar{k}\bar{c}) \times \left(U^{(\mathcal{P})} \right)^2 \times \|\mathcal{X} - \mathcal{X}'\|^2
\end{aligned}
$$

Hence, we can conclude that $\|\mathcal{P}(\mathcal{X}) - \mathcal{P}(\mathcal{X}')\| \leq L_{\mathcal{P}} \times \|\mathcal{X} - \mathcal{X}'\|$, defining the Lipschitz constant $L_{\mathcal{P}} = \sqrt{\bar{n}(\bar{d} + \bar{c} + \bar{k}\bar{c})} \times U^{(\mathcal{P})} > 0$, which completes the proof. ■

Proof of Theorem 5.9: Theorem 5.8, Propositions 5.2, 5.3, and 5.4, as well as Corollary 5.4 immediately complete the proof. ■

C.2 Data Set of the Example with 10 Supply Chains

Table C.2: Data set of the random instance including the network of Figure 5.1

DMU	Performance Indicators						
	x_1^{Sup1}	x_2^{Sup1}	x_1^{Sup2}	x_2^{Sup2}	$x_1^{Man.}$	$x_2^{Man.}$	$x_3^{Man.}$
SC_1	190.0	120.0	130.0	149.0	14.0	19.0	94.0
SC_2	300.0	345.0	335.0	340.0	125.0	125.0	452.0
SC_3	288.0	350.0	345.0	330.0	110.0	155.0	329.0
SC_4	320.0	330.0	350.0	325.0	105.0	132.0	442.0
SC_5	290.0	275.0	370.0	320.0	135.0	149.0	526.0
SC_6	340.0	210.0	210.0	300.0	142.0	176.0	349.0
SC_7	325.0	370.0	220.0	295.0	159.0	125.0	527.0
SC_8	330.0	250.0	250.0	290.0	130.0	192.0	397.0
SC_9	349.0	320.0	275.0	290.0	115.0	156.0	309.0
SC_{10}	295.0	335.0	320.0	288.0	100.0	145.0	403.0

DMU	Performance Indicators							
	$z_{t.1}^{Sup1\text{-}Man}$	$z_{t.2}^{Sup1\text{-}Man}$	$z_{t.1}^{Sup2\text{-}Man}$	$z_{t.2}^{Sup2\text{-}Man}$	y_1^{Sup1}	y_1^{Sup2}	$y_1^{Man.}$	$y_2^{Man.}$
SC_1	999,961.0	483,342.7	343,477.3	642,430.8	2,250.0	2,101.8	2.00645	300.0
SC_2	999,966.0	65,421.0	99,987.1	697,244.8	1,295.0	2,318.6	0.00599	2.0
SC_3	999,954.0	486,457.8	515,020.8	989,770.9	1,320.0	1,651.1	0.00654	3.0
SC_4	999,968.0	986,359.8	1,009,565.9	624,045.2	1,259.0	3,374.1	0.00556	3.0
SC_5	999,947.0	928,035.4	862,750.0	207,894.1	1,320.0	2,987.5	0.00599	2.0
SC_6	999,938.0	642,430.8	789,519.4	483,342.7	1,349.0	2,803.6	0.00641	3.0
SC_7	999,961.0	697,244.8	500,393.4	65,421.0	1,329.0	1,866.1	0.00562	3.0
SC_8	999,955.0	989,770.9	1,000,003.5	486,457.8	1,276.0	1,660.0	0.00549	2.0
SC_9	999,928.0	624,045.2	992,092.0	986,359.8	1,293.0	1,920.2	0.00599	3.0
SC_{10}	999,958.0	207,894.1	1,002,310.6	928,035.4	1,302.0	2,191.9	0.00575	3.0

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