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Sustainable Supply Chains: Multicriteria Decision-Making and Policy Analysis for the Environment

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SUSTAINABLE SUPPLY CHAINS: MULTICRITERIA DECISION-MAKING AND POLICY ANALYSIS FOR THE ENVIRONMENT

A Dissertation Presented

by

TRISHA D. WOOLLEY

Submitted to the Graduate School of the
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To my family.

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ABSTRACT

SUSTAINABLE SUPPLY CHAINS: MULTICRITERIA DECISION-MAKING AND POLICY ANALYSIS FOR THE ENVIRONMENT

FEBRUARY 2010

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It is believed that the critical next step from examinations of operations and the environment is the study of sustainability and supply chains (Linton, Klassen, and Jayaraman (2007)). Environmental quality and preservation as well as meeting the stress of emission reductions is rapidly becoming an important issue for public policy (Wilkinson, Hill, and Gollan (2001)). However, Lambertini and Mantovani (2007) note the disregard, unrelated to regulatory requirements, of research practitioners to the potential benefits of appropriate competition policy measures and consumer pressures (Srivastara (2007)). In addition, a firm's success, notably, in terms of financial and/or environmental practices, has been tied, in part, to the strength of its ability to coordinate and integrate activities along the entire supply chain (Spekman,

Kamauff Jr., and Myhr (1998)), and to effectively implement multicriteria decision-making tools to aid in their strategic decisions.

I present five essays in this dissertation. For each model I utilize the theory of variational inequalities, derive the formulation, present qualitative properties, and provide numerical examples. The first essay develops the multitiered sustainable supply chain network model with multicriteria decision-making. In the second essay I construct a modeling and computational framework that allows for the determination of optimal carbon taxes applied to electric power plants in the context of electric power supply chain (generation/distribution/consumption) networks. The third essay considers electric power supply chain networks and develops a model of tradable pollution permits in the case of multiple pollutants and spatially distinct receptor points. In the fourth essay, I quantify and assess, from a system-optimized sustainable supply chain network perspective, the environmental effects resulting when a horizontal supply chain integration occurs. In the fifth and final essay, I extend the work of Nagurney (2009) to the multiproduct supply chain network domain to quantify the impacts.

This dissertation is heavily based on the following papers: Nagurney, Liu, and Woolley (2006), Nagurney, Liu, and Woolley (2007), Woolley, Nagurney, and Stranlund (2009), Nagurney and Woolley (2009) and Nagurney, Woolley, and Qiang (2009).

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INTRODUCTION

In this dissertation, I develop a novel framework to incorporate sustainability into multitiered, multicriteria supply chain network models with policy interventions. I explicitly address in a modeling context the application of multicriteria decision-making, environmental supply chain management; alternatively, green logistics, and policy schemes that include taxation and tradable permit markets. I also analyze, quantitatively, the relationship between environmental and cost synergy as a result of supply chain integration through pre and post horizontal mergers; as well as the synergy benefits through mergers/acquisitions associated with the general and richer multiproduct domain.

I represent the decision-makers throughout the entire supply chain, which, according to the literature, can lead to the realization of the minimization of environmental emissions and waste through a multicriteria decision-making framework (Oakley (1993)). Government mandated policies can then be applied to provide incentives for firms to incorporate environmental considerations into their decision-making processes given the current competitive state. Alternatively, due to consumer concern and awareness in regards to environmental quality, firms may voluntarily integrate/merge supply chains to not only achieve cost, but environmental synergistic gains which can be quantitatively assessed.

I present five essays in this dissertation. The first essay includes the sustainable supply chain model with multicriteria decision-making with the introduction of alternative manufacturing plants for each manufacturer with distinct associated environmental emissions. In the second essay I develop a modeling and computational framework that allows for the determination of optimal carbon taxes applied to electric power plants in the context of electric power supply chain (generation/distribution/consumption) networks. The third essay considers electric power supply chain networks in which the power generators have distinct power plants and associated technologies and I develop a model of tradable pollution permits in the case of multiple pollutants and spatially distinct receptor points. In the fourth essay, I quantify and assess, from the sustainable supply chain network perspective, the environmental effects resulting when a merger/integration occurs and the resulting synergy from possible strategic gains. In the fifth and final essay, I present the multiproduct supply chain network models with explicit capacities, prior to and post their horizontal integration and propose a measure to allow for the quantification and assessment of the synergy benefits, if any. For each model I provide the network formulation and structure, present quantitative properties and equilibrium/optimality conditions, and advocate an appropriate algorithm for the computation of numerical examples.

This Chapter is organized as follows: Section 1.1 includes the research motivation. I provide the appropriate literature review in Section 1.2, and in Section 1.3, I provide an overview of the research for this dissertation.

1.1 Research Motivation

It is believed that the critical next step from examinations of operations and the environment is the study of sustainability and supply chains (Linton, Klassen, and Jayaraman (2007)). Sustainability, which includes environmental quality and preservation as well as meeting the stress of emissions reductions, is rapidly becoming an important issue for business and also for public policy. A survey conducted by the

Business Council reported that over 40% of CEOs consider environmental and global warming issues of critical importance (Creyts et al. (2007)).

3M, the US based global conglomerate which manufactures pressure-sensitive tape, reflective materials, video and audio tape, laser imaging equipment, as well as health-care products, has a program called *Pollution Prevention Pays* (3P). This strategy focuses on the prevention of pollution at the source rather than managing and removing it after it has been created. The company's policy, according to Esty and Winston (2006), is that "anything not in a product is considered a cost...everything coming out of a plant is either a product, by-product (which can be reused or sold), or waste. Why, they ask, should there be any waste? This is a policy that every company needs to start emulating" (Penfield (2008)).

The general definition of sustainability is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED (1987)). Companies are grappling with efforts to limit resources, including energy, to create eco-friendly products, cut toxic emissions, as well as to help the poor and cooperate with nonprofit groups (Engardio et al. (2007)).

Moreover, there is evidence for concern among businesses, consumers, economic development experts, conservationists and human rights activists alike. The release of carbon dioxide into the atmosphere, through the combustion of fossil fuels (coal, oil, and natural gas), has risen 30% in the 200 years since the industrial revolution (Burruss (2004)). The average surface temperature of the earth, expressed as a global average, has increased by about 0.74C over the past hundred years (between 1906 and 2005) with 11 of the 12 warmest years occurring between 1995–2006 (IPCC (2007)). The environmental disamenity has damaged fragile ecosystems, resulting in, for example, altered precipitation patterns, species distinction, natural disasters, changing water supplies, and crop yields.

Sustainability concerns the environmental impact on future generations. In the US alone, greenhouse gas emissions are projected to rise 35% between 2005 and 2030 due to fewer forests and agricultural land to absorb the carbon, an increasing population, expansion of the US economy, and an increased use of fossil fuel fired power plants to generate energy (Creyts et al. (2007)). As a remedy, governmental agencies can support sustainability by the provision of environmental standards and regulatory frameworks to conserve resources used for inputs and to monitor quality of life, in an economic environment where industrial competitiveness be negatively affected by the cost to implement such initiatives (Wilkinson, Hill, and Gollan (2001)).

Several environmental regulations have been geared towards, specifically, the electric power industry, which underpins modern society. The power industry is expected to grow by 39% between 2005–2030 due to population growth and other factors. According to the Department of Energy, the cheapest form of electricity generation, coal-fired power plants, are expected to meet this growth in demand, accounting for 81% of the incremental load of electric power through 2030, and of which is also responsible for a majority of the electricity generated carbon emissions (Creyts et al. (2007)). Regulatory mandates lead electric power companies to efficiency improvements, though, for example, taxes and/or tradable pollution permit programs. The benefits of such initiatives, shown in a study conducted by Currie and Neidell (2005) throughout the 1990s in California, which coincides with the 1990 Clean Air Act, found reductions in the level of carbon monoxide saved approximately 1000 infant lives from pollution effects.

Lambertini and Mantovani (2007) note the disregard, unrelated to regulatory requirements, of research practitioners to the potential benefits of appropriate competition policy measures and consumer pressures (Srivastara (2007)). It has been argued that customers and suppliers punish polluters in the marketplace that violate environmental rules, also called a “reputational penalty” (Klein and Leffler (1981), Klassen and McLaughlin (1996)). It is interesting to note, however, that some firms in the public eye have not only met, but exceeded, required environmental mandates (Lyon (2003)). In the US, over 1,200 firms voluntarily participated in the EPA's 33/50 program, agreeing to reduce certain chemical emissions 50% by 1995 (Arora and Cason (1996)). Corporations are influenced by the ecologically-conscious marketplace that, according to a survey sponsored by DuPont and Mohawk Industries in October of 2007, despite the weak economy 65% of consumers are willing to pay an additional 8.3% for products made with renewable resources (Environmental Leader (2008)).

Environmental performance can be seen as a source of reputational, competitive, and financial advantage (Miles and Covin (2000), Fabian (2000)). A method for companies to achieve voluntary efficiency, through supply chain merger/integration, can, possibly, result in synergistic gains. A firm's success, notably, in terms of financial and/or environmental practices, has been tied, in part, to the strength of its ability to coordinate and integrate activities along the entire supply chain (Spekman, Kamauff Jr., and Myhr (1998)), and to effectively implement multicriteria decision-making tools to aid in their strategic decisions.

1.2 Literature Review

This review of the literature includes sustainable supply chains, multicriteria decision-making, and supply chain management. I introduce sustainable policy interventions by first discussing the electric power industry as an application for such policies. I recall notable contributions on the topic of environmental taxes and tradable permit systems.

1.2.1 Sustainable Supply Chains

The integration of an environmental perspective into a business context can be traced back to the 1990s, and is linked to the book *Our Common Future* (WCED (1987)), also referred to as the Brundtland Report (Linton, Klassen, and Jayaraman (2007)). Sustainability requires analyzing activities throughout the supply chain (cf. Croom, Romano, and Giannakis (2000) and references therein), which may require an organization to operate sub-optimally, that is, there is a noted inverse relationship between a cost perspective and creating the greatest value along the supply chain (Linton, Klassen, and Jayaraman (2007)).

Operations research/management science (OR/MS) tools and methods are useful in making these trade-offs in a more coherent way (Bloemhof-Ruwaard and Nunen (2005)). There is still a debate as to the method to operationalize sustainability, as questions arise such as what resources future generations require, the level of emissions that can be released without negatively affecting future generations, what policies would be required to achieve sustainability, the effect of market forces, etc. (Wilkinson, Hill, and Gollan (2001), Linton, Klassen, and Jayaraman (2007)).

The nature of the topic of sustainability and supply chains is broad due to the realm of questions to be addressed. This dissertation focus on pollution management, including source reduction and pollution prevention, throughout the supply chain to help regulatory agencies meet ecological and societal concerns, along with the effect on the key players in the supply chain and their associated interaction. Bloemhof-Ruwaard and Nunen (2005) refer to this as the "*Triple Bottom Line*" (3BL) concept, which focuses on forward logistics (Rodrigue, Slack, and Comtois (2001)) to address the dimensions of *People, Planet and Profit*.

I now introduce seminal papers on multicriteria decision-making as well as supply chain management as related to the framework of sustainable supply chains.

1.2.1.1 Multicriteria Decision-Making

Multicriteria decision-making (MCDM) has been one of the fastest growing methodologies in many disciplines. Research and OR/MS development in the field of sustainable supply chains considers multiple objectives, the central problem being how to evaluate a set of alternatives in terms of a number of criteria (Triantaphyllou (2000)) in which the solution sought must be in accordance with preferences of the decision-maker (Gal, Stewart, and Hanne (1999), Jones, Mirrazavi, and Tamiz (2002)). Since multifunctional groups within organizations and external stakeholders have a role in decisions related to organizations and the natural environment, those decisions be strategic and usually complex. One of the latest issues organizations face, that of greening the supply chain, requires techniques that behavioral decision research has shown humans are poorly equipped to solve (Sarkis (2003), Kiker (2005)).

The first to study multicriteria decision-making on networks, which focused on transportation networks, were Schneider (1968) and Quandt (1967). Since then the literature has grown from considering not only fixed travel times and travel costs with only two criteria, to an infinite number of decision-makers, a large finite number of decision criteria, along with elastic demands. The first model which could handle congestion and, thus, was flow-dependent, was developed by Dafermos (1981) that considered two criteria, while Nagurney and Dong (2000) developed the first general elastic demand multicriteria network equilibrium model with two criteria and fixed weights that were class and link-dependent. Refer to Nagurney and Dong (2002) for a list of noteworthy multicriteria traffic network equilibrium contributions since 1968 as well as to Leurent (1998).

Regarding supply chain applications, traditionally, the research has focused on a single objective to either minimize costs or to maximize profits (Cohen and Lee (1989), Tsiakis, Shah, and Pantelides (2001), Altiparmak et al. (2006)). The initial focus of multiobjective supply chain modeling was developed to allow use of a performance measurement system that included factors such as cost, customer service levels, quality, and flexibility of volume or delivery (Sabri and Beamom (2000), Talluri and Baker (2002), Xu, Liu, and Wang (2008)).

A notable model relating a multicriteria framework to supply chain networks was proposed by Dong, Zhang, and Nagurney (2002) which considered multicriteria decision-making within a supply chain context with two tiers of decision-makers and assumed that the demands at the consumer markets were fixed. Chen and Lee (2004) then studied a multiproduct, multiechelon, and multiperiod scheduling supply chain model with multiple goals and with uncertain market demands and product prices. Dong et al. (2005) presented a model for multicriteria decision-making in a multitiered supply chain network in an equilibrium context, which also accommodated random demands at multiple consumer markets. Nagurney and Matsypura (2005b) studied the dynamics of a multicriteria global supply chain network economy that sought to maximize profits and to minimize perceived risk and uncertainty, which was dependent not only on the decision-makers' transactions, but also on that of others.

The general projections of multicriteria decision-making into environmental applications range from hazardous chemical waste landfill (Accorsi, Apostolakis, and Zio (1999), Bonano et al. (2000), Apostolakis (2001)), water resource management (Gregory et al. (2001)), forestry planning (Kangas et al. (2001)) to fisheries (McDaniels (1995), Brown et al. (2001)). However, in terms of supply chains, the literature is sparse, since environmental issues have only recently received attention, and distinctly in the context of applied studies (see Hitchens, Birnie, and Thompson (2000)), conceptual, and survey studies (cf. Hill (1997) and the references therein).

Nagurney and Toyasaki (2003) were the first to develop a theoretical framework that allowed for multicriteria decision-makers in different tiers of the supply chain with environmental considerations, and the weight of the criteria (environmental) to depend on the environmental consciousness of each decision-maker. Product prices, quantities, and the emissions generated were then computed. Cruz (2008) then built on the work of Nagurney and Toyasaki (2003) to additionally consider the minimization of risk and the associated levels of social responsibility. He explicitly determined the equilibrium levels of social responsibility of the decision-makers, product quantities and prices.

Additional works include that by Oliveira and Antunes (2004) which present a multiple-objective model, that uses input-output environmental/energy matrices, based on the linear structure of inter-industry production linkages that assesses eleven environmental burdens with respect to changes in economic activities. Specific applications of multicriteria decision-making include work by Luo, Zhou, and Caudill (2001) which proposed a multiobjective optimization model for the supply chain of Internet-based manufacturing systems to explore the impact of an emerging e-business on system agility and environmental performance of mechatronic production systems. For additional works see: Luptacik and Bohm (1994), Albino, Izzo, and Uhtz (2002), Sarkis (2003), Ehrgott and Luptacik (2003), Wang, Huang, and Dismukes (2004), Figueira, Greco, and Ehrgott (2005), Ehrgott (2005), Letmathe and Balakrishnan (2005), and Kull and Talluri (2008).

In this dissertation, I utilize the theory of variational inequalities to determine the optimal prices and quantities transacted to maximize profits, as well as to minimize pollution levels. The theory of variational inequalities has been applied to study a plethora of multicriteria decision-making equilibrium problems as related to the environment and supply chains, as well as in the context of transportation and telecommunications (see Nagurney and Dong (2002)). For example, Dong and Nagurney (2001) introduced variable weights in the context of a financial equilibrium model in which each sector of the economy sought to both minimize risk and maximize return. They showed that the economic system conditions governing the instrument prices and financial equilibrium conditions can be formulated as a variational inequality problem. Nagurney, Dong, and Mokhtarian (2002a) then created an abstract multiclass (transportation and telecommunication mode alternatives), multicriteria (time, cost, risk, safety, etc.) network equilibrium model with elastic demand, and also with fixed demand, framework for decision-making in the Information Age and presented the governing equilibrium conditions as well as providing the variational inequality formulations.

In this dissertation, I add to the current literature and develop a theoretical framework which makes a significant extension to the work of Nagurney and Toyasaki (2003) and Nagurney (2000, 2006b) which introduced environmental concerns into a supply chain network equilibrium framework (see also Nagurney, Dong, and Mokhtarian (2002b)), through the introduction of alternative manufacturing plants for each manufacturer with distinct associated environmental emissions. I establish that the prices associated with the environmental criteria of the various decision-makers can be interpreted as taxes. I also prove that the supply chain model with environmental concerns can be reformulated and solved as an elastic demand transportation network equilibrium problem over an appropriately constructed abstract network or supernetwork (Nagurney and Dong (2002)).

1.2.1.2 Supply Chain Management and Integration

As noted earlier, firms that are forced to focus on the bottom line have the opportunity to improve financial and environmental performance through the management of the supply chain as a whole. For example, GM reduced its disposal costs by \$12 million by establishing a reusable container program with its suppliers and Andersen Corporation implemented several programs that reduced waste at its source and had internal rates of return (IRR) exceeding 50% (USEPA (2000)). Logistics costs are estimated to be 30% of cost of goods sold, leading to potential savings through coordination that cannot be ignored due to competitive pressures to decrease costs while maintaining excellent customer service (Thomas and Griffin (1996)).

The coordination of the supply chain involves a set of techniques to improve firm competitiveness and efficiency at the channel level rather than at the firm level, as Albino, Izzo, and Uhtz (2002) state, “the real competition is not company against company but supply chain against supply chain for the cost effective achievement of superior service.” Alliances are created that usually increase the financial and operational performance of each channel member through increased sharing of information and reductions in total cost and inventories (Maloni and Benton (1997)), as well as to reduce the proliferation of unexpected and/or undesirable events through the network (Guilln et al. (2005)). See also Carothers and Adams (1991), Lee and Billington (1992), Langley and Holcomb (1992), Christopher (1992), Shapiro, Singhal, and Wagner (1993), Macbeth and Ferguson (1994), Ragatz, Handfield, and Scannell (1997), Croom, Romano, and Giannakis (2000), Horvath (2001), and Skjoett-Larsen, Thernoe, Andresen (2003), and Langabeer and Seifert (2003)).

The concept of *Supply Chain Management* (SCM) was introduced in the early 1980s; yet it as has seen remarkably growth in importance since only the early 1990s. The growth and development of SCM was not driven by only internal motives, but by a number of external factors such as reliance on outsourcing (for example, by the late 1980s, nearly 60% of the total product cost in the US was attributed to outsourcing (Ballou (1992)), increased globalization, improvements in technology and information availability, the growing consumer awareness of climate change, dwindling natural resources, and general environmental concerns (Gunasekaran, Patel, and Mcgaughey (2004)).

There have been several definitions used to define SCM due to the lack in conceptual understanding of the topic (see Croom, Romano, and Giannakis (2000) and references therein for a synopsis). A general definition is as follows, “a network of firms interacting to deliver a product or service to the end customer, linking flows from raw material supply to final delivery" (Ellram (1990)). There is a wealth of literature addressing both production planning and distribution planning; however, few models attempt to address these problems simultaneously (Cattanach (1995), Thomas and Griffin (1996) and references therein).

A specific supply chain management concept, *Green Supply Chain Management* (GSCM), has recently emerged, in which its contribution lies in identifying collaborations in order to positively impact the environment, carbon footprints, and energy costs (Wycherley (1999)). GSCM consists of "integrating environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end–of–life management of the product after its useful life" (Srivastara (2007)). Not surprisingly, Oakley (1993) noted that total quality environmental management must also consider multicriteria decision-making.

Pertinent GSCM works include that by Krikke, Bloemhof, and Van Wassenhove (2003) which deals with trying to optimize a supply chain design for refrigerators, and analyzing the trade-off between supply chain costs and environmental measures (e.g. energy use and residual waste). See also Beckman, Worhach, and Sheng (1995), Bloemhof-Ruwaard et al. (1995), Zhang et al. (1997), Rodrigue, Slack, and Comtois (2001), Murphy and Poist (2003), Masui (2005), and Srivastava (2007).

An application of supply chain management is the facilitated integration where collaboration in purchasing can occur either by vertical or horizontal mergers between buyers and sellers (Huber, Sweeney, and Smyth (2004)). Equivalently, "network" organizations have been used to represent the collaboration and study the integration effects (Powell (1990), Alstyne (1997)). As an OR/MS application, Ivaldi and Verboven (2005) measured the effects of the proposed VolvoScania horizontal merger using an estimated oligopoly model with product differentiation and computed post-merger equilibrium prices and welfare changes under various alternative scenarios. Additionally, Salant, Switzer, and Reynolds (1983) studied various exogenous market structures, and computed the outputs, prices and resulting profits endogenously using a Cournot-Nash equilibrium model from horizontal mergers. For more literature on the topic refer to Eckbo (1983), Perry and Porter (1985), Farrell and Shapiro (1990) and references therein.

The importance of metrics to evaluate supply chain performance and the resulting implications on horizontal mergers are increasingly important to ensure achievement of organizational goals, and the proper assessment of the effectiveness of the techniques or strategies employed (Gunasekaran, Patel, and Mcgaughey (2004)). However, Beamon (1998) noted, "research in supply chain modeling has only scratched the surface of how supply chain strategies (or decision variables) may affect a given performance measure, or a set of performance measures." Lee and Billington (1993) attribute that incomplete performance measures for the assessment of the entire supply chain may lead to inefficiencies. For an evaluation of performance measurements see Lee and Whang (1993), Chen (1997), and Beamon (1998, 1999).

Operational synergy has been proposed as a means to measure the cost effectiveness of integration of the supply chain through horizontal (same industry) mergers/acquisitions (Chatterjee (1986), Brush (1996)). Synergy is defined by Chatterjee (2007) as "the combination of disparate parts within the new organization can lead to more revenues, more efficiency, or more of both than what the individual parts could muster as stand alone units." Moreover, Chatterjee (2007) believes that, based on academic research, interviews and evidence, when cost reduction rather than potential revenue gain is the stated goal of a merger it is much easier to achieve success.

Even though there have been noted successful mergers (e.g. Kraft-General Foods and Novartis), there have been numerous times when the anticipated synergy was not realized (e.g. AOL/Time-Warner) considering that the merger failure rate is estimated to be between 74% and 83% (Devero (2004)). This leads to the need for efficient tools and understanding of the merger/integration process (Eccles, Lanes, and Wilson (1999)).

Literature on the topic include Soylu et al. (2006) which evaluated synergy using a mixed integer multiperiod, discrete-continuous time model for the integration of various energy process systems and provided a comparative analysis. For additional works see: Farrell and Shapiro (1990, 2001), Juga (1996), Nijkamp and Reggiani (1998), Gowrisankaran (1999), Min and Zhou (2002), Gupta and Gerchak (2002), Stennek (2003), Spector (2003), Alptekinoglu and Tang (2005), and Xu (2007). Nagurney (2009) presented a new theoretical framework for the quantification of strategic advantages associated with horizontal mergers through the integration of system–optimized supply chain networks. She presents both the pre– and post– models of horizontal mergers and defined a measure for the quantification of the associated gains.

Interestingly, Stanwick and Stanwick (2002) claim that the proposed merger can be greatly compromised if environmental issues are ignored. I explicitly address the issue of supply chain integration and environmental concerns in this dissertation. Lambertini and Mantovani (2007) proposed a new framework using a differential game to find that firms collude in the context of a horizontal merger in order to reduce environmental externalities. However, the authors do not consider cost synergies or a supply chain framework.

In this dissertation, I contribute to the current literature to identify the relationship between post-merger operational synergy and the effects on the environment and, thus, ultimately, society, from a quantitative perspective. I build on the work by Nagurney (2009) to quantify and assess, from a supply chain network perspective, the environmental effects resulting when a merger or acquisition occurs and the resulting synergy from possible strategic gains.

Specifically, I develop a multicriteria decision-making supply chain network framework that captures the economic activities of manufacturing, storage, and distribution both pre and post the merger. The models yield the system optima associated with the minimization of the total costs and the total emissions under firm-specific prices associated with environmental criteria. Using a proposed synergy measure that captures the total generalized cost I also provide numerical examples.

I then consider the multiproduct dimension of supply chains with distinct firms and their horizontal integration. Between 1972 and 1997, on the average, two-thirds of US supply firms altered their mix of products every five years (Bernard, Redding, and Schott (2006)). Firms experience efficiency gains by running a multiuse plant where input costs may be divided among different products. While Davis and Wilson (2006) studied differentiated product competition in an equilibrium framework, they did not, however, focus on the integration/merger of the supply chain as a whole.

I develop the multiproduct supply chain network models prior to and post their horizontal integration with explicit capacities associated with the economic activities of production, storage, and distribution; an approach that is closely related to that of Dafermos (1973) who proposed transportation network models with multiple classes of transportation. I build on the novel work of Nagurney (2009) to also focus on the case of horizontal mergers (or acquisitions) and I extend the contributions in Nagurney (2009) to the much more general and richer setting of multiple product supply chains. I utilize a system-optimization perspective for the model development and propose a measure, which allows one to quantify and assess, from a supply chain network perspective, the synergy benefits associated with the integration of multiproduct firms through mergers/acquisitions.

1.2.2 Policy Interventions

The provision of standards and regulatory frameworks help regulatory agencies support environmental sustainability (Wilkinson, Hill, and Gollan (2001)). I specifically focus on the electric power industry as a supply chain application for emission reductions through environmental policies.

The dominant industrial source of air emissions in the US today is the result of electricity generation. For example, fossil fuel-fired power plants are responsible for 67% of the nation's sulfur dioxide emissions, 23% of nitrogen oxide emissions, and 40% of man-made carbon dioxide emissions (USEPA (2007)). The US electric power industry spent $24 billion on compliance with federal environmental laws between 2002–2005. Governments are increasingly constructing legislation aimed to reduce pollution levels; it is estimated that the electric power industry spend $47.8 billion between 2007–2025 to comply with three new federal regulations, namely the Clean Air Interstate Rule, the Clean Air Mercury Rule, and the Clean Air Visibility Rule, which aim to reduce nitrogen oxides, sulfur dioxide, and mercury emissions (USEPA (2005)).

Pollution by the electric power entities can be controlled by price, in the form, for example, of a carbon tax that is imposed for emissions that exceed a predetermined bound, or by quantity, as in the case of pollution permit trading schemes, which involve the trading of permits to emit pollutants. Entities that are given credits (or allowances) by a central authority can then trade, via free markets, providing economic incentives (Tietenberg (2006)).

I utilize the theory of variational inequalities for the quantitative analysis and computation of equilibria of optimal prices and quantities of products transacted as well as the resulting emissions and equilibrium tax and permit prices given a network structure. The theory of variational inequalities has been utilized to study an abundance of equilibrium problems in regards to policy analysis as related to economics and operations research (see Nagurney (1993)). Specifically, the theory has been applied to spatial economic market equilibrium problems with policy interventions (Nagurney and Zhao (1991), Nagurney, Thore, and Pan (1996) and in financial markets (Nagurney and Dong (1995a, 1995b), Dhanda, Nagurney, and Ramanujam (1999)).

In this dissertation I explore both a tradable permit and carbon taxation schemes as means to curb emissions and to improve the environmental quality as related to, specifically, the electric power industry. I first provide insights into the relationship between the two policies; then I introduce an overview of notable works related to the electric power industry. Lastly, I recall the background on each policy scheme and outline the pertinent literature in order to identify opportunities to contribute to the advancement of knowledge on this topic.

1.2.2.1 Tradable Permits *versus* Carbon Taxes

There is a debate as to whether a price or quantity instrument should be used to achieve reductions in emissions and costs imposed on society. The abundance of the literature to-date that discusses the comparison of the policies shows the level of importance, reliance, and implementation of both environmental schemes. The favored policy tool for pollution control by most countries has been taxes, presumably, due to the familiarity and implementation. An exception, however, is the use of permits to control air pollution in the US (e.g. the RECLAIM program) (Norregaard and Reppelin-Hill (2000)).

Pezzey (1992) agues that, “there can be no general presumption that control by quantity is superior to control by price,” due to the variety of circumstances that lead to imperfect competition such as uncertainty (Baumol and Oates (1988), Weitzman (1974), White and Wittman (1983)), vulnerability to monopoly (Malueg (1990), Xepapadeas (1997)), technology investments (Requate (1993)), as well as transaction costs (Koustaal (1997)). Thus, he claims, that efficient control can be achieved though a quantity or price instrument in a symmetrically efficient and acceptable way. Interestingly, a hybrid of taxes and tradable permits may be desirable under uncertainty (Roberts and Spence (1976), Baumol and Oates (1988), Pezzey (2003)). See also Bohm and Russell (1985) for additional dimensions for comparing alternative instruments.

1.2.2.2 The Electric Power Industry

Currently, especially with oil trading at more than $100 per barrel in 2008, energy is the major supply chain focus for companies, with an emphasis on reduction in costs and energy consumption, and the use of alternative energy options (ethanol, biomass, fuel cells, wind, solar, nuclear, and other various energy options) (Penfield (2008)). For example, the retail giant Wal-Mart has at least vowed to become a major sustainability player, as stated on its website, "We have a goal to be supplied by 100% renewable energy, to create zero waste, and to sell products that sustain our resources and environment" (Penfield (2008)).

The impact of the electric power industry on the economy is obvious, as it has been a factor noted to contribute to recessionary periods through the rise in energy prices. For example, the last three recession periods in the US (1974–75, 1980–82, and 1990–91) were preceded by spikes in oil prices (Greenspan (2001)). The electric industry is monitored closely by policymakers for the potential effects of cyclical behavior of the macroeconomy in the short run and for sustainability issues in the long run (Greenspan (2001)).

Noteworthy contributions on the topic of electric power modelling include works on issues such as deregulation and competition (Kahn (1998), Hobbs, Metzler, and Pang (2000), Day, Hobbs, and Pang (2002)), and market power (Bolle (1992), Green and Newbery (1992), von der Fehr and Harbord (1993), Green (1996), Newbery and Pollitt

(1997), Newbery (1998), Wolfram (1998, 1999)). See also Schweppe et al. (1988), Hogan (1992), Chao and Peck (1996), Wu et al. (1996), Jing-Yuan and Smeers (1999), Boucher and Smeers (2001), Conejo and Prieto (2001), Willems (2002), Casazza and Delea (2003), Contreras, Klusch, and Krawczyk (2004), Green (2005), and Nagurney (2006a), and the volumes edited by Singh (1999) and Zaccour (1998).

Nagurney and Matsypura (2005a) were the first to introduce a general electric power supply chain network equilibrium model that included power generators, suppliers, transmission service providers, and consumers at the demand markets. In particular, variational inequality theory was used to determine pricing and computation of solutions. This was based on the supply chain network equilibrium models that handle competition and cooperation and provide the resulting product flows and prices in the work of Nagurney (2006b).

Wu et al. (2006) expanded the work of Nagurney and Matsypura (2005a) and constructed an electric power supply chain network equilibrium model with carbon taxes that are applied a priori to distinct power generator/power plant combinations and demonstrated that the model could be reformulated and solved as a transportation network equilibrium problem with elastic demands.

1.2.2.3 Carbon Tax Policies

The first seminal contribution on the efficiency enhancing use of taxes to correct for negative externalities was by Pigou in 1920; hence, the term *Pigouvian taxes.* The expression *carbon tax* has been used to signify an environmental tax on fossil fuels (coal, oil, gas) in terms of a carbon equivalent, which is the dominant green house gas (Nicoletti and Martins (1992)). In theory, emitters are required to pay a charge per unit of emissions equal to the value of the external social cost or damage caused by the extra unit of emissions.

A carbon tax is an example of a Pigouvian tax because it addresses a negative externality, which represents the social cost of production that is not internalized. If the Pigouvian tax is set equal to the marginal external cost, it induce the polluting firm to internalize the full social costs of its contribution to the pollution damage (Baumol and Oates (1988)). This creates a financial incentive for firms to reduce emissions to the point where the tax is equal to the marginal costs of additional control. However, interestingly, Bovenberg and Goulder (1996) claim that environmental taxes, like all other policy remedies, usually exacerbate pre-existing tax distortions and, optimally, should lie below the Pigouvian level (social marginal damages).

Oates (1995) has been credited with questioning the revenue potential, that is, the ability to create the "double dividend", which not only provides the incentive to reduce emissions and offset other taxes, like labor and capital taxes, but demonstrates that the negative impacts of pollution may be compensated through the use of generated fiscal revenues (Baranzini (1997), Goulder, Parry, and Burtraw (1997), Bovenberg (1999), Baranzini, Goldemberg, and Speck (2000), and Pezzey (2003)). In a study performed by the International Monetary Fund in 1995, Denmark had the highest ratio of green tax revenue to GDP, above 4%, while Mexico and the US had the lowest ratios, about 1% (Norregaard and Reppelin-Hill (2000)).

Researchers have been drawn to the topic of carbon taxes to address issues regarding the short and long run effects. Specifically, the macroeconomic effects of carbon taxes was studied by Sondheimer (1991). A survey of long-run macroeconomic consequences of greenhouse gas abatement was conducted by Boero, Clarke, and Winters (1991). The distributional effects of carbon taxes have been addressed by Poterba (1991), Scott (1992), Smith (1992), and more recently by Metcalf (2007) and Dinan (2007).

The above studies were, subsequently, extended to include behavioral response to the effects brought upon by a carbon tax. Such works include Pearson and Smith

(1991) and Symons, Proops, and Gay (1994). Symons, Proops, and Gay (1994) used an input-output model to study the impact of carbon taxes on fossil fuel and the prices of consumer goods and consumer demand, which was then used to estimate the fossil fuel use and carbon emissions. The model allows for a simulation of various levels of carbon taxes to assess the impact on government revenue and consumer welfare.

Pearce (1991) provides a literature review of carbon tax studies and their effects. For additional research topics addressing carbon taxes, refer to the works by Baumol (1972), Ingham and Ulph (1989), Chandler and Nicholls (1990), Dewees (1992), Nicoletti and Martins (1992), Casler and Rafiqui (1993), Gay and Proops (1993), Proops, Faber, and Wagenhals (1993), Parry, Williams, and Goulder (1999), Goulder et al. (1999), Karki, Mann, and Salehfar (2006), McFarland and Herzog (2006), and Kasahara et al. (2007).

Interesting, Bye and Nyborg (2003) compare a uniform tax regime to a differentiated carbon tax and conclude that there is a slight welfare improvement. They also point out that a uniform carbon tax is equivalent to an auctioned tradable emission permit system. In this dissertation, I add to the current literature and create an electric power supply chain network equilibrium model with alternative technologies that incorporates an endogenous tax. I also show the relationship between this model and that of a sustainable supply chain network.

As noted earlier, Wu et al. (2006) constructed an electric power supply chain network equilibrium model with carbon taxes that are applied a priori to distinct power generator/power plant combinations and demonstrated that the model could be reformulated and solved as a transportation network equilibrium problem with elastic demands. However, in that model, the government authority would have to conduct simulation exercises to determine the carbon tax assignment in order to achieve some goal. In contrast, I demonstrate how carbon taxes can be determined optimally and endogenously within a generalized electric power supply chain network equilibrium model.

In particular, I allow the government to impose bound(s) on the total amount of carbon emissions and the optimal carbon taxes guarantee that the bound(s) are not exceeded. Hence, a mathematical modeling framework that can capture the interactions between decision-makers in an electric power supply chain network from power generators, along with the power plant production options; the suppliers as well as the ultimate consumers, coupled with the incorporation of environmental policies, such as carbon taxes, is of great practical as well as policy-making importance.

1.2.2.4 Emission Trading Schemes

The historical origin of a tradable permit scheme to address pollution issues was first introduced in 1966 by Crocker, whose work was on air pollution, which was followed by Dales in 1968, who studied prices and property rights for water permits. However, the seminal contribution by Montgomery (1972) has provided theoretical insight that much research in this area has been built upon. Montgomery showed that, regardless of the initial allocation, marketable pollution permits be cost-effective, and that markets can attain an equilibrium that meet set standards of environmental quality.

Montgomery had analyzed an ambient-based permit (APS) system (which confers the right to deliver pollutants in terms of pollutant concentrations at receptor points) and an emission-based permit system (EPS) (which grants the holder of the permit the right to emit pollutants up to a specified rate). Krupnick, Oates, and Verg (1983), McGartland and Oates (1985), and McGartland (1988) extended this work to propose, to evaluate, and to compare alternative forms of marketable permit systems.

In theory, marketable permits have been shown to effectively deal with the spatial nature of pollutants, that is, the location of the source as well as the receptor of the environmental damage are considered differentiating among polluters (Baumol and Oates (1988), Tietenberg (1995a), Dhanda, Nagurney, and Ramanujam (1999)). Studies show that, for certain pollutants, if spatial differentiation is not built into the system, then the cost-savings from employing an economic-incentive-based approach be lost (Mendelsohn (1986)). Spatial differentiation be illustrated in the models of my dissertation.

Researchers contributed to the theoretical expansion of the knowledge of tradable permits and focused on the interaction of the efficiency and effectiveness of a tradable permit system in the presence of market imperfections such as market power (Hahn (1984), Misiolek and Elder (1989)), technological change (Milliman and Prince (1989)), research and development (Magat (1978), Spence (1984), Levin and Reiss (1988)), transaction costs (Stavins (1995)), uncertainty (Roberts and Spence (1976), Baumol and Oates (1988), Stavins (1996)), and noncompliance (Malik (1990), Keeler (1991), Egteren and Weber (1996), Stranlund (2007)). See Tietenberg (1980) and Tietenberg (1995b) for a comprehensive survey of the literatures on tradable permits.

Nagurney and Dhanda (1996) were the first to use utilize the theory of variational inequality as a methodology for the qualitative analysis and computation of equilibria in the markets of emission permits. The model takes into account various market structures, the spatial nature of the pollutants to compute the equilibrium allocation of licenses and prices, as well as the quantity and prices of firm product transactions. Nagurney, Dhanda, and Stranlund (1997) then expanded on this work to construct a general market model that includes multiple products and multiple pollutants and computed the profit-maximized quantities of the multiple products, the equilibrium quantities, allocation and prices of emission permits. See also the book by Dhanda, Nagurney, and Ramanujam (1999).

There are few models that consider interactions of electricity markets with tradable permit markets. Johnson and Pekelney (1996), Tschirhart and Wen (1999), as well as Lapierda, Ventosa, and Llamas (2003) modeled the electric power industry with an endogenous permit price but did not show the effect of all the decision-makers in the electric power supply chain network. For example, Montero (2001) considers multipollutants, but not the electric power industry. Mansur (2001) developed a process model that incorporated the electricity and a multiple permit market of sulfur dioxide and nitrous oxide permits. The model computed the equilibrium electricity prices in the PJM market (which stands for Pennsylvania, New Jersey, and Maryland and is the largest power grid operator in North America). However, the permit prices were exogenous to the model and the production cost curves included the permit effects on electricity costs.

Chen and Hobbs (2005) included the electric power market and the marketable permits using linear complementarity models of Nash-Cournot competition. The model determined, endogenously, nitrous oxide permit prices only. Chen and Hobbs (2005) also considered market power in the emission market and included a network representation to allow for transmission congestion. They claimed that, if market power is exercised to withdraw generation from the network, the emissions impact is a function of the substitution generation that occurs. Crespo and Herrera (2002) stated that the estimates of costs, emissions, and prices could be distorted without an adequate representation of transmission.

The work of Chen and Hobbs (2005) was further extended to incorporate market power, that is, the ability of the largest producer in an electric power market to influence the price of not only the electricity, but the permits market. The largest firm follows a Stackelberg game in which, the smaller sized firms act second and follow a Cournot game (Chen et al. (2006)). However, while the work of Chen and Hobbs (2005) and Chen et al. (2006) consider the tradable permits market with the interaction of the electric power market, they only consider, endogenously, a single pollutant. Conversely, while Nagurney, Dhanda, and Stranlund (1997) endogenously determine the prices and quantities transacted in a multiple permit markets, they do not consider the electric power supply chain context.

Schwarz (2005), who focused on the electric power industry, noted that there has been little economics-related research on multipollutants and their effects. This is deemed necessary since the equivalency ratio between two pollutants may vary between seasons, across regions, and, possibly, over time as the composition of the atmosphere changes (WRAP (2003)). Multipollutant regulations aid in the investment decisions of firms when future emission regulations are mandated (Schwarz (2005)) as technology investments for pollutants vary.

To add to the current literature I model the permit market in the case of emissions generated by electric power production to include multiple pollutants and, thus, multiple permit markets for those pollutants as well as spatially dispersed emission receptor points. Moreover, unlike the previous literature, I emphasize the use of alternative power plants as well as the underlying supply chain aspects of electric power generation and distribution.

Technology is a particulary pertinent issue as it relates to the nature of tradable permit schemes. Title IV of the 1990 Amendments to the Clean Air Act declared marketable emission permits as an economic incentive-based environmental program that encourages firms to use alternative forms of technologies to reduce emissions and thus trade excess permits in the market for revenue (Wooley and Morss (2001)). Hence, not only I consider spatially distinct receptor points, but also alternative forms of technology to generate electricity.

The new model allows for the determination of the equilibrium numbers and prices of the various tradable pollution permits simultaneously with the equilibrium electric power flows and prices. The model builds upon the electric power supply chain model with alternative power plant technologies developed by Wu et al. (2006), which, however, only considered a single pollutant (and, in effect, a single receptor point), and was transformed into a transportation network equilibrium model (see also, e.g., Nagurney and Liu (2005)).

1.3 Research Overview

This dissertation consists of eight chapters. In the first Chapter, I aim to provide an overview of the motivation, contribution, and background literature to the research that I conducted. Chapter 2 includes the methodologies and foundational models, theories, and applications that this research is based on.

In Chapter 3 of the dissertation, I develop a novel supply chain model in which the manufacturers can produce the homogeneous product in different manufacturing plants with associated distinct environmental emissions. I assume that the manufacturers, the retailers with which they transact, as well as the consumers at the demand markets for the product are multicriteria decision-makers with the environmental criteria priced distinctly by the different decision-makers. Additionally, I establish that the prices associated with the environmental criteria of the various decision-makers can be interpreted as taxes.

Also in Chapter 3, I prove that the supply chain model with environmental concerns can be reformulated and solved as an elastic demand transportation network equilibrium problem. This research, hence, begins the construction of a bridge between sustainable supply chains and transportation networks, which aid the computational efficiency. This Chapter of the dissertation is based on Nagurney, Liu, and Woolley (2007) but includes the generalization of emission functions which allows for numerous applications of the model.

In Chapter 4, I develop a modeling and computational framework that allows for the determination of optimal carbon taxes applied to electric power plants in the context of electric power supply chain (generation/distribution/consumption) networks. The adoption of carbon/pollution taxes both internationally and regionally has been fueled by global climate change and fuel security risks with a significant portion of such policy interventions directed at the electric power industry.

The general framework that I develop in Chapter 4 allows for three distinct types of carbon taxation environmental policies, beginning with a completely decentralized scheme in which taxes can be applied to each individual generator/power plant in order to guarantee that each assigned emission bound is not exceeded, to two versions of a centralized scheme, one which assumes a fixed bound over the entire electric power supply chain in terms of total carbon emissions and the other which allows the bound to be a function of the tax. Chapter 4 of the dissertation is based on Nagurney, Liu, and Woolley (2006), but, as in Chapter 3, includes the generalization of emission functions.

In Chapter 5 of the dissertation I model the trading of emission rights by electric power producers who emit multiple pollutants with impacts that depend on the spatial dispersion of sources and receptors. The control of multiple, spatially differentiated pollutants via emission trading calls for multiple pollution permit markets. Moreover, unlike the previous literature, I emphasize the use of alternative power production technologies as well as the underlying supply chain aspects of electric power generation and distribution.

The new model developed in Chapter 5 allows for the determination of the equilibrium numbers and prices of the various tradable pollution permits simultaneously with the equilibrium electric power flows and prices. The model builds upon the electric power supply chain model with alternative power plant technologies developed by Wu et al. (2006), which, however, only considered a single pollutant (and, in effect, a single receptor point). This Chapter of the dissertation is based on Woolley, Nagurney, and Stranlund (2009).

In Chapter 6 of the dissertation I quantify and assess, from a supply chain network perspective, the environmental effects resulting when a merger or acquisition occurs and the resulting synergy from possible strategic gains. I develop a multicriteria decision-making supply chain network framework that captures the economic activities of manufacturing, storage, and distribution pre and post the merger (or integration). The models yield the system optima associated with the minimization of the total costs and the total emissions under firm-specific prices. This work is built on the recent work of Nagurney (2009) who developed a system-optimization perspective for supply chain network integration in the case of horizontal mergers. In this Chapter, I also focus on the case of horizontal mergers (or acquisitions) and I extend the contributions in Nagurney (2009) to include multicriteria decision-making and environmental concerns. This multicriteria decision-making optimization framework that not only minimizes costs but also minimizes emissions.

In addition, in Chapter 6, I propose a synergy measure which is then used to analyze the synergy effects associated with a merger, in terms of the operational synergy, that is, the reduction, if any, in the cost of production, storage, and distribution, as well as the environmental benefits in terms of the reduction of associated emissions (if any). There is virtually no literature to-date that discusses the relationship between post-merger operational synergy and the effects on the environment and, thus, ultimately, society. I attempt to address this issue from a quantitative perspective. This Chapter of the dissertation is based on Nagurney and Woolley (2009).

In Chapter 7 of the dissertation, I develop multiproduct supply chain network models prior to and post their horizontal integration with explicit capacities associated with the economic activities of production, storage, and distribution; an approach that is closely related to that of Dafermos (1973) who proposed transportation network models with multiple classes of transportation. I build on the novel work of Nagurney (2009) to also focus on the case of horizontal mergers (or acquisitions) and I extend the contributions in Nagurney (2009) to the much more general and richer setting of multiple product supply chains. I utilize a system-optimization perspective for the model development and provide the variational inequality formulations.

I develop a measure to quantify the synergy, if any, and the respective relationships from the production, shipment, and final consumption of multiple products throughout the network pre and post merger. I provide the variational inequality formulations as well as propose a computational procedure which fully exploits the underlying network structure to illustrate the theoretical and computational framework with numerical examples. This Chapter of the dissertation is based on Nagurney, Woolley, and Qiang (2009).

I conclude the dissertation in Chapter 8 and provide venues for future research.

CHAPTER 2

METHODOLOGIES AND BASIC MODELS

This Chapter provides the methodologies and fundamental models that are used in the dissertation. I first recall variational inequality theory, which is the basic methodology for this dissertation, and is applied in Chapter 3 through Chapter 7 of this dissertation. It is a powerful methodology that can be applied to numerous problems to solve network economic equilibrium models as well as system-optimized problems. I also provide qualitative results of solutions.

Additionally, in this Chapter, I recall the elastic demand transportation network equilibrium problem with known travel disutility functions due to Dafermos (1982) which is utilized in Chapter 3 to establish the supernetwork equivalence of the supply chain network equilibrium model to that of the transportation network equilibrium model with known travel disutility functions. Next, I briefly relate user-optimization to system-optimization problems before introducing the system-optimized problem which is related to Chapter 6 and Chapter 7. The system-optimized problem is utilized for supply chain network integration in the case of horizontal mergers/acquisitions. Subsequently, I introduce the system-optimized problem for multiple modes/classes of transportation that is utilized in Chapter 7 of this dissertation.

Lastly, I provide the algorithms for the solution of finite-dimensional variational inequalities. I first recall the Euler method (cf. Dupuis and Nagurney (1993)) which is utilized in Chapter 3 through Chapter 5 of this dissertation. Then, I recall the modified projection method (Korpelevich (1977)) and the equilibration algorithm (cf.

Dafermos and Sparrow (1969), Nagurney (1993)), which are utilized in Chapter 6 and Chapter 7. Moreover, I briefly relate the modified projection method to that of the Euler method.

2.1 Variational Inequality Theory

In this Section I briefly provide an overview of the theory of variational inequalities. Except where noted, all theorems and definitions presented in this Chapter are taken from Nagurney (1999). Variational inequality theory, which was first defined over infinite-dimensional space by Hartman and Stampacchia (1966), is used throughout this dissertation to solve finite-dimensional network equilibrium problems. Finite-dimensional theory was advanced when Dafermos (1980) recognized that traffic network equilibrium conditions, as stated by Smith (1979), had a structure of a variational inequality. For further discussion and proofs see Nagurney (1999).

Definition 2.1

The finite-dimensional variational inequality problem, VI$(F,\mathcal{K})$*, is to determine a vector* $X^* \in \mathcal{K} \subset \mathcal{R}^n$*, such that*

$$\langle F(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{2.1}$$

where F *is a given continuous function from* $\mathcal{K}$ *to* $\mathcal{R}^n$*,* $\mathcal{K}$ *is a given closed convex set and* $\langle \cdot, \cdot \rangle$ *denotes the inner product in n-dimensional Euclidean space.*

Optimization problems, including constrained and unconstrained, can be formulated as variational inequality problems. The following definition identify the relationship between variational inequality theory and an optimization problem.

Proposition 2.1

Let X^* be a solution to the optimization problem:

$$Minimize \quad f(X) \tag{2.2}$$

$$\text{subject to: } X \in \mathcal{K},$$

where f is continuously differentiable and $\mathcal{K}$ is closed and convex. Then X^* is a solution of the variational inequality problem:

$$\langle \nabla f(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{2.3}$$

where $\nabla f(X)$ is the gradient vector of f with respect to X.

Proposition 2.2

If $f(X)$ is a convex function and X^* is a solution to $\mathrm{VI}(\nabla f, \mathcal{K})$, then X^* is a solution to the optimization problem (2.2). If the feasible set $\mathcal{K} = \mathcal{R}^n$, then the unconstrained optimization problem is also a variational inequality problem.

The variational inequality problem can be reformulated as an optimization problem given that certain symmetry conditions hold. I now present the definition of positive semidefinite, positive definite and strongly positive definite.

Definition 2.2

An $n \times n$ matrix $M(X)$, whose elements $m_{ij}(X); i = 1, \ldots, n; j = 1, \ldots, n$ are functions defined on the set $S \subset \mathcal{R}^n$, is said to be positive semidefinite on S if

$$v^T M(X) v \geq 0, \forall v \in \mathcal{R}^n, X \in S. \tag{2.4}$$

It is said to be positive definite on S if

$$v^T M(X) v > 0, \forall v \neq 0, v \in \mathcal{R}^n, X \in S. \tag{2.5}$$

It is said to be strongly positive definite on S if

$$v^T M(X)v \geq \alpha \|v\|^2, for\ \ some\ \ \alpha > 0, \forall v \in \mathcal{R}^n, X \in S. \tag{2.6}$$

The variational inequality problem can be reformulated as a convex optimization problem when the Jacobian matrix of $F(X)$ is symmetric and positive semidefinite. However, the variational inequality is the more general problem formulations that can also handle a function $F(X)$ with an asymmetric Jacobian.

Theorem 2.1

Assume that $F(X)$ is continuously differentiable on $\mathcal{K}$ and that that Jacobian matrix

$$\nabla f(X) = \begin{bmatrix} \frac{\partial F_1}{\partial X_1} & \cdots & \frac{\partial F_1}{\partial X_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_n}{\partial X_1} & \cdots & \frac{\partial F_n}{\partial X_n} \end{bmatrix} \tag{2.7}$$

is symmetric and positive semidefinite. Then there is a real-valued convex function $f : \mathcal{K} \longmapsto \mathcal{R}^1$ satisfying

$$\nabla f(X) = F(X) \tag{2.8}$$

with X^* the solution of VI$(F, \mathcal{K})$ *also being the solution of the mathematical programming problem:*

$$Minimize \quad f(X)$$

$$subject\ to\text{: } X \in \mathcal{K},$$

where $f(X) = \int F(X)^T dx$, and $\int$ is a line integral.

I now provide the conditions for basic existence and uniqueness results of solutions to the variational inequality problem.

Theorem 2.2

If $\mathcal{K}$ is a compact set and F(X) is continuous on $\mathcal{K}$, then the variational inequality problem admits at least one solution X^*.

Theorem 2.3

If the feasible set $\mathcal{K}$ is unbounded, then $\mathrm{VI}(F, \mathcal{K})$ *admits a solution if and only if there exists an $\mathcal{R} > 0$ and a solution of* $\mathrm{VI}(F, \mathcal{S})$*, X^*_R, such that $\|X^*_R\| < \mathcal{R}$, where $\mathcal{S} = \{X : \|X\| \leq \mathcal{R}\}$.*

Theorem 2.4

Suppose that F(X) satisfies the coercivity condition

$$\frac{\langle (F(X) - F(X_0))^T, X - X_0 \rangle}{\|X - X_0\|} \to \infty \tag{2.9}$$

as $\|X\| \to \infty$ for $X \in \mathcal{K}$ and for some $X_0 \in \mathcal{K}$, then $\mathrm{VI}(F, \mathcal{K})$ *always has a solution.*

Given certain monotonicity conditions, the qualitative properties of existence and uniqueness can be obtained easily. I now recall definitions of monotonicity, strict monotonicity, strong monotonicity, and Lipschitz continuity.

Definition 2.3 (Monotonicity)

F(X) is monotone on $\mathcal{K}$ if

$$\langle [F(X^1) - F(X^2)]^T, X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{2.10}$$

Definition 2.4 (Strict Monotonicity)

F(X) is strictly monotone on $\mathcal{K}$ if

$$\langle [F(X^1) - F(X^2)]^T, (X^1 - X^2) \rangle > 0, \quad \forall X^1, X^2 \in \mathcal{K}, X^1 \neq X^2. \tag{2.11}$$

Definition 2.5 (Strong Monotonicity)

F(X) is strongly monotone on $\mathcal{K}$ *if for some* $\alpha > 0$

$$\langle [F(X^1) - F(X^2)]^T, (X^1 - X^2) \rangle \geq \alpha \|X^1 - X^2\|^2, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{2.12}$$

Definition 2.6 (Lipschitz Continuity)

F(X) is Lipschitz continuous on $\mathcal{K}$ *if there exists an* $L > 0$*, where L is the Lipschitz constant, such that*

$$\|F(X^1) - F(X^2)\| \leq L\|(X^1 - X^2)\|, \quad \forall X^1, X^2 \in \mathcal{K}. \tag{2.13}$$

Theorem 2.5

Suppose that F(X) is strictly monotone on $\mathcal{K}$*. Then the solution is unique, if one exists.*

Theorem 2.6

There exists precisely one solution X^* *to* $\mathrm{VI}(F, \mathcal{K})$ *if F(X) is strongly monotone.*

It is important to note that strong monotonicity of the function F guarantees both existence and uniqueness given an unbounded feasible set $\mathcal{K}$. However, if the feasible set $\mathcal{K}$ is compact, hence closed and bounded, then only the strict monotonicity condition needs to hold for uniqueness to be guaranteed, while existence is guaranteed if F is continuous.

2.2 The Transportation Network Equilibrium Model with Given Disutility Functions

In this Section, I recall the transportation network equilibrium model with elastic demands with given travel disutility functions, due to Dafermos (1982), in which the travel disutility functions are assumed continuous, known and given. This model is utilized in Chapter 3 to establish the supernetwork equivalence of the supply chain network equilibrium model to that of the transportation network equilibrium model with known travel disutility functions.

Consider a network $\mathcal{G}$ with the set of links L with n_L elements, the set of paths P with n_P elements, and the set of origin/destination (O/D) pairs W with n_W elements. I denote the set of paths joining O/D pair w by P_w. Links are denoted by a, b, etc; paths by p, q, etc., and O/D pairs by w_1, w_2, etc.

Denote the flow on path p by x_p and the flow on link a by f_a. The user travel cost on a link a is denoted by c_a and the user travel cost on a path p by C_p.

The link flows are related to the path flows through the following conservation of flow equations:

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L, \tag{2.14}$$

where $\delta_{ap} = 1$ if link a is contained in path p, and $\delta_{ap} = 0$, otherwise. Hence, the flow on a link is equal to the sum of the flows on paths that contain that link.

The user costs on paths are related to user costs on links through the following equations:

$$C_p = \sum_{a \in L} c_a \delta_{ap}, \quad \forall p \in P, \tag{2.15}$$

that is, the user cost on a path is equal to the sum of user costs on links that make up the path.

For the sake of generality, one can allow the user cost on a link to depend upon the entire vector of link flows, denoted by f, so that

$$c_a = c_a(f), \quad \forall a \in L. \tag{2.16}$$

I assume, as given, continuous travel disutility functions, such that

$$\lambda_w = \lambda_w(d), \quad \forall w, \tag{2.17}$$

where d is the vector of travel demands with travel demand associated with O/D pair w being denoted by d_w.

The following conservation of flow equations must hold:

$$\sum_{p \in P_w} x_p = d_w, \quad \forall w. \tag{2.18}$$

Definition 2.7 (Transportation Network Equilibrium with Given Disutility Functions)

In equilibrium, the following conditions must hold for each O/D pair $w \in W$ and each path $p \in P_w$:

$$C_p(x^*) - \lambda_w(d^*) \begin{cases} = 0, & \textit{if} \quad x_p^* > 0, \\ \geq 0, & \textit{if} \quad x_p^* = 0. \end{cases} \tag{2.19}$$

The interpretation of conditions (2.19) is as follows: only those paths connecting an O/D pair are used that have minimal travel costs and those costs are equal to the travel disutility associated with traveling between that O/D pair. As proved in Dafermos (1982), the transportation network equilibrium conditions (2.19) are equivalent to the following variational inequality in path flows: determine $(x^*, d^*) \in \mathcal{K}_2^1$ (where the following notation is used: $\mathcal{K}_j^i$ is the feasible set i in Chapter j), such that

$$\sum_{w \in W} \sum_{p \in P_w} C_p(x^*) \times \left[x_p - x_p^*\right] - \sum_{w \in W} \lambda_w(d^*) \times [d_w - d_w^*] \geq 0, \quad \forall (x, d) \in \mathcal{K}_2^1,$$

where

$$\mathcal{K}_2^1 \equiv \{(x, d) | (x, d) \in R_+^{n_P + n_W} \text{and } d_w = \sum_{p \in P_w} x_p, \forall w\}. \tag{2.20}$$

I now recall the equivalent variational inequality in link form due to Dafermos (1982).

Theorem 2.7

A link flow pattern and associated travel demand pattern is a transportation network equilibrium if and only if it satisfies the variational inequality problem: determine $(f^*, d^*) \in \mathcal{K}_2^2$ *satisfying*

$$\sum_{a \in L} c_a(f^*) \times (f_a - f_a^*) - \sum_{w \in W} \lambda_w(d^*) \times (d_w - d_w^*) \geq 0, \quad \forall (f, d) \in \mathcal{K}_2^2, \tag{2.21}$$

where $\mathcal{K}_2^2 \equiv \{(f, d) \in R_+^{n_L + n_W} \,|$ *there exists an* x *satisfying* (2.14)
and $d_w = \sum_{p \in P_w} x_p, \forall w\}$.

Beckmann, McGuire, and Winsten (1956) were the first to formulate rigorously the transportation network equilibrium conditions (2.19) in the context of user link cost functions and travel disutility functions that admitted symmetric Jacobian matrices so that the equilibrium conditions (2.19) coincided with the Kuhn-Tucker optimality conditions of an appropriately constructed optimization problem. The variational inequality formulation, in turn, allows for asymmetric functions (see also, e.g., Nagurney (1999) and the references therein).

2.3 User-Optimization *versus* System-Optimization

In the following Section 2.4, I recall the system-optimized problem. I would like to briefly compare system-optimization (S-O) to that of user-optimization (U-O). Wardrop (1952) proposed two principles to characterize users' behavior in a transportation network. The first principle, coined later by Dafermos and Sparrow (1969) as *User-Optimization*, stated that "the journey times of all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route" (Wardrop (1952)). The second principle stated "the average journey time is minimal" (Wardrop (1952)), which was later coined by Dafermos and Sparrow (1969) as *System-Optimization*.

The behavior of the users of the networks themselves in a user-optimized network is that of noncooperation. Individuals seek to minimize their own travel cost or time, which, although *optimal* from each traveler's perspective, it may not be optimal from a societal one, where a central controller seeks to minimize the total cost throughout the network. The user-optimized network equilibrium conditions require that all utilized paths connecting an O/D pair have equal and minimal travel costs. However, in the system-optimized problem, optimality conditions state that the marginal of the total cost on each used path connecting an O/D pair is equalized and minimal (Nagurney (2002)). For more information, see also Beckmann, McGuire, and Winsten (1956), Dafermos and Sparrow (1969), Nagurney (1999), and Yang and Huang (2004).

2.4 The System-Optimized Model

In this Section, I recall the system-optimized (S-O) model that is utilized in Chapter 6 of the dissertation for supply chain network integration in the case of horizontal mergers/acquisitions. It should be noted that in Chapter 6, with the addition of link capacities, direct system-optimized formulations are not used. As in Section 2.2, the network $\mathcal{G} = [N, L]$ and the user link cost functions are assumed to be continuous. However, in the S-O problem, there is a central controller who routes the traffic in an optimal manner so as to minimize the total cost in the network.

Moreover, the demand associated with each O/D pair is now fixed. I denote the travel demand associated with traveling between O/D pair w by d_w where d_w is assumed fixed and known for all w.

For simplicity, the user link cost functions are now assumed to be $c_a = c_a(f_a), \ \forall a \in L$. The total cost on link a, denoted by $\hat{c}_a(f_a)$, is, hence, given by:

$$\hat{c}_a(f_a) = c_a(f_a) \times f_a, \ \forall a \in L, \tag{2.22}$$

that is, the total cost on a link is equal to the user link cost on the link times the flow on the link.

As noted earlier, in the system-optimized problem, there exists a central controller who seeks to minimize the total cost in the network system, that is,

$$\text{Minimize}_{f\in\mathcal{K}_2^3} \quad \sum_{a\in L} \hat{c}_a(f_a), \tag{2.23}$$

where the total cost, TC, is expressed as

$$TC = \sum_{a\in L} \hat{c}_a(f_a), \tag{2.24}$$

and $\mathcal{K}_2^3 \equiv \{f \in R_+^{n_L} \,|\, \text{there exists an } x \text{ satisfying}\, d_w = \sum_{p\in P_w} x_p, \forall w \;\text{ and}$
$f_a = \sum_{p\in P} x_p\delta_{ap}, \forall a \in L\}$. It is assumed that the total link cost functions are convex. Clearly, the feasible set is convex.

The associated cost on each path, p, denoted by $\hat{C}_p$, is as follows:

$$\hat{C}_p = C_p x_p, \;\; \forall p \in P, \tag{2.25}$$

which is the user cost on a path times the flow on the path, where the user cost on a path, C_p, is given by (2.15).

In lieu of (2.14), (2.15), and (2.16), the cost on a path p can be expressed as a function of the path flow variables. Hence, objective function (2.23), alternatively, stated in path flow variables only, is as follows:

$$\text{Minimize}_{x\in\mathcal{K}_2^4} \quad \sum_{p\in P} C_p(x)x_p \tag{2.26}$$

subject to (2.18) and the nonnegativity of the path flows, where
$\mathcal{K}_2^4 \equiv \{x | x \in R_+^{n_P} \,\text{and}\, d_w = \sum_{p\in P_w} x_p, \forall w \,\text{holds}\}$.

Definition 2.8 (System-Optimality Conditions)

The objective function (2.23) in the S-O problem is convex, and the feasible set $\mathcal{K}^2$ *is convex, under the assumption of increasing user link cost functions. Therefore, the optimality conditions are: for each O/D pair* $w \in W$ *and each path* $p \in P_w$*, the flow pattern* x *(and the corresponding link flow pattern* f*), satisfying constraints (2.14) and (2.18), and the nonnegativity of the path flows, must satisfy:*

$$\hat{C}'_p(x) \begin{cases} = \mu_w, & \text{if} \quad x_p > 0, \\ \geq \mu_w, & \text{if} \quad x_p = 0, \end{cases} \tag{2.27}$$

where $\hat{C}'_p(x)$ *denotes the marginal of the total cost on path p, given by:*

$$\hat{C}'_p(x) = \sum_{a \in L} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \delta_{ap}, \tag{2.28}$$

evaluated in (2.27) at the solution and μ_w *is the Lagrange multiplier associated with constraint (2.18) for that O/D pair* w*.*

According to the optimality conditions (2.27), in the S-O problem, the marginal of the total cost on each used path connecting an O/D pair is equalized and minimal (see also, e.g., Dafermos and Sparrow (1969)).

2.4.1 The System-Optimized Model for Multiple Modes/Classes of Transportation

In this Section, I present the system-optimized (S-O) problem with multiple modes/classes that is extended in Chapter 7 of the dissertation for supply chain network integration in the case of horizontal mergers/acquisitions with multiple modes/ classes of transportation. This work is most closely related to Dafermos (1973) who proposed transportation network models with multiple modes/classes of transportation. The notation used is as described in Section 2.4, the network, $\mathcal{G} = [N, L]$, and the user link cost functions are assumed continuous, there is a central controller, and the demand associated with each O/D pair is fixed.

I include now the multiple modes/classes of transportation denoted as i; $i = 1, \ldots, I$. The following conservation of flow equations must hold:

$$f_a^i = \sum_{p \in P} x_p^i \delta_{ap}, \quad \forall a \in L; i = 1, \ldots, I, \tag{2.29}$$

where $\delta_{ap} = 1$ if link a is contained in path p, and $\delta_{ap} = 0$, otherwise. Additionally, the following conservation of flow equations must hold:

$$\sum_{p \in P_w} x_p^i = d_w^i, \quad \forall i = 1, \ldots, I; \forall w. \tag{2.30}$$

The total cost function on a link, a, with transportation mode/class i, is denoted by $\hat{c}_a^i(f_a^1, \ldots, f_a^I)$, is, hence, given by:

$$\hat{c}_a^i(f_a^1, \ldots, f_a^I) = c_a^i(f_a^1, \ldots, f_a^I) \times f_a^i, \ \forall a \in L, i = 1 \ldots I \tag{2.31}$$

where the user link cost functions are given as $c_a^i = c_a^i(f_a^1, \ldots, f_a^I)$, $\forall a \in L; i = 1, \ldots, I$. It is assumed that the cost on each link is a function of the flow of all the modes/classes on the link.

The objective in the multimode/class system-optimized problem to minimize the total cost in the network system, can now be expressed as,

$$\text{Minimize}_{f \in \mathcal{K}_2^5} \quad \sum_{a \in L} \sum_{i=1}^{I} \hat{c}_a^i(f_a^1, \ldots, f_a^I), \tag{2.32}$$

where the total cost, TC, is expressed as

$$TC = \sum_{a \in L} \sum_{i=1}^{I} \hat{c}_a^i(f_a^1, \ldots, f_a^I), \tag{2.33}$$

and $\mathcal{K}_2^5 \equiv \{f \in R_+^{n_L} \,|\, \text{there exists an } x \text{ satisfying } d_w^i = \sum_{p \in P_w} x_p^i, \forall w; \forall i = 1, \ldots, I$ and

$f_a^i = \sum_{p \in P} x_p^i \delta_{ap}, \forall a \in L; \forall i = 1, \ldots, I\}$. As in Section 2.4 the feasible set $\mathcal{K}_2^5$ is convex.

The associated cost on each path, p, for mode/class i, denoted by $\hat{C}_p^i$, is as follows:

$$\hat{C}_p^i = C_p^i x_p^i, \ \forall p \in P; i = 1, \ldots, I. \tag{2.34}$$

The objective function (2.32), alternatively, stated in path flow variables only, is as follows:

$$\text{Minimize}_{x \in \mathcal{K}_2^6} \quad \sum_{p \in P} \sum_{i=1}^{I} C_p^i(x) x_p^i \tag{2.35}$$

subject to (2.30) and the nonnegativity of the path flows, where
$\mathcal{K}_2^6 \equiv \{x | x \in R_+^{n_P} \text{ and } d_w^i = \sum_{p \in P_w} x_p^i, \forall w \ ; i = 1 \ldots I, \text{holds}\}$.

Definition 2.9 (Multimodal/Multiclass System-Optimality Conditions) *The optimality conditions for each O/D pair $w \in W$ and each path $p \in P_w$, and each mode/class i, the flow pattern x (and the corresponding link flow pattern f), satisfying constraints (2.29) and (2.30), and the nonnegativity of the path flows, must satisfy:*

$$\hat{C}'^i_p(x) \begin{cases} = \mu_w^i, & \textit{if} \quad x_p^i > 0, \\ \geq \mu_w^i, & \textit{if} \quad x_p^i = 0, \end{cases} \tag{2.36}$$

where $\hat{C}'^i_p(x)$ denotes the marginal of the total cost on path p, with mode/class i, given by:

$$\hat{C}'^i_p(x) = \sum_{a \in L} \sum_{j=1}^{I} \delta_{ap} \frac{\partial \hat{c}_a^j}{\partial f_a^i} \tag{2.37}$$

evaluated in (2.36) at the solution and μ_w is the Lagrange multiplier associated with constraint (2.30) for that O/D pair w.

2.5 Algorithms

The iterative progression to the equilibrium by a variational inequality algorithm is usually through some equilibration procedure. In this Section I recall the Euler method (for use in Chapter 3 through Chapter 5 of this dissertation), the modified projection method, and the equilibration algorithm (related to Chapter 6 and Chapter 7). I also provide a brief comparison of modified projection and the Euler method.

2.5.1 The Euler Method

In this Section, I recall the Euler method, which is induced by the general iterative scheme of Dupuis and Nagurney (1993). Nagurney and Zhang (1996) applied the Euler method to solve variational inequality (2.20), which is in path flows (see also Zhang and Nagurney (1997)).

I now present the Euler method for the solution of variational inequality (2.1). Convergence results can be found in the above references. Note that $\mathcal{T}$ represents an iteration counter.

Step 0: Initialization

Set $X^0 \in \mathcal{K}$.

Let $\mathcal{T} = 1$ and set the sequence $\{\alpha_{\mathcal{T}}\}$ so that $\sum_{\mathcal{T}=1}^{\infty} \alpha_{\mathcal{T}} = \infty$, $\alpha_{\mathcal{T}} > 0$ for all $\mathcal{T}$, and $\alpha_{\mathcal{T}} \to 0$ as $\mathcal{T} \to \infty$.

Step 1: Computation

Compute $X^{\mathcal{T}} \in \mathcal{K}$ by solving variational inequality subproblem:

$$\langle X^{\mathcal{T}} + \alpha_{\mathcal{T}} F(X^{\mathcal{T}-1}) - X^{\mathcal{T}-1}, X - X^{\mathcal{T}} \rangle \geq 0, \ \ \forall X \in \mathcal{K}. \tag{2.38}$$

Step 2: Convergence Verification

If $|X^{\mathcal{T}} - X^{\mathcal{T}-1}| \leq \epsilon$, with $\epsilon > 0$, a pre-specified tolerance, then stop; otherwise, set $\mathcal{T} =: \mathcal{T} + 1$, and go to Step 1.

For convergence conditions, see Dupuis and Nagurney (1993).

2.5.2 The Modified Projection Method

The modified projection method of Korpelevich (1977) can be used to solve a finite-deminsional variational inequality problem. For convergence, this method requires monotonicity and Lipschitz continuity of the function F that enters variational inequality (2.1) (and that a solution exists).

I now present the modified projection method. Note that $\mathcal{T}$ represents an iteration counter.

Step 0: Initialization

Set $X^0 \in \mathcal{K}$. Let $\mathcal{T} = 1$ and let α be a scalar such that $0 < \alpha \leq \frac{1}{L}$, where L is the Lipschitz continuity constant (cf. (2.13)).

Step 1: Computation

Compute $\overline{X}^{\mathcal{T}}$ by solving the variational inequality subproblem:

$$\langle \overline{X}^{\mathcal{T}} + \alpha F(X^{\mathcal{T}-1}) - X^{\mathcal{T}-1}, X - \overline{X}^{\mathcal{T}} \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{2.39}$$

Step 2: Adaptation

Compute $X^{\mathcal{T}}$ by solving the variational inequality subproblem:

$$\langle X^{\mathcal{T}} + \alpha F(\overline{X}^{\mathcal{T}-1}) - X^{\mathcal{T}-1}, X - X^{\mathcal{T}} \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{2.40}$$

Step 3: Convergence Verification

If max $|X_l^{\mathcal{T}} - X_l^{\mathcal{T}-1}| \leq \epsilon$, for all l, with $\epsilon > 0$, a pre-specified tolerance, then stop; else set $\mathcal{T} =: \mathcal{T} + 1$, and go to Step 1.

Theorem 2.9 (Convergence)

If F(X) is monotone and Lipschitz continuous (and a solution exists), the modified projection algorithm converges to a solution of variational inequality (2.1).

2.5.3 The Equilibration Algorithms

The equilibration algorithms of Dafermos and Sparrow (1969) (see also Nagurney (1993)) can be used to exploit the problem structure to efficiently proceed to the equilibrium. The modified projection method utilizes a sequence of diagonal quadratic programming problems that are network optimization problems where the feasible set has a characteristic network structure. Thus, a sequence of, typically, symmetric network equilibrium problems are solved when the variational inequality algorithms are applied to the network equilibrium problems. Traffic network equilibrium problems are an example of variational inequality problems where the feasible set has a network structure.

The efficiency of the modified projection method depends on the network-based algorithm used for the solution of the embedded mathematical programming problem. I now present, for the solution of the S-O problem in the case of linear and separable user link travel cost functions, the S-O equilibration algorithm that can be embedded in the modified projection method to attain the solution to the S-O problem. It should be noted that there are both S-O and U-O versions of the equilibration algorithms. For more information see Dafermos and Sparrow (1969) and Nagurney (1999).

The first equilibration algorithm is given for a single O/D pair in which the central controller seek to minimize the total cost in the network (cf. (2.23)). The user link cost functions (cf. 2.16) are assumed given by

$$c_a = g_a f_a + h_a, \quad \forall a \in L; \quad g_a, h_a \geq 0, \quad \forall a. \tag{2.41}$$

The total cost on a link is then defined as:

$$\hat{c}_a(f_a) = (g_a f_a + h_a) \times f_a; \quad \forall a \in L; \quad g_a, h_a \geq 0, \quad \forall a. \tag{2.42}$$

The total cost on a path p, $\hat{C}_p$, is:

$$\hat{C}_p = \sum_{a \in L} \hat{c}_a(f_a)\delta_{ap}, \quad \forall p \in P. \tag{2.43}$$

The marginal of the total cost on the paths is given as

$$\hat{C}'_p = \sum_{a \in L} \hat{c}'_a \delta_{ap}, \quad \forall p \in P, \tag{2.44}$$

where

$$\hat{c}'_a(f_a) = 2g_a f_a + h_a, \quad \forall a \in L; \;\; g_a, h_a \geq 0, \quad \forall a. \tag{2.45}$$

The second S-O equilibration algorithm can be utilized for multiple O/D pairs.

2.5.3.1 Single O/D Pair Equilibration

Step 0: Initialization

Create an initial feasible link flow pattern that is also a feasible path flow pattern. Set $\mathcal{T} = 1$ where $\mathcal{T}$ represents an iteration counter.

Step 1: Selection and Convergence Verification

Determine

$$r = \{p | \max_p \hat{C}'_p, \quad x_p^{\mathcal{T}-1} > 0\}$$

$$q = \{p | \min_p \hat{C}'_p\}.$$

If $|\hat{C}'_r - \hat{C}'_q| \leq \epsilon$, with the prespecified tolerance, $\epsilon > 0$, then stop; else go to Step 2.

Step 2: Computation

Compute the following:

$$\Delta' = \frac{[\hat{C}'_r - \hat{C}'_q]}{\sum_{a\in\mathcal{L}} 2g_a(\delta_{aq} - \delta_{ar})^2} \tag{2.46}$$
$$\Delta = \min\{\Delta', x_r^{\mathcal{T}-1}\}.$$

Set:

$$x_r^{\mathcal{T}} = x_r^{\mathcal{T}-1} - \Delta; \quad x_q^{\mathcal{T}} = x_q^{\mathcal{T}-1} + \Delta$$

$$x_p^{\mathcal{T}} = x_p^{\mathcal{T}-1}, \quad \forall p \neq q \cup r.$$

Then let $\mathcal{T} = \mathcal{T} + 1$ and proceed to Step 1.

2.5.3.2 Multiple O/D Pair Equilibration

To start, Let $E^1 \equiv E_{w_J} \circ \ldots \circ E_{w_1}$ where E_{w_i} is the equilibration operator for a fixed O/D pair w_i.

Step 0: Initialization

Create an initial feasible link flow pattern that is also a feasible path flow pattern. Set $\mathcal{T} = 1$ where $\mathcal{T}$ represents an iteration counter.

Step 1: Equilibration

Apply E^1. Note that E^1 equilibrates only one pair of paths for an O/D pair before proceeding to the next O/D pair, and so on.

Step 2: Convergence Verification

If $|\hat{C}'_{r_{w_i}} - \hat{C}'_{q_{w_i}}| \leq \epsilon$; $i = 1, ..., J$, with the prespecified tolerance, $\epsilon > 0$, where $r = \{p|\max_{p_{w_i}} \hat{C}'_{p_{w_i}},\ x_{p_{w_i}}^{\mathcal{T}-1} > 0\}$; $i = 1, ..., J$, and $q = \{p_{w_i}|\min_{p_{w_i}} \hat{C}'_{p_{w_i}}\}$; $i = 1, ..., J$, then stop; else let $\mathcal{T} = \mathcal{T} + 1$ and proceed to Step 1.

2.5.4 Comparison of the Modified Projection and the Euler Method

The Euler method (2.38) and the modified projection method (2.39) – (2.40) differ in the step size, α. The modified projection method utilizes a constant step size, α, while the Euler method makes use of an altering step size, $\alpha_{\mathcal{T}}$, that diminishes with each $\mathcal{T}$. The Euler method can be used as an alternative discrete-time approximation method for the continuous-time projected dynamical system (cf. Dupuis and Nagurney (1993)) while the modified projection method focuses on the solution of the variational inequality.

CHAPTER 3

SUSTAINABLE SUPPLY CHAIN AND TRANSPORTATION NETWORKS

Transportation provides the foundation for the linking of economic activities. Without transportation, inputs to production processes do not arrive, nor can finished goods reach their destinations. In today's globalized economy, inputs to production processes may lie continents away from assembly points and consumption locations, further emphasizing the critical infrastructure of transportation in product supply chains.

At the same time that supply chains have become increasingly globalized, environmental concerns due to global warming and associated security risks regarding energy supplies have drawn the attention of numerous constituencies (cf. Cline (1992), Poterba (1993), and Painuly (2001)). Indeed, companies are increasingly being held accountable not only for their own performance in terms of environmental accountability, but also for that of their suppliers, subcontractors, joint venture partners, distribution outlets and, ultimately, even for the disposal of their products. Consequently, poor environmental performance at any stage of the supply chain may damage the most important asset that a company has, which is its reputation.

As noted in the Introduction, in this Chapter, a significant extension of the supply chain network model of Nagurney and Toyasaki (2003), which introduced environmental concerns into a supply chain network equilibrium framework (see also Nagurney, Dong, and Mokhtarian (2002b)), is made through the introduction of alternative manufacturing plants for each manufacturer with distinct associated environmental emissions. In addition, I demonstrate that the new supply chain network equilibrium model can be transformed into a transportation network equilibrium model with elastic demands over an appropriately constructed abstract network or supernetwork. This theoretical result can be exploited in practice through the computation of numerical examples.

This Chapter is based on Nagurney, Liu, and Woolley (2007), but includes the generalization of emission functions which aids in the numerous possible applications of the model, and is organized as follows. Section 3.1 develops the multitiered, multicriteria supply chain network model with distinct manufacturing plants and associated emissions and presents the variational inequality formulation of the governing equilibrium conditions. It is also established that the prices associated with the environmental criteria of the various decision-makers can be interpreted as taxes. Section 3.2 demonstrates how the new supply chain network model with environmental concerns can be transformed into a transportation network equilibrium model over an appropriately constructed abstract network or supernetwork. This equivalence provides a new interpretation of the equilibrium conditions governing sustainable supply chains in terms of path flows. In Section 3.3 the Euler method algorithm (see Section 2.5.1) developed for the computation of solutions to elastic demand transportation network equilibrium problems is applied to solve numerical supply chain network problems in which there are distinct manufacturing plants available for each manufacturer and emissions associated with production as well as with transportation/transaction and the operation of the retailers are included. The numerical examples illustrate the potential power of this approach for policy analysis. Summary and conclusions are presented in Section 3.4.

The contributions in this Chapter further demonstrate the generality of the concepts of transportation network equilibrium, originally proposed in the seminal book of Beckmann, McGuire, and Winsten (1956) (see also Boyce, Mahmassani, and Nagurney (2005)). Indeed, recently, it has been shown by Nagurney (2006a) that supply chains can be reformulated and solved as transportation network problems. Moreover, the papers by Nagurney and Liu (2005) and Wu et al. (2006) demonstrate, as hypothesized by Beckmann, McGuire, and Winsten (1956), that electric power generation and distribution networks can be reformulated and solved as transportation network equilibrium problems. See also the book by Nagurney (2006b) for a variety of transportation-based supply chain network models and applications and the book by Nagurney (2000) on sustainable transportation networks.

3.1 The Supply Chain Model with Alternative Manufacturing Plants and Environmental Concerns

In this Section I develop the supply chain network model that includes manufacturing plants as well as multicriteria decision-making associated with environmental concerns. I consider I manufacturers, each of which generally owns and operates M manufacturing plants. Each manufacturing plant is associated with a different primary production process and energy consumption combination with associated environmental emissions. There are also J retailers, T transportation/transaction modes between each retailer and demand market, with a total of K demand markets, as depicted in Figure 3.1. The majority of the needed notation is given in Table 3.1. An equilibrium solution is denoted by "*". All vectors are assumed to be column vectors, except where noted otherwise.

The top-tiered nodes in the supply chain network in Figure 3.1, enumerated by $1, \ldots, i \ldots, I$, represent the I manufacturers, who are the decision-makers who own and operate the manufacturing plants denoted by the second tier of nodes in the network. The manufacturers produce a homogeneous product using the different plants and sell the product to the retailers in the third tier.

Table 3.1. The Notation for the Supply Chain Network Model

Notation	**Definition**
q_{im}	quantity of product produced by manufacturer i using plant m, where $i = 1, \ldots, I; m = 1, \ldots, M$
q_m	I-dimensional vector of the product generated by manufacturers using plant m with components: $q_{1m}, \ldots, q_{Im}$
q	IM-dimensional vector of all the production outputs generated by the manufacturers at the plants
Q^1	IMJ-dimensional vector of flows between the plants of the manufacturers and the retailers with component imj denoted by q_{imj}
Q^2	JTK-dimensional vector of product flows between retailers and demand markets with component jtk denoted by q^t_{jk} and denoting the flow between retailer j and demand market k via transportation/transaction mode t
d	K-dimensional vector of market demands with component k denoted by d_k
$f_{im}(q_m)$	production cost function of manufacturer i using plant m with marginal production cost with respect to q_{im} denoted by $\frac{\partial f_{im}}{\partial q_{im}}$
$c_{imj}(q_{imj})$	transportation/transaction cost incurred by manufacturer i using plant m in transacting with retailer j with marginal transaction cost denoted by $\frac{\partial c_{imj}(q_{imj})}{\partial q_{imj}}$
h	J-dimensional vector of the retailers' supplies of the product with component j denoted by h_j, with $h_j \equiv \sum_{i=1}^{I} \sum_{m=1}^{M} q_{imj}$
$c_j(h) \equiv c_j(Q^1)$	operating cost of retailer j with marginal operating cost with respect to h_j denoted by $\frac{\partial c_j}{\partial h_j}$ and the marginal operating cost with respect to q_{imj} denoted by $\frac{\partial c_j(Q^1)}{\partial q_{imj}}$
$c^t_{jk}(q^t_{jk})$	the transportation/transaction cost associated with the transaction between retailer j and demand market k via transportation/transaction t
$\hat{c}^t_{jk}(Q^2)$	unit transportation/transaction cost incurred by consumers at demand market k in transacting with retailer j via mode t
$\rho_{3k}(d)$	demand market price function at demand market k

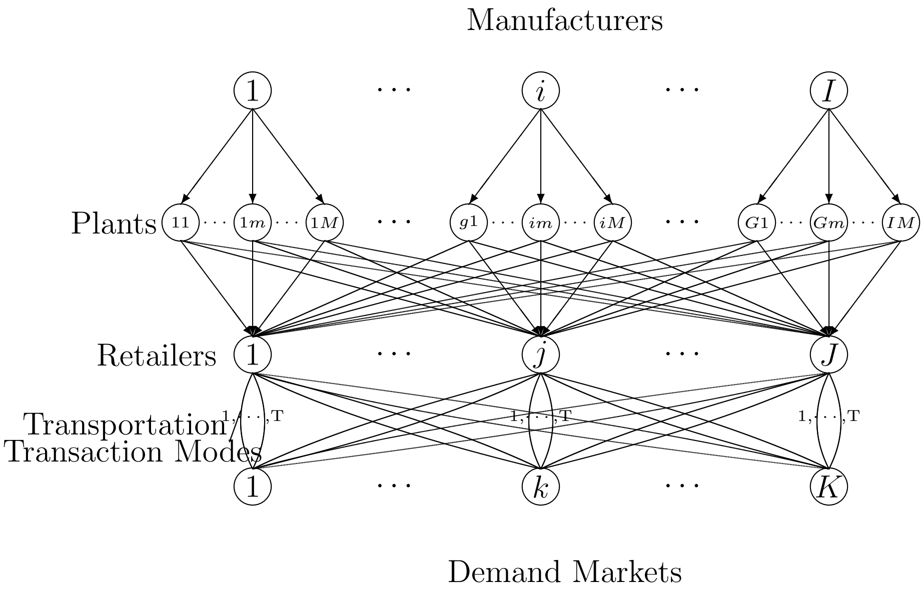

Figure 3.1. The Supply Chain Network with Manufacturing Plants

Node im in the second tier corresponds to manufacturer i's plant m, with the second tier of nodes enumerated as: $11, \ldots, IM$. It is assumed that each manufacturer seeks to determine his optimal production portfolio across his manufacturing plants and his sales allocations of the product to the retailers in order to maximize his own profit. It is also assumed that each manufacturer seeks to minimize the total emissions associated with production and transportation to the retailers.

Retailers, which are represented by the third-tiered nodes in Figure 3.1, function as intermediaries. The nodes corresponding to the retailers are enumerated as: $1, \ldots, j, \ldots, J$ with node j corresponding to retailer j. They purchase the product from the manufacturers and sell the product to the consumers at the different demand markets. It is assumed that the retailers compete with one another in a noncooperative manner. Also, it is assumed that, due to consumer pressures to influence firms to behave environmentally responsibly (Srivastara (2007)), the retailers are multicriteria decision-makers with environmental concerns and they also seek to minimize the emissions associated with transacting (which can include transportation) with the consumers as well as in operating their retail outlets.

The bottom-tiered nodes in Figure 3.1 represent the demand markets, which can be distinguished from one another by their geographic locations or the type of associated consumers such as whether they correspond, for example, to businesses or to households. There are K bottom-tiered nodes with node k corresponding to demand market k.

The retailers need to cover the direct costs and to decide which transportation/transaction modes should be used and how much product should be delivered. The structure of the network in Figure 3.1 guarantees that the conservation of flow equations associated with the production and distribution are satisfied. The flows on the links joining the manufacturers in Figure 3.1 to the plant nodes are respectively: $q_{11}, \ldots, q_{im}, \ldots, q_{IM}$; the flows on the links from the plant nodes to the retailer nodes are given, respectively, by the components of the vector Q^1, whereas the flows on the links joining the retailer nodes with the demand markets are given by the respective components of the vector: Q^2.

Of course, if a particular manufacturer does not own M manufacturing plants, then the corresponding links (and nodes) can just be removed from the supply chain network in Figure 3.1 and the notation reduced accordingly. Similarly, if a mode of transportation/transaction is not available for a retailer/demand market pair, then the corresponding link may be removed from the supply chain network in Figure 3.1 and the notation changed accordingly. On the other hand, multiple modes of transportation/transaction from the plants to the retailers can easily be added as links to the supply chain network in Figure 3.1 joining the plant nodes with the retailer nodes (with an associated increase in notation).

I now describe the behavior of the manufacturers, the retailers, and the consumers at the demand markets. I then state the equilibrium conditions of the supply chain network and provide the variational inequality formulation.

3.1.1 The Multicriteria Decision-Making Behavior of the Manufacturers and Their Optimality Conditions

Let ρ^*_{1imj} denote the unit price charged by manufacturer i for the transaction with retailer j for the product produced at plant m. ρ^*_{1imj} is an endogenous variable and can be determined once the complete supply chain network equilibrium model is solved. Since it is assumed that each individual manufacturer i; $i = 1, \ldots, I$, is a profit maximizer, the profit-maximization objective function of manufacturer i can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{j=1}^{J} \rho^*_{1imj} q_{imj} - \sum_{m=1}^{M} f_{im}(q_m) - \sum_{m=1}^{M}\sum_{j=1}^{J} c_{imj}(q_{imj}). \tag{3.1a}$$

The first term in the objective function (3.1a) represents the revenue and the next two terms represent the production cost and transportation/transaction costs, respectively.

In addition, it is assumed that manufacturer i is concerned with the total amount of emissions generated both in production of the product at the various manufacturing plants as well as in transportation of the product to the various retailers. Letting $e_{im}(q_{im})$ denote the emissions generation function for those emissions generated per unit of product produced at plant m of manufacturer i; and $e_{imj}(q_{imj})$ the emissions generation function for those emissions generated in transporting the product from plant m of manufacturer i to retailer j, one would have that the second objective function of manufacturer i is given by:

$$\text{Minimize} \sum_{m=1}^{M} e_{im}(q_{im}) + \sum_{m=1}^{M}\sum_{j=1}^{J} e_{imj}(q_{imj}). \tag{3.1b}$$

A nonnegative constant, α_i, is now assigned to the emissions-generation criterion (3.1*b*). α_i can be assumed the price that each manufacturer, i, would be willing to pay for each unit of emission. Thus, α_i, represents the environmental concern for each manufacturer, i, and a higher α_i represents a greater concern for the environment. Thus, one can construct a *value function* for each manufacturer (see e.g., Nagurney and Dong (2002), Nagurney and Toyasaki (2003), and the references therein). Consequently, the multicriteria decision-making problem for manufacturer i is transformed into:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{j=1}^{J}\rho^*_{1imj}q_{imj} - \sum_{m=1}^{M} f_{im}(q_m) - \sum_{m=1}^{M}\sum_{j=1}^{J} c_{imj}(q_{imj})$$

$$-\alpha_i(\sum_{m=1}^{M} e_{im}(q_{im}) + \sum_{m=1}^{M}\sum_{j=1}^{J} e_{imj}(q_{imj})) \tag{3.1c}$$

subject to:

$$\sum_{j=1}^{J} q_{imj} = q_{im}, \quad m = 1, \ldots, M, \tag{3.2}$$

$$q_{imj} \geq 0, \quad m = 1, \ldots, M; j = 1, \ldots, J. \tag{3.3}$$

Conservation of flow equation (3.2) states that the amount of product produced at a particular plant of a manufacturer is equal to the amount of product transacted by the manufacturer from that plant with all the retailers (and this holds for each of the manufacturing plants). Expression (3.3) guarantees that the quantities of the product produced at the various manufacturing plants are nonnegative.

Assume that the production cost, the transportation cost, and the emission functions for each manufacturer are continuously differentiable and convex (cf. (3.1*c*), subject to (3.2) and (3.3)), and that the manufacturers compete in a noncooperative manner in the sense of Nash (1950, 1951). The optimality conditions for all manufacturers simultaneously, under the above assumptions (see also Gabay and Moulin

(1980), Bazaraa, Sherali, and Shetty (1993), and Nagurney (1999)), coincide with the solution of the following variational inequality: determine $(q^*, Q^{1*}) \in \mathcal{K}_3^1$ satisfying

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}} + \alpha_i \frac{\partial e_{im}(q_{im}^*)}{\partial q_{im}}\right] \times [q_{im} - q_{im}^*]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}\left[\frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}} + \alpha_i \frac{\partial e_{imj}(q_{imj}^*)}{\partial q_{imj}} - \rho_{1imj}^*\right] \times [q_{imj} - q_{imj}^*] \geq 0,$$

$$\forall (q, Q^1) \in \mathcal{K}_3^1, \quad where \quad \mathcal{K}_3^1 \equiv \{(q, Q^1) | (q, Q^1) \in R_+^{IM+IMJ} \text{ and (3.2) holds}\}. \tag{3.4}$$

3.1.2 The Multicriteria Decision-Making Behavior of the Retailers and Their Optimality Conditions

The retailers, in turn, are involved in transactions both with the manufacturers and with the consumers at demand markets.

It is reasonable to assume that the total amount of product sold by a retailer j; $j = 1, \ldots, J$, is equal to the total amount of the product that he purchased from the manufacturers and that was produced via the different manufacturing plants available to the manufacturers. This assumption can be expressed as the following conservation of flow equations:

$$\sum_{k=1}^{K}\sum_{t=1}^{T} q_{jk}^t = \sum_{i=1}^{I}\sum_{m=1}^{M} q_{imj}, \quad j = 1, \ldots, J. \tag{3.5}$$

Let ρ_{2jk}^{t*} denote the price charged by retailer j to demand market k via transportation/transaction mode t. This price is determined endogenously in the model once the entire network equilibrium problem is solved. As noted above, it is assumed that each retailer seeks to maximize his own profit. Hence, the profit-maximization objective function faced by retailer j may be expressed as follows:

$$\text{Maximize} \quad \sum_{k=1}^{K}\sum_{t=1}^{T}\rho_{2jk}^{t*}q_{jk}^{t} - c_j(Q^1) - \sum_{i=1}^{I}\sum_{m=1}^{M}\rho_{1imj}^{*}q_{imj} - \sum_{k=1}^{K}\sum_{t=1}^{T}c_{jk}^{t}(q_{jk}^{t}). \qquad (3.6a)$$

The first term in (3.6a) denotes the revenue of retailer j; the second term denotes the operating cost of the retailer, and the third term denotes the payments for the product to the various manufacturers. The last term in (3.6a) denotes the transportation/transaction costs. Note that here imperfect competition is assumed in terms of the operating cost but, of course, if the operating cost functions c_j; $j = 1, \dots, J$ depend only on the product handled by j (and not also on the product handled by the other retailers), then the dependence of these functions on Q^1 can be simplified accordingly (and this is a special case of the model). The latter would reflect perfect competition.

In addition, for notational convenience, let

$$h_j \equiv \sum_{i=1}^{I}\sum_{m=1}^{M} q_{imj}, \quad j = 1, \dots, J. \qquad (3.7)$$

As defined in Table 3.1, the operating cost of retailer j, c_j, is a function of the total product inflows to the retailer, that is:

$$c_j(h) \equiv c_j(Q^1), \quad j = 1, \dots, J. \qquad (3.8)$$

Hence, his marginal cost with respect to h_j is equal to the marginal cost with respect to q_{imj}:

$$\frac{\partial c_j(h)}{\partial h_j} \equiv \frac{\partial c_j(Q^1)}{\partial q_{imj}}, \quad j = 1, \dots, J; \quad m = 1, \dots, M. \qquad (3.9)$$

In addition, assume that each retailer seeks to minimize the emissions associated with managing his retail outlet and with transacting with consumers at the demand markets. Let $e_j(h_j)$ denote the emissions generation function representing those emissions generated by retailer j; $j = 1, \dots, J$, and is a function of all product inflows to the retailer; and let $e^t_{jk}(q^t_{jk})$ denote the amount of emissions generated which is a function of each unit of product transacted between k and j via t, for $j = 1, \dots, J$; $k = 1, \dots, K$, and $t = 1, \dots, T$. Then one would have that the second objective function of retailer j is given by:

$$\text{Minimize} \quad e_j(h_j) + \sum_{k=1}^{K} \sum_{t=1}^{T} e^t_{jk}(q^t_{jk}). \tag{3.6b}$$

A nonnegative constant, β_j, is now assigned to the emissions-generation criterion (3.6b). β_j can be assumed the price that each retailer, j, would be willing to pay for each unit of emission; which represents the environmental concern for each retailer, j, and a higher β_j represent a greater concern for the environment. One can construct retailer j's multicriteria decision-making problem, given by:

$$\text{Maximize} \quad \sum_{k=1}^{K} \sum_{t=1}^{T} \rho^{t*}_{2jk} q^t_{jk} - c_j(Q^1) - \sum_{i=1}^{I} \sum_{m=1}^{M} \rho^*_{1imj} q_{imj} - \sum_{k=1}^{K} \sum_{t=1}^{T} c^t_{jk}(q^t_{jk}) \tag{3.6c}$$

$$-\beta_j(e_j(h_j) + \sum_{k=1}^{K} \sum_{t=1}^{T} e^t_{jk}(q^t_{jk}))$$

subject to (3.7) and:

$$\sum_{k=1}^{K} \sum_{t=1}^{T} q^t_{jk} = \sum_{i=1}^{I} \sum_{m=1}^{M} q_{imj}, \tag{3.10}$$

$$q_{imj} \geq 0, \quad i = 1, \dots, I, \quad m = 1, \dots, M, \tag{3.11}$$

$$q^t_{jk} \geq 0, \quad k = 1, \dots, K; t = 1, \dots, T. \tag{3.12}$$

Assume that the transaction costs, the operating costs (cf. (3.6a)), and the emission functions (cf. 3.6b) are all continuously differentiable and convex, and that the retailers compete in a noncooperative manner. Hence, the optimality conditions for all retailers, simultaneously, under the above assumptions (see also Dafermos and

Nagurney (1987), Nagurney, Dong, and Zhang (2002)), can be expressed as the following variational inequality: determine $(h^*, Q^{2*}, Q^{1*}) \in \mathcal{K}_3^3$ such that

$$\sum_{j=1}^{J} \left[\frac{\partial c_j(h^*)}{\partial h_j} + \beta_j \frac{\partial e_j(h_j^*)}{\partial h_j} \right] \times [h_j - h_j^*]$$

$$+ \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{t=1}^{T} \left[\frac{\partial c_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t} + \beta_j \frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t} - \rho_{2jk}^{t*} \right] \times [q_{jk}^t - q_{jk}^{t*}]$$

$$+ \sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{j=1}^{J} \left[\rho_{1imj}^* \right] \times [q_{imj} - q_{imj}^*] \geq 0, \qquad \forall (h, Q^1, Q^2,) \in \mathcal{K}_3^3, \tag{3.13}$$

where $\mathcal{K}_3^3 \equiv \{(h, Q^2, Q^1) | (h, Q^2, Q^1) \in R_+^{J(1+TK+IM)} \text{and (3.7) and (3.10) hold}\}$.

3.1.3 The Equilibrium Conditions for the Demand Markets

At each demand market k; $k = 1, \ldots, K$, the following conservation of flow equation must be satisfied:

$$d_k = \sum_{j=1}^{J} \sum_{t=1}^{T} q_{jk}^t. \tag{3.14}$$

Assume also that the consumers at the demand markets may be environmentally-conscious in choosing their modes of transaction with the retailer with an associated nonnegative constant of η_k for demand market k. Since the demand market price functions are given, the market equilibrium conditions at demand market k then take the form: for each retailer j; $j = 1, ..., J$ and transportation/transaction mode t; $t = 1, ..., T$:

$$\rho_{2jk}^{t*} + \hat{c}_{jk}^t(Q^{2*}) + \eta_k \frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t} \begin{cases} = \rho_{3k}(d^*), & \text{if} \quad q_{jk}^{t*} > 0, \\ \geq \rho_{3k}(d^*), & \text{if} \quad q_{jk}^{t*} = 0. \end{cases} \tag{3.15}$$

Equation (3.15) above states that if the quantity consumed at demand market, k, shipped by retailer j, via transaction/transportation mode t, is positive, the total cost to each demand market (which includes the price that the the retailer charges the demand market plus the transaction costs that the demand market ensues for those transactions with retailer, j, plus the marginal cost of emissions for each demand market, k) must be equal to the price the demand market is willing to pay; else the quantity consumed at demand market, k, shipped by retailer j, via transaction/transportation mode t, is zero.

Nagurney and Toyasaki (2003) (see also Nagurney and Toyasaki (2005)) considered similar demand market equilibrium conditions but in the case in which the demand functions, rather than the demand price functions as above, were given. The demand price functions were given for the demand market equilibrium conditions in Nagurney, Liu, and Woolley (2007) and the emission functions were fixed and given.

The interpretation of conditions (3.15) is as follows: consumers at a demand market purchase the product from a retailer via a transportation/transaction mode, provided that the purchase price plus the unit transportation/transaction cost plus the marginal cost of emissions associated with that transaction is equal to the price that the consumers are willing to pay at that demand market. If the purchase price plus the unit transportation/transaction cost plus the marginal cost of emissions associated with that transaction exceeds the price the consumers are willing to pay, then there be no transaction between that retailer and demand market via that transportation/transaction mode. The equivalent variational inequality governing all the demand markets takes the form: determine $(Q^{2*}, d^*) \in \mathcal{K}_3^4$, such that

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\rho_{2jk}^{t*} + \hat{c}_{jk}^{t}(Q^{2*}) + \eta_k \frac{\partial e_{jk}^{t}(q_{jk}^{t*})}{\partial q_{jk}^{t}}\right] \times [q_{jk}^{t} - q_{jk}^{t*}] - \sum_{k=1}^{K} \rho_{3k}(d^*) \times [d_k - d_k^*] \geq 0,$$

$$\forall (Q^2, d) \in \mathcal{K}_3^4, \; where \, \mathcal{K}_3^4 \equiv \{(Q^2, d) | (Q^2, d) \in R_+^{K(JT+1)} \text{and (3.14) holds}\}. \quad (3.16)$$

3.1.4 The Equilibrium Conditions for the Supply Chain Network with Manufacturing Plants and Environmental Concerns

In equilibrium, the optimality conditions for all the manufacturers, the optimality conditions for all the retailers, and the equilibrium conditions for all the demand markets must be simultaneously satisfied so that no decision-maker has any incentive to alter his transactions.

Definition 3.1 (Supply Chain Network Equilibrium with Manufacturing Plants and Environmental Concerns)

The equilibrium state of the supply chain network with manufacturing plants and environmental concerns is one where the product flows between the tiers of the network coincide and the product flows and prices satisfy the sum of conditions (3.4), (3.13), and (3.16).

I now state and prove:

Theorem 3.1 (Variational Inequality Formulation of the Supply Chain Network Equilibrium with Manufacturing Plants and Environmental Concerns)

The equilibrium conditions governing the supply chain network according to Definition 3.1 coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*) \in \mathcal{K}_3^5$ *satisfying:*

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}}+\alpha_i\frac{\partial e_{im}(q_{im}^*)}{\partial q_{im}}\right]\times[q_{im}-q_{im}^*]+\sum_{j=1}^{J}\left[\frac{\partial c_j(h^*)}{\partial h_j}+\beta_j\frac{\partial e_j(h_j^*)}{\partial h_j}\right]\times[h_j-h_j^*]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}\left[\frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}}+\alpha_i\frac{\partial e_{imj}(q_{imj}^*)}{\partial q_{imj}}\right]\times[q_{imj}-q_{imj}^*]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t}+\hat{c}_{jk}^t(Q^{2*})+(\beta_j+\eta_k)\frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t}\right]\times[q_{jk}^t-q_{jk}^{t*}]$$

$$-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]\geq 0,\quad \forall(q,h,Q^1,Q^2,d)\in\mathcal{K}_3^5, \tag{3.17}$$

where $\mathcal{K}_3^5\equiv\{(q,h,Q^1,Q^2,d)|(q,h,Q^1,Q^2,d)\in R_+^{IM+J+IMJ+TJK+K}$ *and* (3.2), (3.5), *and* (3.7) *hold*$\}$.

Proof:

I first prove that an equilibrium according to Definition 3.1 coincides with the solution of variational inequality (3.17). Indeed, summation of (3.4), (3.13), and (3.16), after algebraic simplifications, yields (3.17).

I now prove the converse, that is, a solution to variational inequality (3.17) satisfies the sum of conditions (3.4), (3.13), and (3.16), and is, therefore, a supply chain network equilibrium pattern according to Definition 3.1.

First, add the term $\rho_{1imj}^*-\rho_{1imj}^*$ to the first term in the third summand expression in (3.17). Then, the term $\rho_{2jk}^{t*}-\rho_{2jk}^{t*}$ is added to the first term in the fourth summand expression in (3.17). Since these terms are all equal to zero, they do not change (3.17). Hence, one would obtain the following inequality:

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}}+\alpha_i\frac{\partial e_{im}(q_{im}^*)}{\partial q_{im}}\right]\times[q_{im}-q_{im}^*]+\sum_{j=1}^{J}\left[\frac{\partial c_j(h^*)}{\partial h_j}+\beta_j\frac{\partial e_j(h_j^*)}{\partial h_j}\right]\times[h_j-h_j^*]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}\left[\frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}}+\alpha_i\frac{\partial e_{imj}(q_{imj}^*)}{\partial q_{imj}}+\rho_{1imj}^*-\rho_{1imj}^*\right]\times[q_{imj}-q_{imj}^*]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t}+\hat{c}_{jk}^t(q_{jk}^{t*})+(\beta_j+\eta_k)\frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t}+\rho_{2jk}^{t*}-\rho_{2jk}^{t*}\right]\times[q_{jk}^t-q_{jk}^{t*}]$$

$$-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]\geq 0,\quad \forall(q,h,Q^1,Q^2,d)\in\mathcal{K}_3^5, \tag{3.18}$$

which can be rewritten as:

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}}+\alpha_i\frac{\partial e_{im}(q_{im}^*)}{\partial q_{im}}\right]\times[q_{im}-q_{im}^*]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{g=1}^{G}\left[\frac{\partial c_{imj}(q^*_{imj})}{\partial q_{imj}}-\rho^*_{1imj}+\alpha_i\frac{\partial e_{imj}(q^*_{imj})}{\partial q_{imj}}\right]\times[q_{imj}-q^*_{imj}]$$

$$+\sum_{j=1}^{J}\left[\frac{\partial c_j(h^*)}{\partial h_j}+\beta_j\frac{\partial e_j(h^*_j)}{\partial h_j}\right]\times[h_j-h^*_j]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c^t_{jk}(q^{t*}_{jk})}{\partial q^t_{jk}}-\rho^{t*}_{2jk}+\beta_j\frac{\partial e^t_{jk}(q^{t*}_{jk})}{\partial q^t_{jk}}\right]\times[q^t_{jk}-q^{t*}_{jk}]$$

$$+\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{i=1}^{I}[\rho^*_{1imj}]\times[q_{imj}-q^*_{imj}]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\rho^{t*}_{2jk}+\hat{c}^t_{jk}(q^{t*}_{jk})+\eta_k\frac{\partial e^t_{jk}(q^{t*}_{jk})}{\partial q^t_{jk}}\right]\times[q^t_{jk}-q^{t*}_{jk}]-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d^*_k]\geq 0,$$

$$\forall(q,h,Q^1,Q^2,d)\in\mathcal{K}^5_3. \qquad (3.19)$$

Clearly, (3.19) is the sum of the optimality conditions (3.4) and (3.13), and the equilibrium conditions (3.16), and is, hence, according to Definition 3.1 a supply chain network equilibrium.

Remark

Note that, in the above model, it is assumed that the various decision-makers are environmentally conscious (to a certain degree) depending upon the prices that they assign to the respective environmental criteria denoted by α_i; $i=1,\ldots,I$ for the manufacturers; by β_j; $j=1,\ldots,J$ for the retailers, and by η_k; $k=1,\ldots,K$ for the consumers at the respective demand markets. These prices are associated with the environmental emissions generated in production, transportation/transaction, and the operation of the retail outlets as the product “moves” through the supply chain, driven by the demand for the product at the demand markets. This implies (assuming all prices are not identically equal to zero), environmentally-conscious decision-makers. It is worth emphasizing that the prices can also be interpreted as *taxes*, for example, *carbon* taxes (cf. Wu et al. (2006) and Nagurney, Liu, and Woolley (2007)), which would be assigned by a governmental authority. Such a framework was devised by Wu et al. (2006) in the case of electric power supply chains. However, in that model, the carbon emissions only occurred in the production of electric power using alternative power-generation plants, which could utilize different forms of energy (renewable or not, for example). Hence, the carbon taxes were only associated with the manufacturers and the power-generating plants. In the case of the supply chain network model in this Chapter, in contrast, pollution can be emitted not only at the production stage, but also in the transportation of the product, as well as during the operation of the retail outlets. In order to construct sustainable supply chains, it is essential to have a system-wide view of pollution generation.

I now describe how to recover the prices associated with the first and third tiers of nodes in the supply chain network. Clearly, the components of the vector ρ_3^* can be directly obtained from the solution to variational inequality (3.17). I now describe how to recover the prices ρ_{1imj}^*, for all i, m, j, and ρ_{2jk}^{t*} for all j, k, t, from the solution of variational inequality (3.17). The prices associated with the retailers can be obtained by setting (cf. (3.15)) $\rho_{2jk}^{t*} = \rho_{3k}^* - \eta_k \frac{\partial e_{jk}^t(q_{jk}^{t*})}{\partial q_{jk}^t} - \hat{c}_{jk}^t(Q^{2*})$ for any j, t, k such that $q_{sk}^{t*} > 0$. The top-tiered prices, in turn, can be recovered by setting (cf. (3.4)) $\rho_{1imj}^* = \frac{\partial f_{im}(q_m^*)}{\partial q_{imj}} + \frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}} + \alpha_i \frac{\partial e_{imj}(q_{imj}^*)}{\partial q_{imj}}$ for any i, m, j such that $q_{imj}^* > 0$.

Corollary 3.1 (Variational Inequality Formulation for the Case of Fixed Emissions)

Assume that the emission functions are fixed and given (see Nagurney, Liu, and Woolley (2007)). Hence, in this special case, variational inequality (3.17) collapses to: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*) \in \mathcal{K}_3^6$ *satisfying:*

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\left[\frac{\partial f_{im}(q_m^*)}{\partial q_{im}} + \alpha_i e_{im}\right] \times [q_{im} - q_{im}^*] + \sum_{j=1}^{J}\left[\frac{\partial c_j(h^*)}{\partial h_j} + \beta_j e_j\right] \times [h_j - h_j^*]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}\left[\frac{\partial c_{imj}(q_{imj}^*)}{\partial q_{imj}} + \alpha_i e_{imj}\right] \times [q_{imj} - q_{imj}^*]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c^t_{jk}(q^{t*}_{jk})}{\partial q^t_{jk}}+\hat{c}^t_{jk}(Q^{2*})+(\beta_j+\eta_k)e^t_{jk}\right]\times[q^t_{jk}-q^{t*}_{jk}]-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d^*_k]\geq 0,$$

$$\forall (q,h,Q^1,Q^2,d)\in\mathcal{K}^6_3, \qquad (3.20)$$

where

$$\mathcal{K}^6_3\equiv\{(q,h,Q^1,Q^2,d)|(q,h,Q^1,Q^2,d)\in R^{IM+J+IMJ+TJK+K}_+$$

The proof is straightforward.

In this Chapter, I have focused on the development of a supply chain network model with a view towards sustainability in which the price associated with environmental concern (equivalently, taxes) are known/assigned a priori. In order to achieve a particular environmental goal (see also Nagurney (2000)), for example, in the case of a bound on the total emissions in the entire supply chain, one could conduct simulations associated with the different prices in order to achieve the desired policy result. An interesting extension would be to construct a model in which the prices/taxes are endogenous, as was done in the case of electric power supply chains and carbon taxes by Nagurney, Liu, and Woolley (2007). However, as also discussed therein, the transportation network equilibrium reformulation may be lost for the full supply chain (although still exploited computationally during the iterative algorithmic process).

3.2 The Transportation Network Equilibrium Reformulation of the Supply Chain Network Equilibrium Model with Manufacturing Plants and Environmental Concerns

In this Section, I show that the supply chain network equilibrium model presented in Section 3.1 is isomorphic to a properly configured transportation network equilibrium model as in Section 2.2 through the establishment of a supernetwork equivalence of the former.

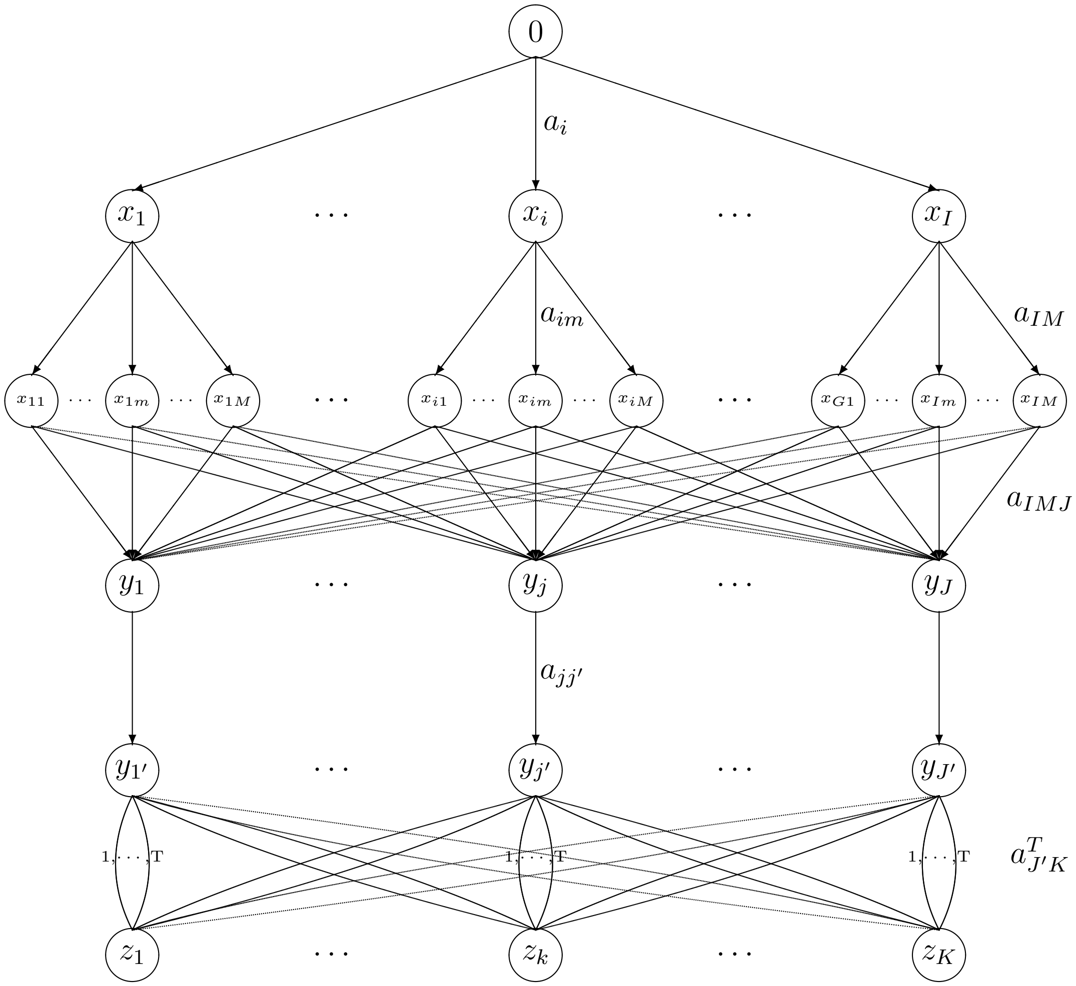

Figure 3.2. The $\mathcal{G}_{\mathcal{S}}$ Supernetwork Representation of the Supply Chain Network Equilibrium with Manufacturing Plants

I now establish the supernetwork equivalence of the supply chain network equilibrium model to the transportation network equilibrium model with known travel disutility functions described in Section 2.2. This transformation allows, as demonstrated in Section 3.3, to apply algorithms developed for the latter class of problems to solve the former.

Consider a supply chain network with manufacturing plants as discussed in Section 3.1 with given manufacturers: $i = 1, \ldots, I$; given manufacturing plants for each manufacturer: $m = 1, \ldots, M$; retailers: $j = 1, \ldots, J$; transportation/transaction modes: $t = 1, \ldots, T$, and demand markets: $k = 1, \ldots, K$. The supernetwork, $\mathcal{G}_{\mathcal{S}}$, of the isomorphic transportation network equilibrium model is depicted in Figure 3.2 and is constructed as follows.

It consists of six tiers of nodes with the origin node 0 at the top or first tier and the destination nodes at the sixth or bottom tier. Specifically, $\mathcal{G}_{\mathcal{S}}$ consists of a single origin node 0 at the first tier, and K destination nodes at the bottom tier, denoted, respectively, by: $z_1, \ldots, z_K$. There are K O/D pairs in $\mathcal{G}_{\mathcal{S}}$ denoted by $w_1 = (0, z_1)$, $\ldots$, $w_k = (0, z_k)$,$\ldots$, $w_K = (0, z_K)$. Node 0 is connected to each second-tiered node x_i; $i = 1, \ldots, I$ by a single link. Each second-tiered node x_i, in turn, is connected to each third-tiered node x_{im}; $i = 1, \ldots, I$; $m = 1, \ldots, M$ by a single link, and each third-tiered node is then connected to each fourth-tiered node y_j; $j = 1, \ldots, J$ by a single link. Each fourth-tiered node y_j is connected to the corresponding fifth-tiered node $y_{j'}$ by a single link. Finally, each fifth-tiered node $y_{j'}$ is connected to each destination node z_k; $k = 1, \ldots, K$ at the sixth tier by T parallel links.

Hence, in $\mathcal{G}_{\mathcal{S}}$, there are $I + IM + 2J + K + 1$ nodes; $I + IM + IMJ + J + JTK$ links, K O/D pairs, and $IMJTK$ paths. I now define the link and link flow notation. Let a_i denote the link from node 0 to node x_i with associated link flow f_{a_i}, for $i = 1, \ldots, I$. Let a_{im} denote the link from node x_i to node x_{im} with link flow $f_{a_{im}}$ for $i = 1, \ldots, I$; $m = 1, \ldots, M$. Also, let a_{imj} denote the link from node x_{im} to node y_j

with associated link flow $f_{a_{imj}}$ for $i = 1, \ldots, I$; $m = 1, \ldots, M$, and $j = 1, \ldots, J$. Let $a_{jj'}$ denote the link connecting node y_j with node $y_{j'}$ with associated link flow $f_{a_{jj'}}$ for $jj' = 11', \ldots, JJ'$. Finally, let $a^t_{j'k}$ denote the t-th link joining node $y_{j'}$ with node z_k for $j' = 1', \ldots, J'$; $t = 1, \ldots, T$, and $k = 1, \ldots, K$ and with associated link flow $f_{a^t_{j'k}}$. The link flows are grouped into the vectors as follows: group the $\{f_{a_i}\}$ into the vector f^1; the $\{f_{a_{im}}\}$ into the vector f^2, the $\{f_{a_{imj}}\}$ into the vector f^3; the $\{f_{a_{jj'}}\}$ into the vector f^4, and the $\{f_{a^t_{j'k}}\}$ into the vector f^5.

Thus, a typical path connecting O/D pair $w_k = (0, z_k)$, is denoted by $p^t_{imjj'k}$ and consists of five links: $a_i, a_{im}, a_{imj}, a_{jj'}$, and $a^t_{j'k}$. The associated flow on the path is denoted by $x_{p^t_{imjj'k}}$. Finally, let d_{w_k} be the demand associated with O/D pair w_k where λ_{w_k} denotes the travel disutility for w_k.

Note that the following conservation of flow equations must hold on the network $\mathcal{G}_{\mathcal{S}}$:

$$f_{a_i} = \sum_{m=1}^{M}\sum_{j=1}^{J}\sum_{j'=1}^{J'}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{p^t_{imjj'k}}, \quad i = 1, \ldots, I, \tag{3.21}$$

$$f_{a_{im}} = \sum_{j=1}^{J}\sum_{j'=1'}^{J'}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{p^t_{imjj'k}}, \quad i = 1, \ldots, I; m = 1, \ldots, M, \tag{3.22}$$

$$f_{a_{imj}} = \sum_{j'=1'}^{J'}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{p^t_{imjj'k}}, \quad i = 1, \ldots, I; m = 1, \ldots, M; j = 1, \ldots, J, \tag{3.23}$$

$$f_{a_{jj'}} = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{p^t_{imjj'k}}, \quad jj' = 11', \ldots, JJ', \tag{3.24}$$

$$f_{a^t_{j'k}} = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} x_{p^t_{imjj'k}}, \quad j' = 1', \ldots, J'; t = 1, \ldots, T; k = 1, \ldots, K. \tag{3.25}$$

Also, one would have that

$$d_{w_k} = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{jj'=11'}^{JJ'}\sum_{t=1}^{T} x_{p^t_{imjj'k}}, \quad k = 1, \ldots, K. \tag{3.26}$$

If all path flows are nonnegative and (3.21)–(3.26) are satisfied, the feasible path flow pattern induces a feasible link flow pattern.

A feasible link flow pattern can be constructed for $\mathcal{G}_{\mathcal{S}}$ based on the corresponding feasible supply chain flow pattern in the supply chain network model, $(q, h, Q^1, Q^2, d) \in \mathcal{K}^5_3$, in the following way:

$$q_i \equiv f_{a_i}, \quad i = 1, \ldots, I, \tag{3.27}$$

$$q_{im} \equiv f_{a_{im}}, \quad i = 1, \ldots, I; m = 1, \ldots, M, \tag{3.28}$$

$$q_{imj} \equiv f_{a_{imj}}, \quad i = 1, \ldots, I; m = 1, \ldots, M; j = 1, \ldots, J, \tag{3.29}$$

$$h_j \equiv f_{a_{jj'}}, \quad jj' = 11', \ldots, JJ', \tag{3.30}$$

$$q^t_{jk} = f_{a^t_{j'k}}, \quad j = 1, \ldots, J; j' = 1', \ldots, J'; t = 1, \ldots, T; k = 1, \ldots, K, \tag{3.31}$$

$$d_k = \sum_{j=1}^{J} \sum_{t=1}^{T} q^t_{jk}, \quad k = 1, \ldots, K. \tag{3.32}$$

Observe that although q_i is not explicitly stated in the model in Section 3.1, it is inferred in that

$$q_i = \sum_{m=1}^{M} q_{im}, \quad i = 1, \ldots, I, \tag{3.33}$$

and simply represents the total amount of product produced by manufacturer i.

Note that if (q, Q^1, h, Q^2, d) is feasible then the link flow and demand pattern constructed according to (3.27)–(3.32) is also feasible and the corresponding path flow pattern which induces this link flow (and demand) pattern is also feasible.

One can now assign user (travel) costs on the links of the network $\mathcal{G}_{\mathcal{S}}$ as follows: with each link a_i one can assign a user cost c_{a_i} defined by

$$c_{a_i} \equiv 0, \quad i = 1, \ldots, I, \tag{3.34}$$

$$c_{a_{im}} \equiv \frac{\partial f_{im}}{\partial q_{im}} + \alpha_i \frac{\partial e_{im}}{\partial q_{im}}, \quad i = 1, \ldots, I; m = 1, \ldots, M, \tag{3.35}$$

with each link a_{imj} assigned a user cost $c_{a_{imj}}$ defined by:

$$c_{a_{imj}} \equiv \frac{\partial c_{imj}}{\partial q_{imj}} + \alpha_i \frac{\partial e_{imj}}{\partial q_{imj}}, \quad i = 1, \ldots, I; m = 1, \ldots, M; j = 1, \ldots, J, \tag{3.36}$$

with each link jj' assigned a user cost defined by

$$c_{a_{jj'}} \equiv \frac{\partial c_j}{\partial h_j} + \beta_j \frac{\partial e_j}{\partial h_j}, \quad jj' = 11', \dots, JJ'. \tag{3.37}$$

Finally, a user cost is assigned for each link $a^t_{j'k}$ which is defined by

$$c_{a^t_{j'k}} \equiv \frac{\partial c^t_{jk}}{\partial q^t_{jk}} + \hat{c}^t_{jk} + (\beta_j + \eta_k)\frac{\partial e^t_{jk}}{\partial q^t_{jk}}, \quad j' = j = 1, \dots, J; t = 1, \dots, T; k = 1, \dots, K. \tag{3.38}$$

Then a user of path $p^t_{imjj'k}$, for $i = 1, \dots, I$; $m = 1, \dots, M$; $jj' = 11', \dots, JJ'$; $t = 1, \dots, T$; $k = 1, \dots, K$, on network $\mathcal{G}_{\mathcal{S}}$ in Figure 3.2 experiences a path travel cost $C_{p^t_{imjj'k}}$ given by

$$C_{p^t_{imjj'k}} = c_{a_i} + c_{a_{im}} + c_{a_{imj}} + c_{a_{jj'}} + c_{a^t_{j'k}}$$

$$= \frac{\partial f_{im}}{\partial q_{im}} + \alpha_i \frac{\partial e_{im}}{\partial q_{im}} + \frac{\partial c_{imj}}{\partial q_{imj}} + \alpha_i \frac{\partial e_{imj}}{\partial q_{imj}} + \frac{\partial c_j}{\partial h_j} + \beta_j \frac{\partial e_j}{\partial h_j} + \frac{\partial c^t_{jk}}{\partial q^t_{jk}} + \hat{c}^t_{jk} + (\beta_j + \eta_k)\frac{\partial e^t_{jk}}{\partial q^t_{jk}}. \tag{3.39}$$

Also, the (travel) demands associated with the O/D pairs are assigned as follows:

$$d_{w_k} \equiv d_k, \quad k = 1, \dots, K, \tag{3.40}$$

and the (travel) disutilities:

$$\lambda_{w_k} \equiv \rho_{3k}, \quad k = 1, \dots, K. \tag{3.41}$$

Consequently, the equilibrium conditions (2.19) for the transportation network equilibrium model on the network $\mathcal{G}_{\mathcal{S}}$ state that for every O/D pair w_k and every path connecting the O/D pair w_k:

$$C_{p^t_{imjj'k}} - \lambda_{w_k} = \frac{\partial f_{im}}{\partial q_{im}} + \alpha_i \frac{\partial e_{im}}{\partial q_{im}} + \frac{\partial c_{imj}}{\partial q_{imj}} + \alpha_i \frac{\partial e_{imj}}{\partial q_{imj}}$$

$$+\frac{\partial c_j}{\partial h_j}+\beta_j\frac{\partial e_j}{\partial h_j}+\frac{\partial c^t_{jk}}{\partial q^t_{jk}}+\hat{c}^t_{jk}+(\beta_j+\eta_k)\frac{\partial e^t_{jk}}{\partial q^t_{jk}}-\lambda_{w_k}\begin{cases}=0, & \text{if} \quad x^*_{p^t_{imjj'k}}>0,\\ \geq 0, & \text{if} \quad x^*_{p^t_{imjj'k}}=0.\end{cases} \tag{3.42}$$

I now show that the variational inequality formulation of the equilibrium conditions (3.42) in link form as in (2.22) is equivalent to the variational inequality (3.17) governing the supply chain network equilibrium with manufacturing plants and environmental concerns. For the transportation network equilibrium problem on $\mathcal{G}_{\mathcal{S}}$, according to Theorem 2.7, one would have that a link flow and travel disutility pattern $(f^*,d^*)\in\mathcal{K}^2_2$ is an equilibrium (according to (3.41)), if and only if it satisfies the variational inequality:

$$\sum_{i=1}^{I}c_{a_i}(f^{1*})\times(f_{a_i}-f^*_{a_i})+\sum_{i=1}^{I}\sum_{m=1}^{M}c_{a_{im}}(f^{2*})\times(f_{a_{im}}-f^*_{a_{im}})$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}c_{a_{imj}}(f^{3*})\times(f_{a_{imj}}-f^*_{a_{imj}})+\sum_{jj'=11'}^{JJ'}c_{a_{jj'}}(f^{4*})\times(f_{a_{jj'}}-f^*_{a_{jj'}})$$

$$+\sum_{j'=1'}^{J'}\sum_{k=1}^{K}\sum_{t=1}^{T}c_{a^t_{j'k}}(f^{5*})\times(f_{a^t_{j'k}}-f^*_{a^t_{j'k}})-\sum_{k=1}^{K}\lambda_{w_k}(d^*)\times(d_{w_k}-d^*_{w_k})\geq 0, \quad \forall(f,d)\in\mathcal{K}^2_2. \tag{3.43}$$

After the substitution of (3.27)–(3.38) and (3.40)–(3.41) into (3.43), one would have the following variational inequality: determine $(q^*,h^*,Q^{1*},Q^{2*},d^*)\in\mathcal{K}^5_3$ satisfying:

$$\sum_{i=1}^{I}\sum_{m=1}^{M}[\frac{\partial f_{im}(q^*_i)}{\partial q_{im}}+\alpha_i\frac{\partial e_{im}(q^*_{im})}{\partial q_{im}}]\times[q_{im}-q^*_{im}]+\sum_{j=1}^{J}[\frac{\partial c_j(h^*)}{\partial h_j}+\beta_j\frac{\partial e_j(h^*_j)}{\partial h_j}]\times[h_j-h^*_j]$$

$$+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J}[\frac{\partial c_{imj}(q^*_{imj})}{\partial q_{imj}}+\alpha_i\frac{\partial e_{imj}(q^*_{imj})}{\partial q_{imj}}]\times[q_{imj}-q^*_{imj}]$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}[\frac{\partial c^t_{jk}(q^{t*}_{jk})}{\partial q^t_{jk}}+\hat{c}^t_{jk}(Q^{2*})+(\beta_j+\eta_k)\frac{\partial e^t_{jk}(q^{t*}_{jk})}{\partial q^t_{jk}}]\times[q^t_{jk}-q^{t*}_{jk}]$$

$$-\sum_{k=1}^{K} \rho_{3k}(d^*) \times [d_k - d_k^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d) \in \mathcal{K}_3^5. \tag{3.44}$$

Variational inequality (3.44) is precisely variational inequality (3.17) governing the supply chain network equilibrium. Hence, one would have the following result:

Theorem 3.2

A solution $(q^*, h^*, Q^{1^*}, Q^{2^*}, d^*) \in \mathcal{K}_3^5$ *of the variational inequality (3.17) governing the supply chain network equilibrium coincides with the (via (3.27)–(3.38) and (3.40)–(3.42)) feasible link flow and travel demand pattern for the supernetwork* $\mathcal{G}_{\mathcal{S}}$ *constructed above and satisfies variational inequality (3.43). Hence, it is a transportation network equilibrium according to Theorem 2.7.*

I now further discuss the interpretation of the supply chain network equilibrium conditions. These conditions define the supply chain network equilibrium in terms of paths and path flows, which, as shown above, coincide with Wardrop's (1952) first principle of user-optimization in the context of transportation networks over the network given in Figure 3.2. Hence, one now have an entirely new interpretation of supply network equilibrium with environmental concerns which states that only minimal cost paths be used from the super source node 0 to any destination node. Moreover, the cost on the utilized paths for a particular O/D pair is equal to the disutility (or the demand market price) that the users are willing to pay.

In Section 3.3, Theorem 3.2 can be utilized to exploit algorithmically the theoretical results obtained above through the computation of equilibrium patterns of numerical supply chain network examples using an algorithm previously used for the computation of elastic demand transportation network equilibria. Of course, existence and uniqueness results obtained for elastic demand transportation network equilibrium models as in Dafermos (1982) as well as stability and sensitivity analysis results (see also Nagurney and Zhang (1996)) can now be transferred to sustainable supply chain networks using the formalism/equivalence established above.

3.3 Numerical Examples

In this Section, numerical examples are provided to demonstrate how the theoretical results in this Chapter can be applied in practice. These examples are from Nagurney, Liu, and Woolley (2007). The Euler method was used for the numerical computations. The Euler method (cf. Section 2.5.1) is induced by the general iterative scheme of Dupuis and Nagurney (1993) and has been applied by Nagurney and Zhang (1996) to solve variational inequality (2.20) in path flows (equivalently, variational inequality (2.21) in link flows). Convergence results can be found in the above references.

The Euler method is described as follows. For the solution of (2.20), the Euler method takes the form: at iteration τ compute the path flows for paths $p \in P$ (and the travel demands) according to:

$$x_p^{\tau+1} = \max\{0, x_p^{\tau} + \alpha_{\tau}(\lambda_w(d^{\tau}) - C_p(x^{\tau}))\}. \tag{3.45}$$

The simplicity of (3.45) lies in the explicit formula that allows for the computation of the path flows in closed form at each iteration. The demands at each iteration simply satisfy (2.18) and this expression can be substituted into the $\lambda_w(\cdot)$ functions.

The Euler method was implemented in FORTRAN and the computer system used was a Sun system at the University of Massachusetts at Amherst. The convergence criterion utilized was that the absolute value of the path flows between two successive iterations differed by no more than 10^{-4}. The sequence $\{\alpha_{\tau}\}$ in the Euler method (cf. (3.44)) was set to: $\{1, \frac{1}{2}, \frac{1}{2}, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}, \ldots\}$. The Euler method was initialized by setting the demands equal to 100 for each O/D pair with the path flows equally distributed. The Euler method was also used to compute solutions to electric power supply chain network examples, reformulated as transportation network equilibrium problems in Wu et al. (2006).

In all the numerical examples, the supply chain network consisted of two manufacturers, with two manufacturing plants each, two retailers, one transportation/ transaction mode, and two demand markets as depicted in Figure 3.3. The supernetwork representation which allows for the transformation (as proved in Section 3.2) to a transportation network equilibrium problem is given also in Figure 3.3. Hence, in the numerical examples (see also Figure 3.2) one would have that: $I = 2$, $M = 2$, $J = 2$, $J' = 2'$, $K = 2$, and $T = 1$.

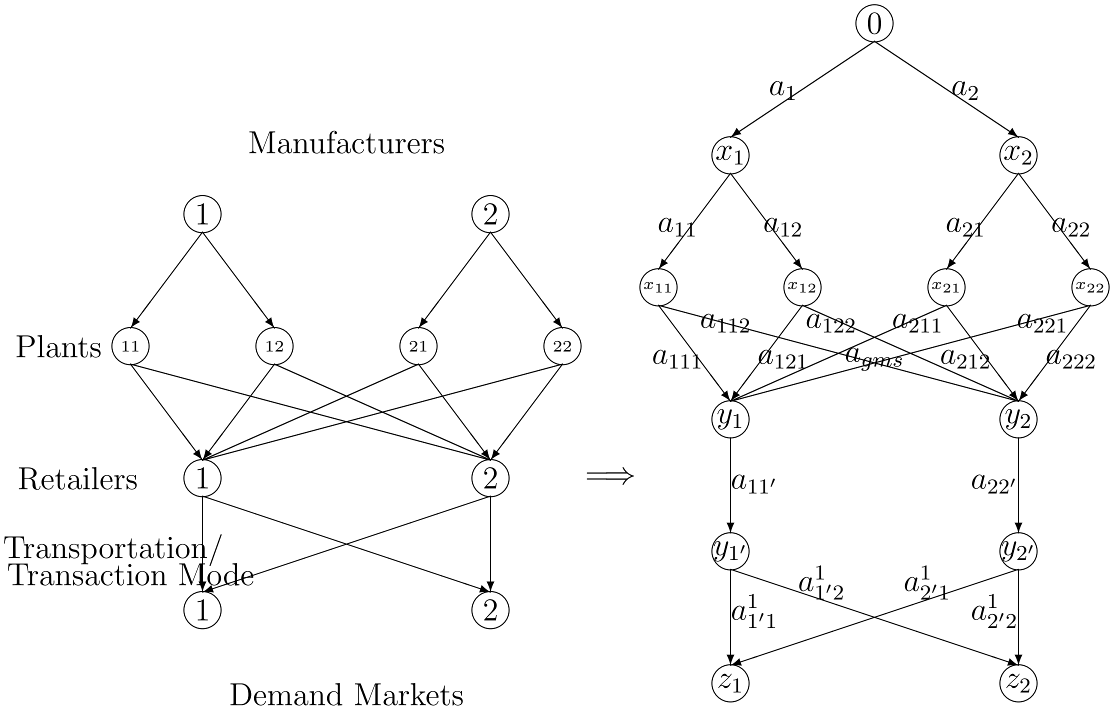

Figure 3.3. The Supply Chain Network and Corresponding Supernetwork $\mathcal{G}_{\mathcal{S}}$ for the Numerical Examples

The notation is presented here and in the subsequent examples in the form of the supply chain network equilibrium model of Section 3.1. The equilibrium solutions for the numerical examples, along with the translations of the computed equilibrium link flows, and the travel demands (and disutilities) into the equilibrium supply chain flows and prices are given in Table 3.2.

3.3.1 Example 3.1

The data for the first numerical example is given below. In order to construct a benchmark, it was assumed that all the prices associated with the environmental criteria were equal to zero, that is: $\alpha_1 = \alpha_2 = 0$, $\beta_1 = \beta_2 = 0$, and $\eta_1 = \eta_2 = 0$.

The production cost functions for the manufacturers were given by:

$$f_{11}(q_1) = 2.5q_{11}^2 + q_{11}q_{21} + 2q_{11}, \quad f_{12}(q_2) = 2.5q_{12}^2 + q_{11}q_{12} + 2q_{22},$$
$$f_{21}(q_1) = .5q_{21}^2 + .5q_{11}q_{21} + 2q_{21}, \quad f_{22}(q_2) = .5q_{22}^2 + q_{12}q_{22} + 2q_{22}.$$

The transportation/transaction cost functions faced by the manufacturers and associated with transacting with the retailers were given by:

$$c_{imj}(q_{imj}) = .5q_{imj}^2 + 3.5q_{imj}, i = 1; m = 1,2; j = 1,2;$$
$$c_{imj}(q_{imj}) = .5q_{imj}^2 + 2q_{imj}, i = 2; m = 1,2; j = 1,2;$$

The operating costs of the retailers, in turn, were given by:

$$c_1(Q^1) = .5(\sum_{i=1}^2 q_{i1})^2, \quad c_2(Q^1) = .5(\sum_{i=1}^2 q_{i2})^2.$$

The demand market price functions at the demand markets were:

$$\rho_{31}(d) = -d_1 + 500, \quad \rho_{32} = -d_2 + 500,$$

and the unit transportation/transaction costs between the retailers and the consumers at the demand markets were given by:

$$\hat{c}_{jk}^1(q_{jk}^1) = q_{jk}^1 + 5, \quad j = 1,2; k = 1,2.$$

All other transportation/transaction costs were assumed to be equal to zero. It was assumed that the manufacturing plants emitted pollutants where $e_{11} = e_{12} = e_{21} = e_{22} = 5$ for emission functions of the following form:

$$e_{im}(q_{im}) = e_{im}q_{im}, \quad i = 1, 2; m = 1, 2.$$

All other emission generation functions were assumed to be equal to zero. The supernetwork representation of this example depicted in Figure 3.3 with the links enumerated as in Figure 3.3 was utilized in order to solve the problem via the Euler method. Note that there are 13 nodes and 20 links in the supernetwork in Figure 3.3. Using the procedure outlined in Section 3.3, one can define an O/D pair as $w_1 = (0, z_1)$ and O/D pair $w_2 = (0, z_2)$ and the O/D pair travel disutilities were associated with the demand market price functions as in (3.48) and the user link travel cost functions as given in (3.41)–(3.45) (analogous constructions were done for the subsequent examples).

The Euler method converged in 56 iterations and yielded the equilibrium solution given in Table 3.2 (c.f. also the supernetwork in Figure 3.3). In Table 3.2 the translations of the computed equilibrium pattern(s) into the supply chain network flow, as well as the demand and price notation using (3.34)–(3.40) and (3.47)–(3.48), were provided.

All eight paths connecting each O/D pair were used, that is, had positive flow and the travel costs for paths connecting each O/D pair were equal to the travel disutility for that O/D pair. The optimality/equilibrium conditions were satisfied with excellent accuracy. The total amount of emissions in this example was: $e_{11}q^*_{11} + e_{12}q^*_{12} + e_{21}q^*_{21} + e_{22}q^*_{22} = 1,089$.

3.3.2 Example 3.2

The following variant of Example 3.1 was solved. The data was kept identical to that in Example 3.1 except that now the prices associated with the environmental concern of the manufacturers were: $\alpha_1 = \alpha_2 = 1$, with all other values equal to zero.

The Euler method converged in 56 iterations and yielded the equilibrium link flows, travel demands and travel disutilities (cf. Figure 3.3) given in Table 3.2. It can be noted that, in this example, all paths were again used. The total emissions generated was equal to: $1,077.85$ and, hence, as expected, given that both manufacturers now associated positive prices with environmental concern, the total emissions were reduced, relative to the amount emitted in Example 3.1.

3.3.3 Example 3.3

Example 3.3 was constructed as follows from Example 3.2. The data were identical to the data in Example 3.2, except that it was now assumed that the first retailer used a polluting mode of transportation to deliver the product to the consumers at the demand markets so that $e^1_{11} = e^1_{12} = 10$ for emission functions of the following form:

$$e^1_{1k}(q^1_{1k}) = e^1_{1k} q^1_{1k}, \quad k = 1, 2.$$

It was also assumed that the consumers were now environmentally conscious and that the prices associated with the environmental criteria at the demand markets were $\eta_1 = \eta_2 = 1$.

The Euler method converged in 67 iterations and yielded the new equilibrium pattern given in Table 3.2. In this example (as in Examples 3.1 and 3.2), all paths connecting each O/D pair were used, that is, they had positive equilibrium flows. The total amount of pollution emitted was now: $e_{11}q^*_{11} + e_{12}q^*_{12} + e_{21}q^*_{21} + e_{22}q^*_{22} + e^{1*}_{11}q^1_{11} + e^{1*}_{12}q^{1*}_{12} = 1,585.95$.

3.3.4 Example 3.4

In Example 3.4, the following question was asked, how high would η_1 and η_2 have to be so that the demand markets did not utilize retailer 1 at all and the associated link flows would be zero on those transportation/transaction links? Simulations were conducted which found that with $\eta_1 = \eta_2 = 32$ the desired result was achieved (with $\eta_1 = \eta_2 = 30$ there were still positive flows on those polluting links).

The Euler method converged in 102 iterations with the computed equilibrium link flows, travel demands and travel disutilities given in Table 3.2, along with the equivalent equilibrium supply chain network flows/transactions, demand, and prices. There were four paths used (and four not used) in each O/D pair. The total amount of emissions was now: 756.70. Hence, environmentally conscious consumers could significantly reduce the environmental emissions through the economics and the underlying decision-making behavior in the supply chain network.

Table 3.2: The Equilibrium solutions of Examples 3.1, 3.2, 3.3, and 3.4

Equilibrium Values	Example 3.1	Example 3.2	Example 3.3	Example 3.4
$f^*_{a_1} = q^*_1$	48.17	47.68	47.17	42.04
$f^*_{a_2} = q^*_2$	169.62	167.89	166.20	109.34
$f^*_{a_{11}} = q^*_{11}$	33.37	33.03	32.69	25.87
$f^*_{a_{12}} = q^*_{12}$	14.80	14.65	14.48	16.37
$f^*_{a_{21}} = q^*_{21}$	33.71	33.37	33.02	26.17
$f^*_{a_{22}} = q^*_{22}$	135.91	134.53	133.17	83.17
$f^*_{a_{11'}} = h^*_1$	108.90	107.79	103.82	0.00
$f^*_{a_{22'}} = h^*_2$	108.90	107.79	109.54	151.58
$f^*_{a_{111}} = q^*_{111}$	16.69	16.52	15.60	0.00
$f^*_{a_{112}} = q^*_{112}$	16.69	16.52	17.09	25.87
$f^*_{a_{121}} = q^*_{121}$	7.40	7.32	6.61	0.00
$f^*_{a_{122}} = q^*_{122}$	7.40	7.32	7.87	16.37
$f^*_{a_{211}} = q^*_{211}$	16.85	16.68	15.77	0.00
$f^*_{a_{212}} = q^*_{212}$	16.85	16.68	17.25	26.17
$f^*_{a_{221}} = q^*_{221}$	67.96	67.26	65.84	0.00
$f^*_{a_{222}} = q^*_{222}$	67.96	67.26	67.33	83.17
$f^*_{a^1_{1'1}} = q^{1*}_{11}$	54.45	53.89	51.91	0.00
$f^*_{a^1_{1'2}} = q^{1*}_{12}$	54.45	53.89	51.91	0.00
$f^*_{a^1_{2'1}} = q^{1*}_{21}$	54.45	53.89	54.77	75.79
$f^*_{a^1_{2'2}} = q^{1*}_{22}$	54.45	53.89	54.77	75.79
$d^*_{w_1} = d^*_1$	108.90	107.79	106.68	75.79
$d^*_{w_2} = d^*_2$	108.90	107.79	106.68	75.79
$\lambda^*_{w_1} = \rho_{31}$	391.11	392.23	393.30	424.41
$\lambda^*_{w_2} = \rho_{32}$	391.11	392.23	393.30	424.41

3.4 Summary and Conclusions

In this Chapter, I developed the multitiered, multicriteria supply chain network model with distinct manufacturing plants and associated emissions and presented the variational inequality formulation of the governing equilibrium conditions. This model was built on the supply chain network model of Nagurney, Liu, and Woolley (2007) to include the generalization of emission functions. Moreover, Nagurney and Toyasaki (2003) introduced environmental concerns into a supply chain network equilibrium framework (see also Nagurney, Dong, and Mokhtarian (2002b)) but not with the inclusion of alternative manufacturer plants. I establish that the prices associated with the environmental criteria of the various decision-makers can be interpreted as taxes.

Recently, it has been shown by Nagurney (2006a) that supply chains can be reformulated and solved as transportation network problems (see also Nagurney (2000), Nagurney and Liu (2005), Nagurney (2006b), and Wu et al. (2006)). The new supply chain network model with environmental concerns developed in this Chapter was then transformed into a transportation network equilibrium model with elastic demands over an appropriately constructed abstract network or supernetwork. This equivalence provides a new interpretation of the equilibrium conditions governing sustainable supply chains in terms of path flows. The generality of the concepts of transportation network equilibrium, originally proposed in the seminal book of Beckmann, McGuire, and Winsten (1956) (see also Boyce, Mahmassani, and Nagurney (2005)) are further demonstrated by the contributions of this Chapter.

CHAPTER 4

OPTIMAL ENDOGENOUS CARBON TAXES FOR ELECTRIC POWER SUPPLY CHAINS WITH POWER PLANTS

Electric power is one of the fundamental resources that have fueled modern economies and societies from the lighting and heating of homes and offices to the running of computers, which underpin the communications, manufacturing processes and financial services, and even transportation. Electric power is so essential to every day lives that when failures arise the impact is wide and vividly apparent as the biggest blackout in US history in 2003 graphically illustrated. Indeed, in modern societies there are few goods or services that do not depend directly on electricity. Globally, in 2002, 16.1 trillion kilowatt hours were supplied, with United States being the largest producer and consumer of electric energy (see Thompson Gale (2006)). In the past half-century, the total annual electricity use in the US alone has grown every year but two. The US electrical industry has more than half a trillion dollars of net assets, \$220 billion in annual sales, and consumes almost 40% of domestic primary energy (coal, natural gas, uranium, and oil), or about 40 quadrillion British Thermal Units (BTUs) (see Edison Electric Institute (2000), Energy Information Administration (2000, 2005)). This industry is growing, expecting the total global consumption of electricity to reach 23.1 trillion kilowatt hours in 2025. For background on the electric power industry, see Casazza and Delea (2003), Singh (1999), Zaccour (1998), as well as Section 1.2.2.2.

However, despite the major positive economic impacts of electric power, the heavy reliance on fossil fuel sources before conversion to electricity has had, at the same time, an immense environmental impact. For example, of the total US emissions of carbon dioxide and nitrous oxide, more than a third arises from generating electricity. In China, in turn, the electric power sector currently accounts for more than one-third of its annual coal consumption with such power plants generating over 75% of the air pollution in China (see Pew Center (2006)). Fossil fuels, which are estimated to be used to generate 36% of electricity production into 2020, and presently account for 39% of the electricity generated worldwide. With growing accumulating evidence of global warming, any policy aimed at mitigating the immense risks of unstable climate must directly consider the electricity industry (Poterba (1993) and Cline (1992)).

As noted in Wu et al. (2006), pollution taxes, and, in particular, carbon taxes are a powerful policy mechanism that can address market failures in energy. Currently, market prices for energy do not capture its many external costs in the form of regional and global pollution and also hide market distortions. The usefulness of carbon taxes has been noted by among others, Baranzini, Goldemberg, and Speck (2000), whereas Painuly (2001) has argued for the encouragement of power generation from renewable sources, including solar power and wind power through the use of green credits. Such credits are now being utilized in the European Union as well as in several states in the US (cf. RECS (1999) and Schaeffer et al. (1999)). Hence, a mathematical modeling framework that can capture the interactions among decision-makers in an electric power supply chain network from power generators, along with the power plant production options; the suppliers as well as ultimate consumers, coupled with the incorporation of environmental policies, such as carbon taxes, is of great practical as well as policy-making importance.

It was shown in Chapter 3 that the prices associated with the environmental emissions generated through production, transportation/transaction, and retail outlet operations as the product "moves" throughout the supply chain can be interpreted as *taxes* assigned by a regulatory agency. Recently, Wu et al. (2006) developed such a framework and proposed an electric power supply chain network equilibrium model with carbon taxes that are applied a priori to distinct power generator/power plant combinations and demonstrated that the model could be reformulated and solved as a transportation network equilibrium problem with elastic demands. However, in that model, the government authority would have to conduct simulation exercises to determine the carbon tax assignment in order to achieve some goal. In this Chapter, in contrast, I demonstrate how carbon taxes can be determined optimally and endogenously within a generalized electric power supply chain network equilibrium model. In particular, I allow the government to impose bound(s) on the total amount of carbon emissions and the optimal carbon taxes guarantee that the bound(s) are not exceeded.

Since electric power plants may be under different governmental jurisdictions either in the US or abroad I propose both a decentralized carbon taxation scheme as well as two centralized schemes. In the former environmental policy framework, a bound on carbon emissions can be applied on each power generator/power plant with a resulting distinct tax; in the latter framework there is a single carbon emission bound imposed on the entire electric power supply chain network with a resulting single tax.

This Chapter is based on Nagurney, Liu, and Woolley (2006), but as in Chapter 3, includes the generalization of emission functions which aids in the numerous applications of the model, and is organized as follows. In Section 4.1, I present the electric power supply chain network equilibrium model with three distinct carbon taxation schemes. In Section 4.2, several numerical examples are presented in which the optimal taxes, the electric power flows between tiers of decision-makers as well as the demand market prices, are computed. The prices at the demand markets at the equilibrium are also reported. In Section 4.3, I summarize the results in this Chapter and present the conclusions.

4.1 The Electric Power Supply Chain Network Model with Power Plants and Optimal Endogenous Carbon Taxes

In this Section I develop the electric power supply chain network equilibrium model that includes power plants as well as carbon taxes under three distinct taxation schemes. I begin with a decentralized taxation scheme outlined in Section 4.1.1 and then turn to the centralized schemes in Section 4.1.2. The presentation of the model follows the description of the electric supply chain network model with pollution taxes (which, however, were fixed and assigned a priori) in Wu et al. (2006).

In particular, I consider G power generators (sometimes also referred to as "gencos"), each of which, typically, owns and operates M power plants. A specific power plant may use a different primary energy fuel such as, for example, coal, natural gas, uranium, oil, sun, wind, etc., with different associated costs. In addition, each power plant also have associated costs that fully reflect policy objectives, which here be in the form of carbon taxes. There are S power suppliers, T transmission service providers, and K consumer markets, as depicted in Figure 4.1. The majority of the needed notation is given in Table 4.1. An equilibrium solution is denoted by "*". All vectors are assumed to be column vectors, except where noted otherwise.

The top-tiered nodes in the electric power supply chain network in Figure 4.1, enumerated by $1, \ldots, g \ldots, G$, represent the G electric power generators, who are the decision-makers who own and operate the electric power generating facilities or power plants denoted by the second tier of nodes in the network. The gencos produce electric power using the different power plants and sell to the power suppliers in the third tier. Node gm in the second tier corresponds to genco g's power plant m, with the second tier of nodes enumerated as: $11, \ldots, GM$. I assume that each electric power generator seeks to determine his optimal production portfolio across his power plants and his sales allocations of the electric power to the suppliers in order to maximize his own profit.

Power suppliers, which are represented by the third tiered nodes in Figure 4.1, function as intermediaries. The nodes corresponding to the power suppliers are enumerated as: $1, \dots, s, \dots, S$ with node s corresponding to supplier s. They purchase electric power from the power generators and are aware as to the types of power plants used by the generators. They also sell the electric power to the consumers at the different demand markets. I assume that the power suppliers compete with one another in a noncooperative manner. However, the suppliers do not physically possess electric power at any stage of the supplying process; they only hold and trade the right for the electric power.

The bottom-tiered nodes in Figure 4.1 represent the demand markets, which can be distinguished from one another by their geographic locations or the type of associated consumers such as whether they correspond, for example, to businesses or to households. There are K bottom-tiered nodes with node k corresponding to demand market k.

A transmission service is necessary for the physical delivery of electric power from the power generators to the points of consumption. The transmission service providers are the entities who own and operate the electric power transmission and distribution systems, and distribute electric power from power generators to the consumption markets. Since the transmission service providers do not make decisions such as to where or from whom the electric power be delivered, they are not represented by nodes in the network model. The structure of the network in Figure 4.1 guarantees that the conservation of flow equations associated with the electric power production and distribution are satisfied. The flows on the links joining the genco nodes in Figure 4.1 to the power plant nodes are respectively: $q_{11}, \dots, q_{gm}, \dots, q_{GM}$; the flows on the links from the power plant nodes to the supplier nodes are given, respectively, by the components of the vector Q^1, whereas the flows on the links joining the supplier nodes with the demand markets are given by the respective components of the vector: Q^2.

4.1.1 A Decentralized Carbon Taxation Scheme

I now describe the behavior of the electric power generators, the suppliers, and the consumers at the demand markets. I first consider a decentralized carbon taxation scheme. I then state the equilibrium conditions of the electric power supply chain network and provide the variational inequality formulation. Subsequently, I discuss how centralized taxation schemes can be substituted for the decentralized scheme.

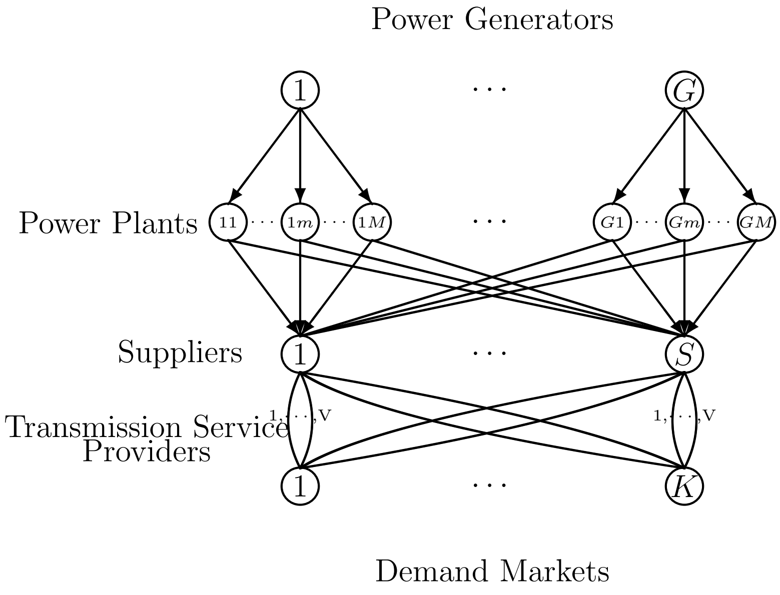

Figure 4.1. The Electric Power Supply Chain Network with Power Plants

4.1.1.1 The Behavior of the Power Generators and Their Optimality Conditions

Let ρ^*_{1gms} denote the unit price charged by power generator g for the transaction with power supplier s for power produced at plant m with $g = 1, \ldots, G$; $m = 1, \ldots, M$ and $s = 1, \ldots, S$. ρ^*_{1gms} is an endogenous variable and can be determined once the complete electric power supply chain network equilibrium model is solved.

Table 4.1. The Notation for the Electric Power Supply Chain Network Model

Notation	**Definition**
q_{gm}	quantity of electricity produced by generator g using power plant m, where $g = 1, \ldots, G; m = 1, \ldots, M$
q_m	G-dimensional vector of electric power generated by the gencos using power plant m with components: $g_{1m}, \ldots, g_{Gm}$
q	GM-dimensional vector of all the electric power outputs generated by the gencos at the power plants
Q^1	GMS-dimensional vector of electric power flows between the power plants of the power generators and the power suppliers with component gms denoted by q_{gms}
Q^2	STK-dimensional vector of power flows between suppliers and demand markets with component stk denoted by q^t_{sk} and denoting the flow between supplier s and demand market k via transmission provider t
d	K-dimensional vector of market demands with component k denoted by d_k
$f_{gm}(q_m)$	power generating cost function of power generator g using power plant m with marginal power generating cost with respect to q_{gm} denoted by $\frac{\partial f_{gm}}{\partial q_{gm}}$
$c_{gms}(q_{gms})$	transaction cost incurred by power generator g using power plant m in transacting with power supplier s with marginal transaction cost denoted by $\frac{\partial c_{gms}(q_{gms})}{\partial q_{gms}}$
$e_{gm}(q_{gm})$	amount of carbon emitted by genco g using power plant m as a function of each unit of electric power produced with marginal emissions generation denoted by $\frac{\partial e_{gm}(q_{gm})}{\partial q_{gm}}$
h	S-dimensional vector of the power suppliers' supplies of the electric power with component s denoted by h_s, with $h_s \equiv \sum_{g=1}^{G} \sum_{m=1}^{M} q_{gms}$
$c_s(h) \equiv c_s(Q^1)$	operating cost of power supplier s with marginal operating cost with respect to h_s denoted by $\frac{\partial c_s}{\partial h_s}$ and the marginal operating cost with respect to q_{gms} denoted by $\frac{\partial c_s(Q^1)}{\partial q_{gms}}$
$c^t_{sk}(q^t_{sk})$	transaction cost incurred by power supplier s in transacting with demand market k via transmission provider t with marginal transaction cost with respect to q^t_{sk} denoted by $\frac{\partial c^t_{sk}(q^t_{sk})}{\partial q^t_{sk}}$
$\hat{c}_{gms}(q_{gms})$	transaction cost incurred by power supplier s in transacting with power generator g for power generated by plant m with marginal transaction cost denoted by $\frac{\partial \hat{c}_{gms}(q_{gms})}{\partial q_{gms}}$
$\hat{c}^t_{sk}(Q^2)$	unit transaction cost incurred by consumers at demand market k in transacting with power supplier s via transmission provider t
$\rho_{3k}(d)$	demand market price function at demand market k

Let τ_{gm}; $g = 1, \ldots, G$; $m = 1, \ldots, M$, denote the unit tax that the governmental or responsible environmental authority charge genco g operating power plant m for its carbon emissions and group all these taxes into the vector τ. The optimal values of these taxes, denoted by the components of the vector τ^*, are endogenous and are determined once the complete model is solved. As I later see, the taxes guarantee that bounds on the carbon emissions, also imposed by the responsible authority, are not exceeded. The bounds are denoted by $\bar{B}_{gm}$; $g = 1, \ldots, G$; $m = 1, \ldots, M$ and reflect the maximum, or cap on carbon emissions allowed by the responsible authority for the particular genco/power plant combination. It is assumed that, to reduce emissions below the bound set by the governing authority, a particular generator, g, using power plant, m, must substitute toward cleaner technologies. The complete electric power supply chain network equilibrium model captures the complex interactions among the various decision-makers and its solution yields the equilibrium electric power flows and demand market prices as well as the optimal carbon taxes.

Since it is assumed that each individual power generator is a profit-maximizer, the optimization problem of power generator g can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M} \sum_{s=1}^{S} \rho^*_{1gms} q_{gms} - \sum_{m=1}^{M} f_{gm}(q_m) - \sum_{m=1}^{M} \sum_{s=1}^{S} c_{gms}(q_{gms}) - \sum_{m=1}^{M} \tau^*_{gm} e_{gm}(q_{gm}) \tag{4.1}$$

subject to:

$$\sum_{s=1}^{S} q_{gms} = q_{gm}, \quad m = 1, \ldots, M, \tag{4.2}$$

$$q_{gms} \geq 0, \quad m = 1, \ldots, M; s = 1, \ldots, S. \tag{4.3}$$

The first term in the objective function (4.1) represents the revenue and the next two terms represent the power generation cost and transaction costs, respectively. The last term in (4.1) denotes the total payout in carbon taxes by the genco based on the total carbon pollution emitted by his power plants. Conservation of flow equation (4.2) states that the amount of power generated at a particular power plant (and corresponding to a particular genco) is equal to the electric power transacted by the genco from that power plant with all the suppliers and this holds for each of the power plants.

Assume, as was done in Wu et al. (2006), that the generating cost, the transaction cost, as well as the emission functions for each power generator are continuously differentiable and convex, and that the power generators compete in a noncooperative manner in the sense of Nash (1950, 1951). The optimality conditions for all power generators simultaneously, under the above assumptions (cf. Nagurney (1999)), coincide with the solution of the following variational inequality: determine $(q^*, Q^{1*}) \in \mathcal{K}_4^1$ satisfying

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \tau_{gm}^* \frac{\partial e_{gm}(q_{gm}^*)}{\partial q_{gm}}\right] \times [q_{gm} - q_{gm}^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} - \rho_{1gms}^*\right] \times [q_{gms} - q_{gms}^*] \geq 0, \quad \forall (q, Q^1) \in \mathcal{K}_4^1, \qquad (4.4)$$

where $\mathcal{K}_4^1 \equiv \{(q, Q^1) | (q, Q^1) \in R_+^{GM+GMS}$ and (4.2) holds$\}$.

4.1.1.2 The Behavior of Power Suppliers and Their Optimality Conditions

The power suppliers, in turn, are involved in transactions both with the power generators and with the consumers at demand markets through the transmission service providers.

Since electric power cannot be stored, the total amount of electricity sold by a power supplier is equal to the total electric power that he purchased from the generators and produced via the different power plants available to the generators, that is:

$$\sum_{k=1}^{K}\sum_{t=1}^{T} q_{sk}^t = \sum_{g=1}^{G}\sum_{m=1}^{M} q_{gms}, \quad s = 1, \ldots, S. \qquad (4.5)$$

Let ρ_{2sk}^{t*} denote the price charged by power supplier s to demand market k via transmission service provider t. This price is determined endogenously in the model once the entire network equilibrium problem is solved. As noted above, it is assumed that each power supplier seeks to maximize his own profit. Hence the optimization problem faced by supplier s may be expressed as follows:

$$\text{Maximize} \quad \sum_{k=1}^{K}\sum_{t=1}^{T} \rho_{2sk}^{t*} q_{sk}^{t} - c_s(Q^1)$$

$$-\sum_{g=1}^{G}\sum_{m=1}^{M} \rho_{1gms}^{*} q_{gms} - \sum_{g=1}^{G}\sum_{m=1}^{M} \hat{c}_{gms}(q_{gms}) - \sum_{k=1}^{K}\sum_{t=1}^{T} c_{sk}^{t}(q_{sk}^{t}) \tag{4.6}$$

subject to:

$$\sum_{k=1}^{K}\sum_{t=1}^{T} q_{sk}^{t} = \sum_{g=1}^{G}\sum_{m=1}^{M} q_{gms}, \tag{4.7}$$

$$q_{gms} \geq 0, \quad g = 1, \ldots, G, \quad m = 1, \ldots, M, \tag{4.8}$$

$$q_{sk}^{t} \geq 0, \quad k = 1, \ldots, K; t = 1, \ldots, T. \tag{4.9}$$

The first term in (4.6) denotes the revenue of supplier s; the second term denotes the operating cost of the supplier; the third term denotes the payments for the electric power to the various gencos, and the final two terms represent the various transaction costs.

I assume that the transaction costs and the operating costs in (4.6) are all continuously differentiable and convex, and that the power suppliers compete in a noncooperative manner. Hence, the optimality conditions for all suppliers, simultaneously, under the above assumptions (Nagurney and Matsypura (2005a)), can be expressed as the following variational inequality: determine $(Q^{2*}, Q^{1*}) \in \mathcal{K}_4^2$ such that

$$\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T} \left[\frac{\partial c_{sk}^{t}(q_{sk}^{t*})}{\partial q_{sk}^{t}} - \rho_{2sk}^{t*}\right] \times [q_{sk}^{t} - q_{sk}^{t*}]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S} \left[\frac{\partial c_s(Q^{1*})}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^{*})}{\partial q_{gms}} + \rho_{1gms}^{*}\right] \times [q_{gms} - q_{gms}^{*}] \geq 0, \tag{4.10}$$

$\forall (Q^2, Q^1) \in \mathcal{K}_4^2$, where $\mathcal{K}_4^2 \equiv \{(Q^2, Q^1) | (Q^2, Q^1) \in R_{+}^{STK+GMS}$ and (4.7) holds$\}$.

For notational convenience, and as was done in Wu et al. (2006), let

$$h_s \equiv \sum_{g=1}^{G} \sum_{m=1}^{M} q_{gms}, \quad s = 1, \ldots, S. \tag{4.11}$$

As defined in Table 4.1, the operating cost of power supplier s, c_s, is a function of the total electricity inflows to the power supplier, that is:

$$c_s(h) \equiv c_s(Q^1), \quad s = 1, \ldots, S. \tag{4.12}$$

Hence, his marginal cost with respect to h_s is equal to the marginal cost with respect to q_{gms}:

$$\frac{\partial c_s(h)}{\partial h_s} \equiv \frac{\partial c_s(Q^1)}{\partial q_{gms}}, \quad s = 1, \ldots, S, \quad m = 1, \ldots, M, \quad g = 1, \ldots, G. \tag{4.13}$$

After the substitution of (4.11) and (4.13) into (4.10), and algebraic simplification, one obtains a variational inequality equivalent to (4.10), as follows: determine $(h^*, Q^{2*}, Q^{1*}) \in \mathcal{K}_4^3$ such that

$$\sum_{s=1}^{S} \frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*] + \sum_{s=1}^{S} \sum_{k=1}^{K} \sum_{t=1}^{T} \left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} - \rho_{2sk}^{t*} \right] \times [q_{sk}^t - q_{sk}^{t*}]$$

$$+ \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{s=1}^{S} \left[\frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}} + \rho_{1gms}^* \right] \times [q_{gms} - q_{gms}^*] \geq 0, \qquad \forall (h, Q^1, Q^2,) \in \mathcal{K}_4^3, \tag{4.14}$$

where $\mathcal{K}_4^3 \equiv \{(h, Q^2, Q^1) | (h, Q^2, Q^1) \in R_+^{S(1+TK+GM)} \text{and (4.7) and (4.11) hold}\}$.

4.1.1.3 The Equilibrium Conditions for the Demand Markets

At each demand market k the following conservation of flow equation must be satisfied:

$$d_k = \sum_{s=1}^{S} \sum_{t=1}^{T} q_{sk}^t, \quad k = 1, \ldots, K. \tag{4.15}$$

The market equilibrium conditions at demand market k take the form: for each power supplier s; $s = 1, ..., S$ and transaction mode t; $t = 1, ..., T$:

$$\rho_{2sk}^{t*} + \hat{c}_{sk}^{t}(Q^{2*}) \begin{cases} = \rho_{3k}(d^*), & \text{if} \quad q_{sk}^{t*} > 0, \\ \geq \rho_{3k}(d^*), & \text{if} \quad q_{sk}^{t*} = 0. \end{cases} \tag{4.16}$$

According to (4.16) (see also Wu et al. (2006)), consumers at a demand market purchase power from a supplier via a transmission provider, provided that the purchase price plus the unit transaction cost is equal to the price that the consumers are willing to pay at that demand market. If the purchase price plus the unit transaction cost exceeds the price the consumers are willing to pay, then there be no transaction between that supplier and demand market via that transmission provider. The equivalent variational inequality takes the form: determine $(Q^{2*}, d^*) \in \mathcal{K}_4^4$, such that

$$\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\rho_{2sk}^{t*} + \hat{c}_{sk}^{t}(Q^{2*})\right] \times [q_{sk}^{t} - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*] \geq 0, \quad \forall (Q^2, d) \in \mathcal{K}_4^4, \tag{4.17}$$

where $\mathcal{K}_4^4 \equiv \{(Q^2, d) | (Q^2, d) \in R_+^{K(ST+1)} \text{and (4.15) holds}\}$.

4.1.1.4 The Decentralized Carbon Tax Equilibrium Conditions

Unlike the model of Wu et al. (2006), which considered pollution taxes applied to each genco/power plant combination that were fixed and assigned a priori, I here assume that the taxes are endogenous and optimal in the following sense. I assume, as is commonly done in real-life environmental policy-making (see also, e.g., the book by Dhanda, Nagurney, and Ramanujam (1999)), and as was noted earlier, that bounds are applied in terms of the maximum carbon emissions that are allowed for each genco/power plant combination. If the particular genco/power plant emits fewer units of carbon than the imposed limit, then it is not taxed; a tax is assigned, if the emissions equal the bound. Mathematically, this statement corresponds to the following carbon tax equilibrium conditions under a decentralized tax scheme: for all power generators g; $g = 1, \ldots, G$, and for all power plants m; $m = 1, \ldots, M$, a carbon tax policy is said to be in equilibrium if:

$$\bar{B}_{gm} - e_{gm}(q^*_{gm}) \begin{cases} = 0, & \text{if} \quad \tau^*_{gm} > 0, \\ \geq 0, & \text{if} \quad \tau^*_{gm} = 0. \end{cases} \tag{4.18}$$

Of course, if a given genco only has a subset of power plants (which may correspond to different fuel source options), then those links would just be eliminated from the network in Figure 4.1 and the notation altered accordingly.

4.1.1.5 The Equilibrium Conditions for the Electric Power Supply Chain Network

In equilibrium, the optimality conditions for all the power generators, the optimality conditions for all the power suppliers, and the equilibrium conditions for all the demand markets as well as the carbon tax equilibrium conditions must be simultaneously satisfied so that no decision-maker has any incentive to alter his transactions. I now formally state the equilibrium conditions for the entire electric power supply chain network with endogenous, decentralized carbon taxes.

Definition 4.1 (Electric Power Supply Chain Network Equilibrium with Endogenous, Decentralized Carbon Taxes)

The equilibrium state of the electric power supply chain network with power plants and endogenous, decentralized carbon taxes is one where the electric power flows between the tiers of the network coincide and the electric power flows, the demands, and the carbon taxes satisfy the sum of conditions (4.4), (4.14), (4.17), and the decentralized carbon tax equilibrium conditions (4.18).

I now state and prove:

Theorem 4.1 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Decentralized Carbon Taxes)

The equilibrium conditions governing the electric power supply chain network according to Definition 4.1 coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \tau^*) \in \mathcal{K}_4^5$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \tau_{gm}^*\frac{\partial e_{gm}(q_{gm}^*)}{\partial q_{gm}}\right] \times [q_{gm} - q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right] \times [q_{sk}^t - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm} - e_{gm}(q_{gm}^*)\right] \times \left[\tau_{gm} - \tau_{gm}^*\right] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \tau) \in \mathcal{K}_4^5, \quad (4.19)$$

where $\mathcal{K}_4^5 \equiv \{(q, h, Q^1, Q^2, d, \tau) | (q, h, Q^1, Q^2, d, \tau) \in R_+^{2GM+S+GMS+TSK+K}$ *and* (4.2), (4.5), (4.11), *and* (4.15) *hold*$\}$.

Proof:

I first prove that an equilibrium according to Definition 4.1 coincides with the solution of variational inequality (4.19). Note that (see also, e.g., Nagurney (1999)), if $\tau^* \in R_+^{GM}$ satisfies equilibrium conditions (4.18) then it also satisfies the following inequality:

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm} - e_{gm}(q_{gm}^*)\right] \times \left[\tau_{gm} - \tau_{gm}^*\right] \geq 0, \quad \forall \tau \in R_+^{MG}. \quad (4.20)$$

Summation of (4.4), (4.14), (4.17), and (4.20) (which is equivalent to the satisfaction of the carbon tax equilibrium conditions (4.18)), after algebraic simplifications, yields variational inequality (4.19).

I now prove the converse, that is, a solution to variational inequality (4.19) satisfies the sum of conditions (4.4), (4.14), (4.17), and the carbon tax equilibrium conditions (4.18), and is, therefore, an electric power supply chain network equilibrium pattern according to Definition 4.1.

First, I add the term $\rho^*_{1gms} - \rho^*_{1gms}$ to the first term in the third summand expression in (4.19). Then, I add the term $\rho^{t*}_{2sk} - \rho^{t*}_{2sk}$ to the first term in the fourth summand expression in (4.19). Since these terms are all equal to zero, they do not change (4.19). Hence, I obtain the following inequality:

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q^*_m)}{\partial q_{gm}} + \tau^*_{gm}\frac{\partial e_{gm}(q^*_{gm})}{\partial q_{gm}}\right] \times [q_{gm} - q^*_{gm}] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h^*_s]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q^*_{gms})}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q^*_{gms})}{\partial q_{gms}} + \rho^*_{1gms} - \rho^*_{1gms}\right] \times [q_{gms} - q^*_{gms}]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c^t_{sk}(q^{t*}_{sk})}{\partial q^t_{sk}} + \hat{c}^t_{sk}(q^{t*}_{sk}) + \rho^{t*}_{2sk} - \rho^{t*}_{2sk}\right] \times [q^t_{sk} - q^{t*}_{sk}]$$

$$-\sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d^*_k]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm} - e_{gm}(q^*_{gm})\right] \times \left[\tau_{gm} - \tau^*_{gm}\right] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \tau) \in \mathcal{K}^5_4, \quad (4.21)$$

which can be rewritten as:

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q^*_m)}{\partial q_{gm}} + \tau^*_{gm}\frac{\partial e_{gm}(q^*_{gm})}{\partial q_{gm}}\right] \times [q_{gm} - q^*_{gm}]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q^*_{gms})}{\partial q_{gms}} - \rho^*_{1gms}\right] \times [q_{gms} - q^*_{gms}]$$

$$+\sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h^*_s] + \sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c^t_{sk}(q^{t*}_{sk})}{\partial q^t_{sk}} - \rho^{t*}_{2sk}\right] \times [q^t_{sk} - q^{t*}_{sk}]$$

$$+\sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{g=1}^{G}\left[\frac{\partial \hat{c}_{gms}(q^*_{gms})}{\partial q_{gms}} + \rho^*_{1gms}\right] \times [q_{gms} - q^*_{gms}]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\rho_{2sk}^{t*}+\hat{c}_{sk}^{t}(q_{sk}^{t*})\right]\times[q_{sk}^{t}-q_{sk}^{t*}]-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm}-e_{gm}(q_{gm}^*)\right]\times\left[\tau_{gm}-\tau_{gm}^*\right]\geq 0,\quad \forall(q,h,Q^1,Q^2,d,\tau)\in\mathcal{K}_4^5. \quad (4.22)$$

Clearly, (4.22) is the sum of the optimality conditions (4.4) and (4.14) and the inequality formulations of equilibrium conditions (4.16) and (4.18) given, respectively, by (4.17) and (4.20), and is, hence, according to Definition 4.1 an electric power supply chain network equilibrium with endogenous, decentralized carbon taxes.

Note that the solution of variational inequality (4.19) yields the equilibrium electric power flows (see also the network in Figure 4.1), the equilibrium demands, as well as the optimal carbon taxes. If desired, once variational inequality (4.19) is solved, one can also determine the prices associated with the power generators; ρ_{1gms}^* for $g=1,\ldots,G$; $m=1,\ldots,M$, and $s=1,\ldots,S$, as well as the prices associated with the suppliers/transmission providers/demand markets and denoted by ρ_{2sk}^{t*}; $s=1,\ldots,S$; $k=1,\ldots,K$, and $t=1,\ldots,T$. The procedure would be similar to that described in Wu et al. (2006).

Remark

Note that in the case of objective function (4.1) and, hence, also variational inequality (4.19), the taxes could also be interpreted as "prices" associated with the minimization of the carbon emissions for each genco and power plant. Prices associated with environmental criteria in the form of total emission generation in the context of multicriteria decision-making and supply chains have been proposed and discussed in Nagurney and Toyasaki (2003). Of course, such prices would reflect that the gencos assign such prices to pollution emission minimization themselves and are self-directed, whereas environmental policies, in the form of carbon taxes, are imposed by an authority. It is interesting to see, however, that positive, self-induced decision-making in terms of environmental decision-making could have the same result as the imposition of taxes. However, the prices would have to be determined endogenously to have the precise correspondence between the electric supply chain network with multicriteria decision-makers and the model with carbon taxes proposed above. The same analogies can be made for the two carbon taxation schemes below.

Corollary 4.1 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Decentralized Carbon Taxes for the Case of Fixed Emissions)
Assume that the emission functions are fixed and given (see Nagurney, Liu, and Woolley (2006)). Hence, in this special case, variational inequality (4.19) collapses to: The equilibrium conditions governing the electric power supply chain network according to Definition 4.1 coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \tau^*) \in \mathcal{K}_4^6$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \tau_{gm}^* e_{gm}\right] \times [q_{gm} - q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right] \times [q_{sk}^t - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\bar{B}_{gm} - e_{gm}q_{gm}^*\right] \times \left[\tau_{gm} - \tau_{gm}^*\right] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \tau) \in \mathcal{K}_4^6,$$

$$\text{where} \quad \mathcal{K}_4^6 \equiv \{(q, h, Q^1, Q^2, d, \tau) | (q, h, Q^1, Q^2, d, \tau) \in R_+^{2GM+S+GMS+TSK+K}. \quad (4.23)$$

The proof is straightforward.

4.1.2 Centralized Carbon Taxation Schemes

In the case of a centralized carbon taxation scheme, I first consider the case in which there is a fixed bound $\bar{B}$ for all the carbon emissions generated in the electric power supply chain and the carbon tax is now denoted by $\mathcal{T}$. I then turn to the case in which the bound can vary as a function of the tax.

4.1.2.1 The Centralized Carbon Tax Equilibrium Conditions – Fixed Bound

In this case, one has, analogous to equilibrium conditions (4.18), the following centralized carbon tax equilibrium conditions, which state that if the amount of carbon produced in equilibrium is less than the carbon emission bound then the tax be zero; if the tax is positive, then the emissions are at the bound:

$$\bar{B} - \sum_{g=1}^{G} \sum_{m=1}^{M} e_{gm}(q^*_{gm}) \begin{cases} = 0, & \text{if} \quad \mathcal{T}^* > 0, \\ \geq 0, & \text{if} \quad \mathcal{T}^* = 0. \end{cases} \tag{4.24}$$

Clearly equilibrium conditions (4.24) can be formulated as the inequality:

$$\left[\bar{B} - \sum_{g=1}^{G} \sum_{m=1}^{M} e_{gm}(q^*_{gm}) \right] \times [\mathcal{T} - \mathcal{T}^*] \geq 0, \quad \forall \mathcal{T} \geq 0. \tag{4.25}$$

Hence, one would have the following definition.

Definition 4.2 (Electric Power Supply Chain Network Equilibrium with Endogenous, Centralized Carbon Taxes - Fixed Upper Bound Case)
The equilibrium state of the electric power supply chain network with power plants and endogenous, centralized carbon taxes with a fixed upper bound on carbon emissions is one where the electric power flows between the tiers of the network coincide and the electric power flows, the demands, and the carbon taxes satisfy the sum of conditions (4.4), (4.14), and (4.17) with $\mathcal{T}^*$ *substituted for each* τ^*_{gm}*;* $g = 1, \ldots, G$*;* $m = 1, \ldots, M$*, and the centralized carbon tax equilibrium conditions (4.24) also hold.*

The variational inequality for this centralized carbon taxation scheme (cf. (4.19)) is immediate and it takes the form:

Theorem 4.2 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and a Fixed Upper Bound)

The equilibrium conditions governing the electric power supply chain network according to Definition 4.2 coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^7$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^*\frac{\partial e_{gm}(q_{gm}^*)}{\partial q_{gm}}\right]\times[q_{gm}-q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s}\times[h_s-h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right]\times[q_{gms}-q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right]\times[q_{sk}^t-q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]$$

$$+\left[\bar{B}-\sum_{g=1}^{G}\sum_{m=1}^{M}e_{gm}(q_{gm}^*)\right]\times[\mathcal{T}-\mathcal{T}^*]\geq 0, \quad \forall(q,h,Q^1,Q^2,d,\mathcal{T})\in\mathcal{K}_4^7, \qquad (4.26)$$

where $\mathcal{K}_4^7 \equiv \{(q,h,Q^1,Q^2,d,\mathcal{T})|(q,h,Q^1,Q^2,d,\mathcal{T})\in R_+^{GM+S+GMS+TSK+K+1}$ *and* (4.2), (4.5), (4.11), *and* (4.15) *hold*$\}$.

Corollary 4.2 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and a Fixed Upper Bound for the Case of Fixed Emissions)

Assume that the emission functions are fixed and given (see Nagurney, Liu, and Woolley (2006)). Hence, in this special case, variational inequality (4.26) collapses to: The equilibrium conditions governing the electric power supply chain network according to Definition 4.1 coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^8$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^* e_{gm}\right]\times[q_{gm}-q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s}\times[h_s-h_s^*]$$

$$
+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q^*_{gms})}{\partial q_{gms}}+\frac{\partial \hat{c}_{gms}(q^*_{gms})}{\partial q_{gms}}\right]\times[q_{gms}-q^*_{gms}]
$$

$$
+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c^t_{sk}(q^{t*}_{sk})}{\partial q^t_{sk}}+\hat{c}^t_{sk}(Q^{2*})\right]\times[q^t_{sk}-q^{t*}_{sk}]-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d^*_k]
$$

$$
+\left[\bar{B}-\sum_{g=1}^{G}\sum_{m=1}^{M}e_{gm}q^*_{gm}\right]\times[\mathcal{T}-\mathcal{T}^*]\geq 0,\quad \forall(q,h,Q^1,Q^2,d,\mathcal{T})\in\mathcal{K}^8_4, \qquad (4.27)
$$

$$
where\quad \mathcal{K}^8_4\equiv\{(q,h,Q^1,Q^2,d,\mathcal{T})|(q,h,Q^1,Q^2,d,\mathcal{T})\in R^{GM+S+GMS+TSK+K+1}_+
$$

The proof is straightforward.

4.1.2.2 The Centralized Carbon Taxation Scheme - Elastic Bound

I now consider a carbon taxation scheme in which the carbon emission bound is elastic in that it is no longer fixed but is a function of the carbon tax. Such a scheme would reflect, for example, the situation where the government might be willing to assign a different bound on carbon emissions, depending upon the size of the tax. Hence, I now assume rather than a bound $\bar{B}$ as in (4.24), a bound denoted by $B(\mathcal{T})$ where this function is assumed to be continuous.

4.1.2.3 The Centralized Carbon Tax Equilibrium Conditions – Elastic Bound

In this case, the carbon tax equilibrium conditions (cf. 4.24)) would be as follows.

$$
B(\mathcal{T}^*)-\sum_{g=1}^{G}\sum_{m=1}^{M}e_{gm}(q^*_{gm})\begin{cases}=0, & \text{if}\quad \mathcal{T}^*>0,\\ \geq 0, & \text{if}\quad \mathcal{T}^*=0.\end{cases} \qquad (4.28)
$$

Clearly equilibrium conditions (4.24) can be formulated as the inequality:

$$
\left[B(\mathcal{T}^*)-\sum_{g=1}^{G}\sum_{m=1}^{M}e_{gm}(q^*_{gm})\right]\times[\mathcal{T}-\mathcal{T}^*]\geq 0,\quad \forall\mathcal{T}\geq 0. \qquad (4.29)
$$

As for the behavior of the electric power supply chain network decision-makers, it remains as described in Section 4.1.1, except that now I substitute $\mathcal{T}^*$ for each τ^*_{gm};

$g = 1, \ldots, G$; $m = 1, \ldots, M$, as I did for the centralized scheme in the case of a fixed upper bound for carbon emissions. Such a substitution (again) needs to be made in (4.1) and in (4.4) with the resulting definition below:

Definition 4.3 (Electric Power Supply Chain Network Equilibrium with Endogenous, Centralized Carbon Taxes - Elastic Bound Case)

The equilibrium state of the electric power supply chain network with power plants and endogenous, centralized carbon taxes with an elastic carbon emission bound is one where the electric power flows between the tiers of the network coincide and the electric power flows, the demands, and the carbon taxes satisfy the sum of conditions (4.4), (4.14), (4.17), with $\mathcal{T}^*$ *substituted for each* τ^*_{gm}*;* $g = 1, \ldots, G$*;* $m = 1, \ldots, M$*, and the centralized carbon tax equilibrium conditions (4.28) also holds.*

The variational inequality for the centralized carbon taxation scheme with an elastic bound is also immediate:

Theorem 4.3 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and an Elastic Carbon Emission Bound)

The equilibrium conditions governing the electric power supply chain network according to Definition 4.3 coincide with the solution of the variational inequality given by: determine $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}^9_4$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q^*_m)}{\partial q_{gm}} + \mathcal{T}^*\frac{\partial e_{gm}(q^*_{gm})}{\partial q_{gm}}\right] \times [q_{gm} - q^*_{gm}] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h^*_s]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q^*_{gms})}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q^*_{gms})}{\partial q_{gms}}\right] \times [q_{gms} - q^*_{gms}]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c^t_{sk}(q^{t*}_{sk})}{\partial q^t_{sk}} + \hat{c}^t_{sk}(Q^{2*})\right] \times [q^t_{sk} - q^{t*}_{sk}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d^*_k]$$

$$+\left[B(\mathcal{T}^*) - \sum_{g=1}^{G}\sum_{m=1}^{M} e_{gm}(q^*_{gm})\right] \times [\mathcal{T} - \mathcal{T}^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \mathcal{T}) \in \mathcal{K}^9_4. \quad (4.30)$$

Corollary 4.3 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Centralized Carbon Taxes and an Elastic Carbon Emission Bound for the Case of Fixed Emissions) *Assume that the emission functions are fixed and given (see Nagurney, Liu, and Woolley (2006)). Hence, in this special case, variational inequality (4.26) collapses to: The equilibrium conditions governing the electric power supply chain network according to Definition 4.1 coincide with the solution of the variational inequality given by: determine* $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, \mathcal{T}^*) \in \mathcal{K}_4^{10}$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \mathcal{T}^* e_{gm}\right] \times [q_{gm} - q_{gm}^*] + \sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{t=1}^{T}\left[\frac{\partial c_{sk}^t(q_{sk}^{t*})}{\partial q_{sk}^t} + \hat{c}_{sk}^t(Q^{2*})\right] \times [q_{sk}^t - q_{sk}^{t*}] - \sum_{k=1}^{K}\rho_{3k}(d^*) \times [d_k - d_k^*]$$

$$+\left[B(\mathcal{T}^*) - \sum_{g=1}^{G}\sum_{m=1}^{M} e_{gm} q_{gm}^*\right] \times [\mathcal{T} - \mathcal{T}^*] \geq 0, \quad \forall (q, h, Q^1, Q^2, d, \mathcal{T}) \in \mathcal{K}_4^{10}. \quad (4.31)$$

The proof is straightforward.

Each of the variational inequality problems (4.19), (4.26), and (4.30) and be put into standard variational inequality form (cf. (2.1)) given by: determine $X^* \in \mathcal{K}$ such that

$$\langle F(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \quad (4.32)$$

by defining the vector X and the function F that enters the variational inequality accordingly. Qualitative properties of existence of a solution can then be obtained for variational inequalities (4.19) and (4.26) by noting, first, that, due to the bound(s) on the carbon emissions, the electric power outputs are bounded. If one further assumes that the imposed tax can be reasonably assumed to be bounded (although the bound may be vary large), then the feasible set be compact and existence of a solution then follow from the standard theory of variational inequalities (see Nagurney (1999)), since under the previously given assumptions, the corresponding function F is continuous. In the case of variational inequality (4.30), once can assume similar conditions or a coercivity condition on the corresponding function F. Monotonicity of F can be obtained for both variational inequalities (4.19) and (4.26) under analogous assumptions as those given in Nagurney and Matsypura (2005a); the same holds in the case of F for variational inequality (4.30) with the additional assumption that the function $B(\mathcal{T})$ is monotone.

4.2 Numerical Examples

In this Section, numerical examples are provided to demonstrate how the theoretical results in this Chapter can be applied in practice. These examples are from Nagurney, Liu, and Woolley (2006).

Wu et al. (2006) proposed an Euler method for the electric power supply chain network equilibrium problem with power plants and preassigned carbon taxes. It was demonstrated that such the electric power supply chain problem with preassigned taxes could be transformed into a transportation network equilibrium problem over an appropriately constructed abstract network or supernetwork.

In the models developed in this Chapter, however, in which the carbon taxes are no longer pre-assigned but, are endogenous and reflect particular goals of governmental/environmental authorities, one can no longer transform the variational inequalities (4.19), (4.26), and (4.30) directly into transportation network equilibrium problems (as was also done by Nagurney (2006a) for supply chain network equilibrium problems in the case of products). However, one can still exploit the connection by noticing that the variational inequality problems in this Chapter are defined over feasible sets that are, in effect, decomposable into subproblems in the flows and subproblems in carbon taxes. Furthermore, the former subproblems retain the transportation network structure identified in Wu et al. (2006). Analogously, path flow versions of each of these variational inequalities were constructed over the corresponding abstract transportation network and there be an additional term in each case to correspond to the particular carbon taxation scheme equilibrium condition.

The Euler method (cf. Section 2.5.1) was implemented in FORTRAN, and the computer system used was a Sun system at the University of Massachusetts at Amherst. The convergence criterion utilized was that the absolute value of the electric flows and the carbon taxes between two successive iterations differed by no more than 10^{-6}. The sequence $\{\alpha_{\mathcal{T}}\}$ in the Euler method was set to: $\{1, \frac{1}{2}, \frac{1}{2}, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}, \ldots\}$.

In all the numerical examples, the electric power supply chain network consisted of two power generators, with two power plants each, two power suppliers, one transmission provider, and two demand markets as depicted in Figure 4.2.

Examples 4.1 and 4.2, corresponded to instances of the electric power supply chain network equilibrium model with a decentralized carbon taxation scheme as outlined in Section 4.1.1 with variational inequality formulation given by (4.19). Example 4.3, in turn, corresponded to the case of a centralized carbon taxation scheme with a fixed bound on the carbon emissions, as described in Section 4.1.2, with corresponding variational inequality given by (4.26). Examples 4.4, corresponded to the centralized scheme but with a variable carbon emission bound and the variational inequality model is given by (4.30). The results of the computations are given in Table 4.2.

4.2.1 Example 4.1

The data for the first numerical example is given below. The functional forms of the power generating cost functions, the transaction cost functions, the operating cost functions, the emission generation functions, and the demand price functions were identical to those in Example 4.1 in Wu et al. (2006).

The carbon emission generation functions were of the following form,

$$e_{gm}(q_{gm}) = e_{gm}q_{gm}; \quad g = 1,2; m = 1,2$$

with all of the terms: e_{gm}; $g = 1,2$; $m = 1,2$ set equal to 1.

The power generating cost functions for the power generators were given by:

$$f_{11}(q_1) = 2.5q_{11}^2 + q_{11}q_{21} + 2q_{11},\ f_{12}(q_2) = 2.5q_{12}^2 + q_{11}q_{12} + 2q_{22},$$

$$f_{21}(q_1) = .5q_{21}^2 + .5q_{11}q_{21} + 2q_{21},\ f_{22}(q_2) = .5q_{22}^2 + q_{12}q_{22} + 2q_{22}.$$

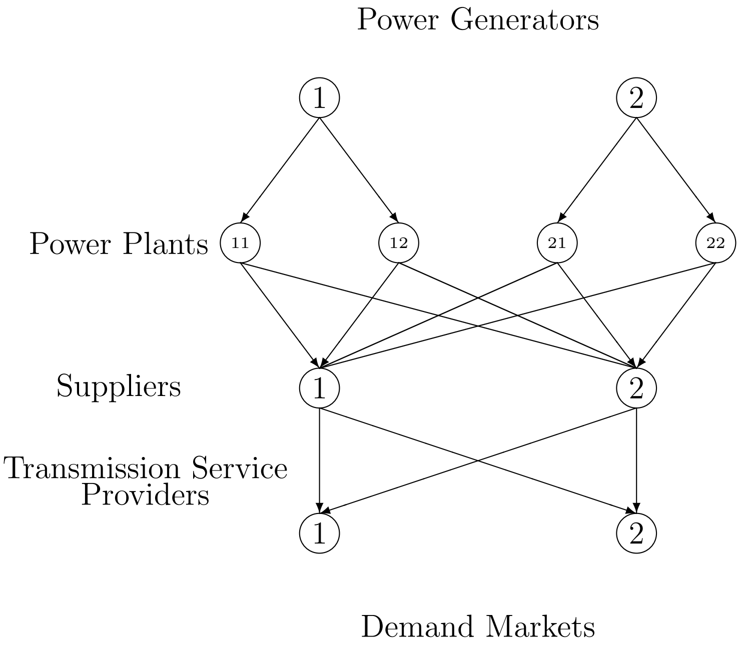

Figure 4.2. The Electric Power Supply Chain Network for the Numerical Examples

The transaction cost functions faced by the power generators and associated with transacting with the power suppliers were given by:

$$c_{111}(q_{111}) = .5q_{111}^2 + 3.5q_{111},\ c_{112}(q_{112}) = .5q_{112}^2 + 3.5q_{112},\ c_{121}(q_{121}) = .5q_{121}^2 + 3.5q_{121},$$
$$c_{122}(q_{122}) = .5q_{122}^2 + 3.5q_{122},\ c_{211}(q_{211}) = .5q_{211}^2 + 2q_{211},\ c_{212}(q_{212}) = .5q_{212}^2 + 2q_{212},$$
$$c_{221}(q_{221}) = .5q_{221}^2 + 2q_{221},\ c_{222}(q_{222}) = .5q_{222}^2 + 2q_{222}.$$

The operating costs of the power generators, in turn, were given by:

$$c_1(Q^1) = .5(\textstyle\sum_{i=1}^2 q_{i1})^2, \quad c_2(Q^1) = .5(\textstyle\sum_{i=1}^2 q_{i2})^2.$$

The demand market price functions at the demand markets were:

$$\rho_{31}(d) = -1.33d_1 + 366.6, \quad \rho_{32} = -1.33d_2 + 366.6,$$

and the transaction costs between the power suppliers and the consumers at the demand markets were given by:

$$\hat{c}_{sk}^1(q_{sk}^1) = q_{sk}^1 + 5, \quad s = 1, 2; k = 1, 2.$$

All other transaction costs were assumed to be equal to zero.

In Example 4.1, the bounds were as follows: $\bar{B}_{11} = \bar{B}_{12} = \bar{B}_{21} = \bar{B}_{22} = 100$. The computed equilibrium electric power flows and demands and the optimal taxes are given in Table 4.2. Note that the imposed bounds were sufficiently high so that all optimal taxes were identically equal to 0.00 since the carbon emissions generated by each genco and power plant combination were less than the imposed bound. The total carbon emissions were: 22.57, 9.93, 22.90, and 92.37, respectively, for genco 1/power plant 1; genco 1/power plant 2, and so on.

The price of electric power at the first demand market was 268.33 and at the second demand market the price was also 263.33. The demand was 73.89 at each demand market.

The optimality/equilibrium conditions were satisfied with excellent accuracy.

4.2.2 Example 4.2

Example 4.2 was constructed from Example 4.1 except that now the emission factor $e_{11} = 2$. Hence, its value was now doubled. Additionally, the bounds were all set as follows: $\bar{B}_{11} = \bar{B}_{12} = \bar{B}_{21} = \bar{B}_{22} = 23$. Hence, the bounds were tightened on all the genco power plants, in comparison to the bounds imposed in Example 4.1. The equilibrium solution is given in Table 4.2. Again, the endogenous carbon taxes had the desired effect in that the carbon emissions at each genco/power plant did not exceed the imposed bounds of 23. Interestingly, the carbon taxes increased for all the gencos and power plants although it was only the first genco and his first power plant that had its emissions factor doubled. The demand for electric power at the demand markets decreased to 40.30 at each demand market since the price of electric power had now increased and it is equal to 313.00 at both demand markets.

4.2.3 Example 4.3

In Example 4.3, a single centralized carbon taxation scheme was assumed in which the bound on carbon emissions was fixed. The remaining data were given in Example 4.1 except that in Example 4.3, $\bar{B} = 100$. Note that this bound represents the bound on the total amount of carbon emitted by all the power plants of all the gencos in the electric power supply chain network. The computed solution for Example 4.3 is given in Table 4.2. The demand was 50.00 at each of the two demand markets and the demand market price was 300.10.

Table 4.2. The Solutions to Examples 4.1, 4.2, 4.3, and 4.4

Equilibrium Solution	Example 4.1	Example 4.2	Example 4.3	Example 4.4
Computed Equilibrium Power Flows				
q_{11}^*	22.56	11.51	15.20	20.41
q_{12}^*	9.93	23.02	6.63	8.96
q_{21}^*	22.90	23.02	15.53	20.74
q_{22}^*	92.38	23.05	62.65	83.68
q_{111}^*	11.28	5.76	7.60	10.20
q_{112}^*	11.28	5.76	7.60	10.20
q_{121}^*	4.97	11.51	3.31	4.48
q_{122}^*	4.97	11.51	3.31	4.48
q_{211}^*	11.45	11.51	7.76	10.37
q_{212}^*	11.45	11.51	7.76	10.37
q_{221}^*	46.19	11.52	31.32	41.84
q_{222}^*	11.28	5.76	31.32	1.84
h_1^*	73.89	40.30	50.00	66.90
h_2^*	73.89	40.30	50.00	66.90
q_{11}^{1*}	36.94	20.15	25.00	33.45
q_{12}^{1*}	36.94	20.15	25.00	33.34
q_{21}^{1*}	36.94	20.15	25.00	33.45
q_{22}^{1*}	36.94	20.15	25.00	33.45
Computed Equilibrium Demands				
d_1^*	73.89	40.30	50.00	66.90
d_2^*	73.89	40.30	50.00	66.90
Computed Optimal Taxes				
τ_{11}^*	0.00	77.86	n/a	n/a
τ_{12}^*	0.00	92.38	n/a	n/a
τ_{21}^*	0.00	105.41	n/a	n/a
τ_{22}^*	0.00	185.96	n/a	n/a
Computed Optimal Tax				
$\mathcal{T}^*$	n/a	n/a	115.50	33.79

4.2.4 Example 4.4

In Example 4.4 it was assumed that the carbon taxation scheme was centralized but now the bound was a function of the tax. Example 4.4 had the same input data as Example 4.3 but the bound on the carbon emissions was now elastic and given by:

$$B(\mathcal{T}) = \mathcal{T}+100.$$

The equilibrium solution is reported in Table 4.4. The total carbon emissions were equal to 133.79 with the value of $B(\mathcal{T}) = 133.79$. The demand was 66.90 at each demand market and the demand market price was 277.63 at each demand market. The optimal carbon tax was now $\mathcal{T}= 33.79$.

4.3 Summary and Conclusions

In this Chapter, a modeling and computational framework that may help policy-makers to determine the optimal carbon taxes on the power plants in the electric power generation industry was presented. This general electric power supply chain network modeling framework utilizes variational inequality theory and is capable of identifying the optimal carbon taxes as well as the equilibrium electric power transaction flows and the demands for electric power (along with the associated prices) under three distinct carbon taxation environmental policies. Specifically, the first model, a completely decentralized scheme, allows the policy-makers to determine the optimal tax for each individual electric power plant which guarantees that the emission bound or quota of each plant is not exceeded. The second and third models, on the other hand, both enforce a "global" emission bound on the entire industry by imposing a uniform tax rate on the generating plants. However, the second policy assumes that the global emission bound is fixed while the third policy allows the bound to be a function of the tax.

The three variational inequality models were decomposable into subproblems that can be efficiently solved using the Euler method. Four numerical examples were presented to illustrate the impacts of the three distinct carbon taxation policies on the electric power supply chain networks. These numerical examples also demonstrate how policy-makers can determine the optimal taxes in order to achieve the environmental objectives.

The research is a contribution to the growing research in the development of rigorous mathematical frameworks for environmental-energy modeling.

CHAPTER 5

SPATIALLY DIFFERENTIATED TRADE OF PERMITS FOR MULTIPOLLUTANT ELECTRIC POWER SUPPLY CHAINS

Electric power plants emit several different air pollutants, such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrous oxide (NO_x), and mercury (Hg) with differing environmental impacts. For example, carbon dioxide is a major cause of global climate change; sulfur dioxide and nitrous oxide are responsible for acid rain and fine particle concentrations in the atmosphere; nitrous oxide also contributes to ground-level ozone, and mercury may travel vast distances before deposited in, for example, waterways, bioaccumulating in the food chain resulting in impaired neurological development (Hanisch (1988), Burtraw et al. (2005)). Moreover, SO_2, NO_x, and Hg have important spatial characteristics; that is, the impacts of these pollutants depend critically on the location of their sources and where their impacts are realized.

Although most environmental regulations attempt to control one pollutant at a time, integrated multipollutant regulations have advantages over the standard piecemeal approach. Multipollutant approaches can account for the substitutability or complementarity of emissions from power plants. As one pollutant is reduced, another may rise, as in, for example, if an electric power generating firm invests in low sulfur coal to reduce SO_2 emissions, this will result in an increased amount of NO_x and Hg emissions (Rubin et al. (1997, 2001)). However, to exploit the complementarity effects of pollutants, firms may invest in electrostatic precipitators (EPSs) that will reduce SO_2 and NO_x together. Thus, a generator will choose a technology that is not the cheapest, but reduces multiple pollutants while meeting the current pollutant standard (Schwarz (2005)). Furthermore, the relationship between pollutants may vary between seasons, across regions, and, possibly, over time as the composition of the atmosphere changes (WRAP (2003)).

Because of such advantages, there have been several existing and proposed regulations to control multiple pollutants. The Regional Clean Air Incentives Market (RECLAIM) program was implemented in California to control NO_x and SO_2 pollutants; the proposed but not enacted Clear Skies was a national cap to reduce SO_2, NO_x, and Hg; and the US Environmental Protection Agency's Clean Air Interstate Rule (CAIR) capped emissions of SO_2 and NO_x in a large region covering more than twenty states, mostly east of the Mississippi, and the District of Columbia (Palmer, Burtraw, and Shih (2007)).

There are two types of emission trading policies, project-based (generators purchase credits from a project aimed to reduce emissions) and an allowance market (also known as cap and trade programs). In the latter type, electric power generators are given credits (or allowances) by a central environmental authority. The advantage of emissions trading is that credit trading generates pollution prices that distribute emissions control in a cost-effective manner. For additional background on tradable pollution permits, see Tietenberg (1985), Nagurney, Dhanda, and Stranlund (1997), Montero (1997, 2001), Nagurney, Ramanujam, and Dhanda (1998), Tschirhart and Wen (1999), and the book by Dhanda, Nagurney, and Ramanujam (1999).

In this Chapter, I model the trading of emission rights by electric power producers who emit multiple pollutants with impacts that depend on the spatial dispersion of sources and receptors (for additional background on the electric power industry and associated modeling issues, see Hogan (1992), Kahn (1998), Zaccour (1998), Jing-Yuan and Smeers (1999), Boucher and Smeers (2001), Nagurney and Matsypura (2005a)). In the Introduction of this proposal, I noted that I will develop a modeling and computational framework that may help policy-makers control emissions in the electric power industry in the form of both a taxation scheme, as presented in Chapter 4, and an emission trading program, as in this Chapter.

However, unlike Chapter 4, this Chapter considers multiple pollutants. The control of multiple, spatially differentiated pollutants via emission trading calls for multiple pollution permit markets. Moreover, unlike the previous literature, I emphasize the use of alternative power production technologies as well as the underlying supply chain aspects of electric power generation and distribution. The results in this Chapter are particularly relevant given the current trends in environmental policies governing emissions in the electric power industry. The new model allows for the determination of the equilibrium numbers and prices of the various tradable pollution permits simultaneously with the equilibrium electric power flows and prices. The model builds upon the electric power supply chain model with alternative power plant technologies developed by Wu et al. (2006), which, however, only considered a single pollutant (and, in effect, a single receptor point).

This Chapter is based on Woolley, Nagurney, and Stranlund (2008) and is organized as follows. In Section 5.1, the model of the electric supply chain network with different power plant technologies is presented with the inclusion of multipollutant tradable permits and multiple receptor points. It is also demonstrated that the environmental standards are achieved. In Section 5.2, the computational procedure which exploits the structure of the problem is described. Also, numerical examples are provided. Section 5.3 summarizes the results in this Chapter and presents the conclusions.

5.1 The Electric Power Supply Chain Network Model with Multipollutant Tradable Permits

I now develop the model that captures the behavior of the electric power supply chain network decision-makers in the presence of a multipollutant permit trading scheme. The decision-makers in the electric power supply chain are the electric power generators, with their associated power plants, the suppliers, the transmission service providers, and the consumers at the demand markets. The equilibrium conditions of the electric power supply chain network will be given as well as the equivalent variational inequality formulation.

The electric power supply chain network is represented in Figure 5.1 with the top tier of nodes consisting of the G power generators (also referred to as "gencos"), enumerated by $1, \ldots, g, \ldots, G$. Power generators are the decision-makers who own and operate the M power plants, with a typical power plant technology denoted by m, and depicted in the second tier of nodes in Figure 5.1. Such nodes are enumerated as $11, \ldots, GM$ with node gm denoting the m-th power plant of genco g. The gencos produce electric power using the different power plants, which are powered, for example, by different forms of technology such as coal, natural gas, uranium, oil, sun, wind, etc., and with different associated costs and environmental impacts. The gencos sell the electric power to the power suppliers in the third tier of nodes in the electric power supply chain, as depicted in Figure 5.1.

In Figure 5.1, I also represent the R receptor points, with a typical receptor point denoted by r, associated with the pollutants generated by the power plants. These receptor points are spatially separated. It is also assumed that there are J pollutants with a typical pollutant denoted by j.

The suppliers do not physically handle the electricity, but function as intermediaries who only hold and trade the right for the electric power. The nodes corresponding to the power suppliers are enumerated as: $1, \ldots, s, \ldots, S$ with node s corresponding to supplier s. Suppliers sell the electric power to the consumers at the different demand markets via the V transmission service providers, who are the entities who own and operate the electric power transmission and distribution systems. A typical transmission provider is denoted by v.

Transmission service providers are not represented as nodes in the network model, since they do not make decisions such as to where or from whom the electric power will be delivered (see also Nagurney and Matsypura (2005a) and Wu et al. (2006)). The bottom-tiered nodes in Figure 5.1 represent the demand markets, which can differ by their geographic location or the type of associated consumers; for example, whether they correspond to businesses or households. The nodes corresponding to the demand markets are enumerated as: $1, \ldots, k, \ldots, K$ with node k corresponding to demand market k. The majority of the notation needed for the model is given in Table 5.1. An equilibrium solution is denoted by "*". All vectors are assumed to be column vectors, except where noted otherwise.

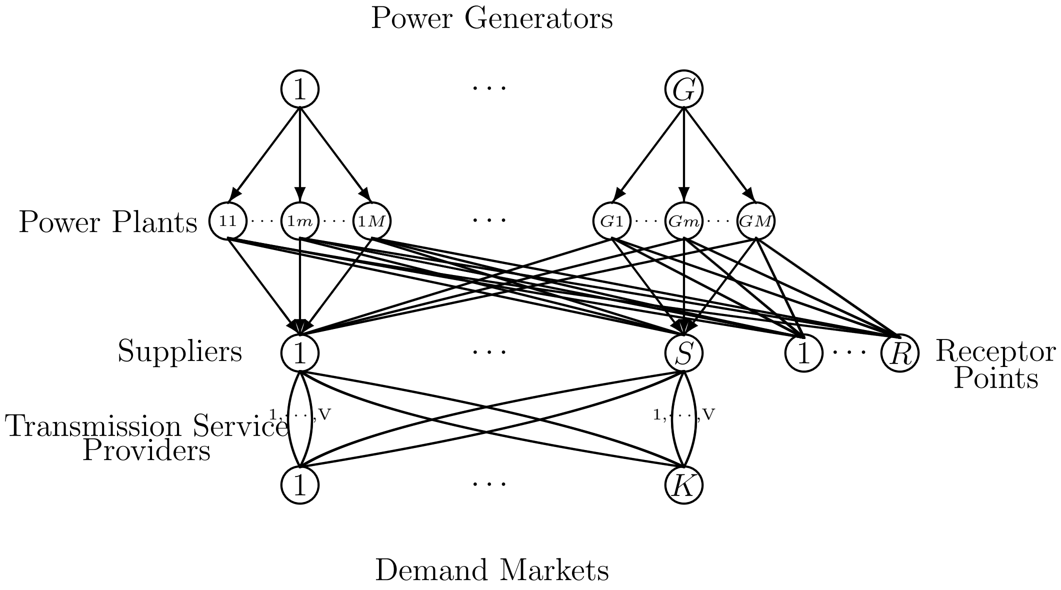

Figure 5.1. The Electric Power Supply Chain Network with Power Plants and Associated Technologies and with Pollutant Receptor Points

Table 5.1. The Notation for the Electric Power Supply Chain Network Model with Power Plants (cf. Wu et al. (2006))

Notation	**Definition**
q_{gm}	quantity of electricity produced by generator g using power plant m, where $g = 1, \dots, G; m = 1, \dots, M$
q_m	G-dimensional vector of electric power generated by the gencos using power plant m with components: $g_{1m}, \dots, g_{Gm}$
q	GM-dimensional vector of all the electric power outputs generated by the gencos at the power plants
Q^1	GMS-dimensional vector of electric power flows between the power plants of the power generators and the power suppliers with component gms denoted by q_{gms}
Q^2	STK-dimensional vector of power flows between suppliers and demand markets with component stk denoted by q^t_{sk} and denoting the flow between supplier s and demand market k via transmission provider t
d	K-dimensional vector of market demands with component k denoted by d_k
$f_{gm}(q_m)$	power generating cost function of power generator g using power plant m with marginal power generating cost with respect to q_{gm} denoted by $\frac{\partial f_{gm}}{\partial q_{gm}}$
$c_{gms}(q_{gms})$	transaction cost incurred by power generator g using power plant m in transacting with power supplier s with marginal transaction cost denoted by $\frac{\partial c_{gms}(q_{gms})}{\partial q_{gms}}$
h	S-dimensional vector of the power suppliers' supplies of the electric power with component s denoted by h_s, with $h_s \equiv \sum_{g=1}^{G} \sum_{m=1}^{M} q_{gms}$
$c_s(h) \equiv c_s(Q^1)$	operating cost of power supplier s with marginal operating cost with respect to h_s denoted by $\frac{\partial c_s}{\partial h_s}$ and the marginal operating cost with respect to q_{gms} denoted by $\frac{\partial c_s(Q^1)}{\partial q_{gms}}$
$c^t_{sk}(q^t_{sk})$	transaction cost incurred by power supplier s in transacting with demand market k via transmission provider t with marginal transaction cost with respect to q^t_{sk} denoted by $\frac{\partial c^t_{sk}(q^t_{sk})}{\partial q^t_{sk}}$
$\hat{c}_{gms}(q_{gms})$	transaction cost incurred by power supplier s in transacting with power generator g for power generated by plant m with marginal transaction cost denoted by $\frac{\partial \hat{c}_{gms}(q_{gms})}{\partial q_{gms}}$
$\hat{c}^t_{sk}(Q^2)$	unit transaction cost incurred by consumers at demand market k in transacting with power supplier s via transmission provider t
$\rho_{3k}(d)$	demand market price function at demand market k

I now focus on the notation for the permits. Similar to the discussion in Nagurney and Dhanda (2000) and Montgomery (1972), let l^j_{gmr}; $j = 1, \ldots, J$; $g = 1, \ldots, G$; $m = 1, \ldots, M$; $r = 1, \ldots, R$ denote the number of permits/licenses for pollutant of type j held by genco g that uses power plant m, and which affects receptor point r with l^{j0}_{gmr} denoting the initial allocation. Group the former permits into the $JGMR$-dimensional vector l.

Let e^j_{gmr}; $j = 1, \ldots, J$; $g = 1, \ldots, G$; $m = 1, \ldots, M$; $r = 1, \ldots, R$ denote the unit contribution of the ambient concentration of pollutant type j affecting the receptor point r generated per unit of electric power produced by genco g using his power plant m. Hence, the total amount of ambient concentration of pollutant j at receptor point r associated with genco g and power plant m is $e^j_{gmr} q_{gm}$.

5.1.1 The Behavior of the Power Generators and Their Optimality Conditions

Let ρ^*_{1gms} denote the unit price charged by power generator g for the transaction with power supplier s for electric power produced at plant m with $g = 1, \ldots, G$; $m = 1, \ldots, M$, and $s = 1, \ldots, S$. ρ^*_{1gms} is an endogenous variable and can be determined once the complete electric power supply chain network equilibrium model is solved. Let τ^{j*}_r; $j = 1, \ldots, J$; $r = 1, \ldots, R$ denote the price of the permit at equilibrium for pollutant of type j of emission affecting receptor point r. These prices are also endogenous to the model and will be determined once the complete model is solved.

It is assumed that each electric power generator seeks to determine his optimal production portfolio across his power plants and his sales allocations of the electric power to the suppliers as well as the optimal holdings of pollution permits in order to maximize his own profit. Since one can assume that each individual power generator is a profit-maximizer, the objective function of power generator g can be expressed as follows:

$$\text{Maximize} \quad \sum_{m=1}^{M}\sum_{s=1}^{S}\rho_{1gms}^{*}q_{gms} - \sum_{m=1}^{M} f_{gm}(q_m) - \sum_{m=1}^{M}\sum_{s=1}^{S} c_{gms}(q_{gms})$$

$$-\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{r=1}^{R}\tau_r^{j*}(l_{gmr}^{j} - l_{gmr}^{j0}). \tag{5.1}$$

The first term in the objective function (5.1) represents the revenue of power generator g and the next two terms represent his power generation cost and transaction costs, respectively. The last term denotes the expenditure or revenue from transacting permits for the generator based on the total pollutants by his power plants affecting the ambient concentrations at the receptor points.

The structure of the network in Figure 5.1 guarantees that the conservation of flow equations associated with the electric power production and distribution are satisfied. Conservation of flow equation (5.2) below states that the amount of power generated at a particular power plant (and corresponding to a particular genco) is equal to the electric power transacted by the genco from that power plant with all the suppliers and this holds for each of the power plants, subject to:

$$\sum_{s=1}^{S} q_{gms} = q_{gm}, \quad m = 1, \ldots, M. \tag{5.2}$$

Equation (5.3) below states that each power plant cannot pollute at an amount greater than the plant is licensed to at that receptor point.

$$l_{gmr}^{j} \geq e_{gmr}^{j} q_{gm}, \quad j = 1 \ldots J; m = 1 \ldots, M; r = 1, \ldots, R. \tag{5.3}$$

The following non-negativity conditions must also hold:

$$q_{gms} \geq 0, \quad m = 1, \ldots, M; s = 1, \ldots, S,$$

$$l_{gmr}^{j} \geq 0, \quad j = 1, \ldots, J; m = 1, \ldots, M; r = 1, \ldots, R. \tag{5.4}$$

Hence, the optimization problem of power generator g; $g = 1, \ldots, G$ consists of (5.1), subject to constraints: (5.2) and (5.3), with the nonnegativity assumption on the electric power outputs at the power plants and the number of permits (cf. following (5.3)). Assume now, as was done in Nagurney, Liu, and Woolley (2006) and Wu et al. (2006), that the generating cost and the transaction cost functions for each power generator are continuously differentiable and convex, and that the power generators compete in a noncooperative manner in the sense of Nash (1950, 1951). The optimality conditions for all power generators, under the above assumptions (cf. Nagurney (1999)), coincide with the solution of the following variational inequality: determine $(q^*, Q^{1*}, l^*, \lambda^*) \in \mathcal{K}_5^1$ satisfying

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \sum_{j=1}^{J}\sum_{r=1}^{R}\lambda_{gmr}^{j*}e_{gmr}^{j}\right] \times [q_{gm} - q_{gm}^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} - \rho_{1gms}^*\right] \times [q_{gms} - q_{gms}^*]$$

$$+\sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{r=1}^{R}\left[\tau_r^{j*} - \lambda_{gmr}^{j*}\right] \times [l_{gmr}^{j} - l_{gmr}^{j*}]$$

$$+\sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{r=1}^{R}\left[l_{gmr}^{j*} - e_{gmr}^{j}q_{gm}^*\right] \times [\lambda_{gmr}^{j} - \lambda_{gmr}^{j*}] \geq 0, \quad \forall (q, Q^1, l, \lambda) \in \mathcal{K}_5^1, \quad (5.5)$$

where $\mathcal{K}_5^1 \equiv \{(q, Q^1, l, \lambda) | (q, Q^1, l, \lambda) \in R_+^{GM+GMS+2JGMR}$ and (5.2) holds$\}$.

Note that λ_{gmr}^{j} is the Lagrange multiplier associated with the (jmr)-th constraint (5.3), which can be referred to as a shadow price.

5.1.2 The Equilibrium Conditions for the Permits

Furthermore, one would know that (cf. Dhanda, Nagurney, and Ramanujam (1999)) the multipollutant permit market is also subject to equilibrium conditions given by the following. For each pollution permit of type j; $j = 1, \ldots, J$ and receptor point r; $r = 1, \ldots, R$, a multipollutant tradable permit scheme is said to be in equilibrium if:

$$\sum_{g=1}^{G} \sum_{m=1}^{M} [l_{gmr}^{j0} - l_{gmr}^{j*}] \begin{cases} = 0, & \text{if} \quad \tau_r^{j*} > 0, \\ \geq 0, & \text{if} \quad \tau_r^{j*} = 0. \end{cases} \tag{5.6}$$

Expression (5.6) states that if the market price of a permit for pollutant of type j and receptor point r is positive, then there is no excess of permits for that pollutant at that receptor point; if the price is zero, then there can be an excess of such permits. Clearly, these equilibrium conditions guarantee that the total number of required permits cannot exceed the initial allocation of permits by the regulatory agency for each receptor point and pollutant.

The optimality conditions for all power generators simultaneously (cf. (5.5)), under the above assumptions (cf. Nagurney (1999)), coupled with the equilibrium conditions (5.6) for all pollutant types and receptor points, coincide, in turn, with the solution of the following variational inequality: determine $(q^*, Q^{1*}, l^*, \lambda^*, \tau^*) \in \mathcal{K}_5^2$ satisfying

$$\sum_{g=1}^{G} \sum_{m=1}^{M} \left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}} + \sum_{j=1}^{J} \sum_{r=1}^{R} \lambda_{gmr}^{j*} e_{gmr}^{j} \right] \times [q_{gm} - q_{gm}^*]$$

$$+ \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{s=1}^{S} \left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}} - \rho_{1gms}^* \right] \times [q_{gms} - q_{gms}^*]$$

$$+ \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{r=1}^{R} \left[\tau_r^{j*} - \lambda_{gmr}^{j*} \right] \times [l_{gmr}^{j} - l_{gmr}^{j*}]$$

$$+ \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{r=1}^{R} \left[l_{gmr}^{j*} - e_{gmr}^{j} q_{gm}^* \right] \times [\lambda_{gmr}^{j} - \lambda_{gmr}^{j*}]$$

$$+ \sum_{j=1}^{J} \sum_{r=1}^{R} \left[\sum_{g=1}^{G} \sum_{m=1}^{M} (l_{gmr}^{j0} - l_{gmr}^{j*}) \right] \times [\tau_r^{j} - \tau_r^{j*}] \geq 0, \quad \forall (q, Q^1, l, \lambda, \tau) \in \mathcal{K}_5^2, \tag{5.7}$$

where $\mathcal{K}_5^2 \equiv \{(q, Q^1, l, \lambda, \tau) | (q, Q^1, l, \lambda, \tau) \in R_+^{GM+GMS+2JGMR+JR}$ and (5.2) holds$\}$.

5.1.3 The Behavior of Power Suppliers and Their Optimality Conditions

The power suppliers transact with the power generators and with the consumers at the demand markets through the transmission service providers. Suppliers are aware as to the types of power plants used and associated costs when purchasing electric power from the power generators. Analogous to the gencos, it is assumed that the power suppliers compete with one another in a noncooperative manner.

Since electric power cannot be stored, the following conservation of flow constraint states that the total amount of electricity sold by a power supplier is equal to the total electric power that he purchased from the generators and produced via the different power plants available to the generators, that is:

$$\sum_{k=1}^{K}\sum_{v=1}^{V} q_{sk}^{v} = \sum_{g=1}^{G}\sum_{m=1}^{M} q_{gms}, \quad s = 1, \ldots, S. \tag{5.8}$$

Let ρ_{2sk}^{v*} denote the price charged by power supplier s to demand market k via transmission service provider v. This price is determined endogenously in the model once the entire network equilibrium problem is solved. One can assume that each power supplier seeks to maximize his own profit, hence the optimization problem faced by supplier s may be expressed as follows:

$$\text{Maximize} \quad \sum_{k=1}^{K}\sum_{v=1}^{V} \rho_{2sk}^{v*} q_{sk}^{v} - c_s(Q^1) - \sum_{g=1}^{G}\sum_{m=1}^{M} \rho_{1gms}^{*} q_{gms} - \sum_{g=1}^{G}\sum_{m=1}^{M} \hat{c}_{gms}(q_{gms})$$

$$-\sum_{k=1}^{K}\sum_{v=1}^{V} c_{sk}^{v}(q_{sk}^{v}) \tag{5.9}$$

subject to:

$$\sum_{k=1}^{K}\sum_{v=1}^{V} q_{sk}^{v} = \sum_{g=1}^{G}\sum_{m=1}^{M} q_{gms}, \tag{5.10}$$

$$q_{gms} \geq 0, \quad g = 1, \ldots, G; m = 1, \ldots, M,$$

$$q_{sk}^{v} \geq 0; \quad k = 1, \ldots, K; v = 1, \ldots, V. \tag{5.11}$$

The first term in (5.9) denotes the revenue of supplier s from the sale of electricity to the demand market k via transmission service provider v, with the associated operating cost in the second term. The third term denotes the cost to purchase electricity for each supplier from each genco, and the last two terms represent the associated transaction costs for transactions with each genco and each demand market, respectively.

It is assumed that the transaction costs and the operating costs in (5.9) are all continuously differentiable and convex, and that the power suppliers compete in a noncooperative manner. Hence, the optimality conditions for all suppliers, simultaneously, under the above assumptions, can be expressed as the following variational inequality: determine $(Q^{2*}, Q^{1*}) \in \mathcal{K}_5^3$ such that

$$\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{v=1}^{V}\left[\frac{\partial c_{sk}^{v}(q_{sk}^{v*})}{\partial q_{sk}^{v}} - \rho_{2sk}^{v*}\right] \times [q_{sk}^{v} - q_{sk}^{v*}]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{s}(Q^{1*})}{\partial q_{gms}} + \frac{\partial \hat{c}_{gms}(q_{gms}^{*})}{\partial q_{gms}} + \rho_{1gms}^{*}\right] \times [q_{gms} - q_{gms}^{*}] \geq 0, \tag{5.12}$$

$\forall (Q^2, Q^1) \in \mathcal{K}_5^3$, where $\mathcal{K}_5^3 \equiv \{(Q^2, Q^1) | (Q^2, Q^1) \in R_{+}^{SVK+GMS}$ and (5.8); equivalently (5.10) holds$\}$.

For notational convenience, and as was done in Wu et al. (2006), let

$$h_s \equiv \sum_{g=1}^{G}\sum_{m=1}^{M} q_{gms}, \quad s = 1, \ldots, S. \tag{5.13}$$

As defined in Table 5.1, the operating cost of power supplier s, c_s, is a function of the total electricity inflows to the power supplier, that is:

$$c_s(h) \equiv c_s(Q^1), \quad s = 1, \ldots, S. \tag{5.14}$$

Hence, his marginal cost with respect to h_s is equal to the marginal cost with respect to q_{gms}:

$$\frac{\partial c_s(h)}{\partial h_s} \equiv \frac{\partial c_s(Q^1)}{\partial q_{gms}}, \quad s = 1, \ldots, S; m = 1, \ldots, M; g = 1, \ldots, G. \tag{5.15}$$

After the substitution of (5.13) and (5.15) into (5.12), and algebraic simplification, one would obtain a variational inequality equivalent to (5.12), as follows: determine $(h^*, Q^{2*}, Q^{1*}) \in \mathcal{K}_5^4$ such that

$$\sum_{s=1}^{S} \frac{\partial c_s(h^*)}{\partial h_s} \times [h_s - h_s^*] + \sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{v=1}^{V} \left[\frac{\partial c_{sk}^v(q_{sk}^{v*})}{\partial q_{sk}^v} - \rho_{2sk}^{v*}\right] \times [q_{sk}^v - q_{sk}^{v*}]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S} \left[\frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}} + \rho_{1gms}^*\right] \times [q_{gms} - q_{gms}^*] \geq 0, \tag{5.16}$$

$\forall (h, Q^2, Q^1,) \in \mathcal{K}_5^4$, where $\mathcal{K}_5^4 \equiv \{(h, Q^2, Q^1) | (h, Q^2, Q^1) \in R_+^{S(1+VK+GM)}$ and (5.10) and (5.13) hold$\}$.

5.1.4 The Equilibrium Conditions for the Demand Markets

At each demand market k the following conservation of flow equation must be satisfied:

$$d_k = \sum_{s=1}^{S}\sum_{v=1}^{V} q_{sk}^v, \quad k = 1, \ldots, K. \tag{5.17}$$

For each power supplier s; $s = 1, ..., S$, and transaction mode v; $v = 1, ..., V$, the market equilibrium conditions at demand market k take the form:

$$\rho_{2sk}^{v*} + \hat{c}_{sk}^v(Q^{2*}) \begin{cases} = \rho_{3k}(d^*), & \text{if} \quad q_{sk}^{v*} > 0, \\ \geq \rho_{3k}(d^*), & \text{if} \quad q_{sk}^{v*} = 0. \end{cases} \tag{5.18}$$

According to Nagurney and Matsypura (2005a), Nagurney, Liu, and Woolley (2006), and Wu et al. (2006), consumers at the demand market will purchase electricity from a supplier via a transmission service provider if the price that the consumer at the demand market is willing to pay is equal to the price charged by the power supplier plus the unit transaction cost. However, if the purchase price plus the unit transaction cost exceeds the purchase price that the consumer is willing to pay, then no transaction will take place. The equivalent variational inequality, given that, in equilibrium, condition (5.18) must hold simultaneously for all demand markets: $k = 1, \ldots, K$, takes the form: determine $(Q^{2*}, d^*) \in \mathcal{K}_5^5$, such that

$$\sum_{s=1}^{S} \sum_{k=1}^{K} \sum_{v=1}^{V} \left[\rho_{2sk}^{v*} + \hat{c}_{sk}^{v}(Q^{2*})\right] \times [q_{sk}^{v} - q_{sk}^{v*}] - \sum_{k=1}^{K} \rho_{3k}(d^*) \times [d_k - d_k^*] \geq 0, \tag{5.19}$$

$\forall (Q^2, d) \in \mathcal{K}_5^5$, where $\mathcal{K}_5^5 \equiv \{(Q^2, d) | (Q^2, d) \in R_+^{KSV+K} \text{and (5.17) holds}\}$.

5.1.5 The Equilibrium Conditions for the Electric Power Supply Chain Network with Multipollutant Permits

In equilibrium, the optimality conditions for all the power generators, the optimality conditions for all the power suppliers, and the equilibrium conditions for all the demand markets as well as the equilibrium conditions for the permits must be simultaneously satisfied so that no decision-maker has any incentive to alter his transactions. I now formally state the equilibrium conditions for the entire electric power supply chain network along with the variational inequality formulation, which follows directly from the definition.

Definition 5.1 (Electric Power Supply Chain Network Equilibrium with Multipollutant Permits)

The equilibrium state of the electric power supply chain network with power plants and multipollutant permits is one where the electric power flows between the tiers of the network coincide and the electric power flows and the multipollutant tradable permits and prices satisfy the sum of conditions (5.7), (5.16), and (5.19).

Theorem 5.1 (Variational Inequality Formulation of the Electric Power Supply Chain Network Equilibrium with Multipollutant Permits)

The equilibrium conditions governing the electric power supply chain network according to Definition 5.1 coincide with the solution of the variational inequality given by: determine the vector of equilibrium electric power production quantities and flows, the demands, the number of permits, the shadow prices, and the permit prices $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, l^*, \lambda^*, \tau^*) \in \mathcal{K}_5^6$ *satisfying:*

$$\sum_{g=1}^{G}\sum_{m=1}^{M}\left[\frac{\partial f_{gm}(q_m^*)}{\partial q_{gm}}+\sum_{j=1}^{J}\sum_{r=1}^{R}\lambda_{gmr}^{j*}e_{gmr}^{j}\right]\times[q_{gm}-q_{gm}^*]+\sum_{s=1}^{S}\frac{\partial c_s(h^*)}{\partial h_s}\times[h_s-h_s^*]$$

$$+\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{s=1}^{S}\left[\frac{\partial c_{gms}(q_{gms}^*)}{\partial q_{gms}}+\frac{\partial \hat{c}_{gms}(q_{gms}^*)}{\partial q_{gms}}\right]\times[q_{gms}-q_{gms}^*]$$

$$+\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{v=1}^{V}\left[\frac{\partial c_{sk}^{v}(q_{sk}^{v*})}{\partial q_{sk}^{v}}+\hat{c}_{sk}^{v}(Q^{2*})\right]\times[q_{sk}^{v}-q_{sk}^{v*}]-\sum_{k=1}^{K}\rho_{3k}(d^*)\times[d_k-d_k^*]$$

$$+\sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{r=1}^{R}\left[\tau_r^{j*}-\lambda_{gmr}^{j*}\right]\times[l_{gmr}^{j}-l_{gmr}^{j*}]$$

$$+\sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{r=1}^{R}\left[l_{gmr}^{j*}-e_{gmr}^{j}q_{gm}^*\right]\times[\lambda_{gmr}^{j}-\lambda_{gmr}^{j*}]$$

$$+\sum_{j=1}^{J}\sum_{r=1}^{R}\left[\sum_{g=1}^{G}\sum_{m=1}^{M}(l_{gmr}^{j0}-l_{gmr}^{j*})\right]\times[\tau_r^{j}-\tau_r^{j*}]\geq 0, \forall (q,h,Q^1,Q^2,d,l,\lambda,\tau)\in\mathcal{K}_5^6, \tag{5.20}$$

where $\mathcal{K}_5^6 \equiv \{(q,h,Q^1,Q^2,d,l,\lambda,\tau)|(q,h,Q^1,Q^2,d,l,\lambda,\tau)$
$\in R_+^{GM+S+GMS+SKV+K+2JGMR+JR}$ and (5.2), (5.10), (5.13), *and* (5.17) hold$\}$.

Variational inequality (5.20) is now put into standard form (cf. (2.1)), which can be expressed as:

$$\langle F(X^*)^T, X-X^*\rangle \geq 0, \quad \forall X\in\mathcal{K}, \tag{5.21}$$

where $X \equiv (q,h,Q^1,Q^2,d,l,\lambda,\tau) \in R_+^{GM+S+GMS+SKV+K+2GMRJ+RJ}$ and $F(X)$ as a column vector consisting of the column vectors (P_{gm}, H_s, Λ_{gms}, G_{skv}, D_k, L_{jgmr}, C_{jgmr},

T_{jr}) with indices: $g = 1, \ldots, G$; $m = 1, \ldots, M$; $s = 1, \ldots, S$; $k = 1, \ldots, K$; $v = 1, \ldots, V$; $j = 1, \ldots, J$; $r = 1, \ldots, R$, and the specific components of F given by the functional terms preceding the multiplication signs in (5.20), respectively. The term $\langle \cdot, \cdot \rangle$ denotes the inner product in n-dimensional Euclidean space R^n.

Additional theoretical results are now provided which are important for environmental decision-making and policy-making. Similar results can be found in Dhanda, Nagurney, and Ramanujam (1999), but not generalized to the electric power industry with multiple power plants. Let $\bar{E}^j_r$; $j = 1, \ldots, J$; $r = 1, \ldots, R$, denote the imposed environmental standard for receptor r and emission type j. One can now state the following:

Theorem 5.2 (Equilibrium Pattern Independence from Initial Permit Allocation)

If $l^{j0}_{gmr} \geq 0$, for all $j = 1, \ldots, J$; $g = 1, \ldots, G$; $m = 1, \ldots, M$, and $r = 1, \ldots, R$, and $\sum_{g=1}^{G} \sum_{m=1}^{M} l^{j0}_{gmr} = \bar{E}^j_r$, for $j = 1, \ldots, J$; $r = 1, \ldots, R$ with each $\bar{E}^j_r$ positive and fixed, then the equilibrium pattern $(q^*, h^*, Q^{1*}, Q^{2*}, d^*, l^*, \lambda^*, \tau^*)$ is independent of $\{l^{j0}_{gmr}\}$.

Proof:

The last term in (5.20) (unlike the first seven in (5.20) which are independent of l^{j0}_{gmr}) depends only on the sum $\sum_{g=1}^{G} \sum_{m=1}^{M} l^{j0}_{gmr}$, for a fixed receptor point j and a fixed pollutant of type j.

In the next Theorem, I provide a means for the selection of the sums of the initial permit/license allocation so that the imposed environmental standards are achieved.

Theorem 5.3 (Attainment of Environmental Standards)

An equilibrium vector, satisfying variational inequality (5.20), attains the environmental quality standards represented by vector $\bar{E} = (\bar{E}_1, \ldots, \bar{E}_R)$ where

$\bar{E}_r = (\bar{E}_r^1, \ldots, \bar{E}_r^J)$ *for* r*;* $r = 1, \ldots, R$*, provided that the following is satisfied:*

$$\sum_{g=1}^{G} \sum_{m=1}^{M} l_{gmr}^{j0} = \bar{E}_r^j, \quad \forall r, \forall j. \tag{5.22}$$

Proof:

It is then clear from the assumption and variational inequality (5.20) that

$$l_{gmr}^{j*} \geq e_{gmr}^j q_{gm}^*, \quad j = 1 \ldots J; m = 1 \ldots, M; r = 1, \ldots, R. \tag{5.23}$$

It then follows from equilibrium conditions (5.6) that

$$\bar{E}_r^j = \sum_{g=1}^{G} \sum_{m=1}^{M} l_{gmr}^{j0} \geq \sum_{g=1}^{G} \sum_{m=1}^{M} l_{gmr}^{j*} \geq \sum_{g=1}^{G} \sum_{m=1}^{M} e_{gmr}^j q_{gm}^* \tag{5.24}$$

for all $j = 1, \ldots, J$; $r = 1, \ldots, R$.

Theorem 5.3 provides a mechanism for the determination of the sums of the initial permit/license allocations so that the environmental standards are attained. Indeed, all one needs to do is to set the initial permit allocation so that (5.22) is satisfied. This is illustrated with examples in the next Section.

5.2 Numerical Examples

Clearly, as also pointed out in Chapter 4, Wu et al. (2006) proposed an Euler method for the electric power supply chain network equilibrium problem with power plants and reassigned carbon taxes and showed that the electric power supply chain problem with preassigned taxes could be transformed into a transportation network equilibrium problem over an appropriately constructed abstract network or supernetwork.

In the model in this Chapter, as well as the models presented in Chapter 4, the variational inequality (5.20) *directly* can no longer be transformed into a transportation network equilibrium problem as was also done by Nagurney (2006a) for supply chain network equilibrium problems. However, the connection can still be exploited by noticing that the variational inequality problems in this Chapter are defined over feasible sets that are, in effect, decomposable into subproblems in the flows and subproblems in the licenses, the shadow prices, and the license prices. Furthermore, the former subproblems retain the transportation network structure identified in Wu et al. (2006) and this can be exploited algorithmically. Hence, the Euler method (cf. Section 2.5.1) was implemented in FORTRAN and the computer system used was a Sun system at the University of Massachusetts at Amherst.

For completeness, several numerical examples are presented. These examples are from Woolley, Nagurney, and Stranlund (2008). The examples consisted of two power generators, each of which had two power plants. There were two power suppliers and two demand markets with a single transmission provider. It was also assumed that there was a single pollutant and a single receptor point, as shown in Figure 5.2.

5.2.1 Example 5.1

The data for the first example is given below. The functional forms of the power generating cost functions, the transaction cost functions, the operating cost functions, and the demand price functions are identical to those in Example 5.1 in Wu et al. (2006).

The emission terms: e_{gm}; $g = 1, 2$; $m = 1, 2$ were all equal to 1. The power generating cost functions for the power generators were given by:

$$f_{11}(q_1) = 2.5q_{11}^2 + q_{11}q_{21} + 2q_{11}, \quad f_{12}(q_2) = 2.5q_{12}^2 + q_{11}q_{12} + 2q_{22},$$

$$f_{21}(q_1) = .5q_{21}^2 + .5q_{11}q_{21} + 2q_{21}, \quad f_{22}(q_2) = .5q_{22}^2 + q_{12}q_{22} + 2q_{22}.$$

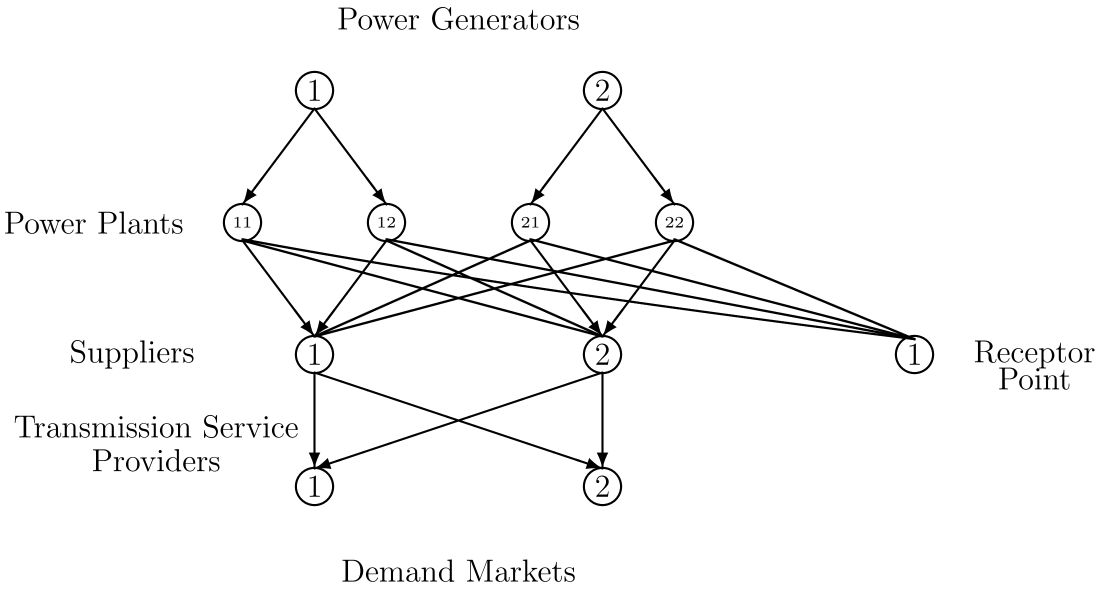

Figure 5.2. The Electric Power Supply Chain Network with a Single Receptor Point for the Examples

The transaction cost functions faced by the power generators and associated with transacting with the power suppliers were given by:

$$c_{111}(q_{111}) = .5q_{111}^2 + 3.5q_{111}, \quad c_{112}(q_{112}) = .5q_{112}^2 + 3.5q_{112},$$

$$c_{121}(q_{121}) = .5q_{121}^2 + 3.5q_{121}, \quad c_{122}(q_{122}) = .5q_{122}^2 + 3.5q_{122},$$

$$c_{211}(q_{211}) = .5q_{211}^2 + 2q_{211}, \quad c_{212}(q_{212}) = .5q_{212}^2 + 2q_{212},$$

$$c_{221}(q_{221}) = .5q_{221}^2 + 2q_{221}, \quad c_{222}(q_{222}) = .5q_{222}^2 + 2q_{222}.$$

The operating costs of the power generators, in turn, were given by:

$$c_1(Q^1) = .5(\sum_{i=1}^{2} q_{i1})^2, \quad c_2(Q^1) = .5(\sum_{i=1}^{2} q_{i2})^2.$$

The demand market price functions at the demand markets were:

$$\rho_{31}(d) = -1.33d_1 + 366.6, \quad \rho_{32} = -1.33d_2 + 366.6,$$

and the transaction costs between the power suppliers and the consumers at the demand markets were given by: $\hat{c}^1_{sk}(q^1_{sk}) = q^1_{sk} + 5$, $s = 1, 2; k = 1, 2$. All other transaction costs were assumed to be equal to zero.

In Example 5.1, the emissions standard, $\bar{E} = 100$, with the initial license allocation given by: $l^0_{11} = l^0_{12} = l^0_{21} = l^0_{22} = 25$. The equilibrium electric power flows and demands and the equilibrium licenses and prices are given in Table 5.2. The demand was 50.00 at each demand market and the demand market price at each market for electric power was 300.10.

5.2.2 Example 5.2

Example 5.2 had the same data as Example 5.1, but now the emissions standard was tightened so that $\bar{E} = 50$. The initial license allocation was now given by: $l^0_{11} = l^0_{12} = l^0_{21} = l^0_{22} = 12.5$. The equilibrium solution is given in Table 5.2. It is clear that, as predicted by the theory, the environmental standard was achieved.

5.2.3 Example 5.3

Example 5.3 had the identical data to that in Examples 5.1 and 5.2, except that the environmental standard was further tightened to $\bar{E} = 20$ with the new initial license allocation given by: $l^0_{11} = l^0_{12} = l^0_{21} = l^0_{22} = 5$. The new equilibrium pattern is reported in Table 5.2. In this example, it is also clear that the equilibrium license numbers are such that the environmental standard was attained.

5.2.4 Example 5.4

Example 5.4 had the same data as Example 5.3 except that the second demand market price function for electric power was modified to:

$$\rho_{32}(d) = -1.33d_2 + 733.30.$$

The new equilibrium electric power flow, license, and price pattern is also reported in Table 5.2. In this example, there was zero demand for electric power at the first demand market. As in the preceding examples, the environmental standard was achieved. Note that as the equilibrium price of the permits increases, as expected, as the environmental standard was tightened for each successive example.

5.3 Summary and Conclusions

As noted earlier, pollution by electric power entities can be controlled by price, in the form, for example, of a carbon tax that is imposed for emissions that exceed a predetermined bound (and as modeled in Wu et al. (2006) and Nagurney, Liu, and Woolley (2006), or by quantity, as in the case of emission trading schemes. In this Chapter, a multipollutant permit trading model was developed in the case of electric power supply chains in which there are different technologies associated with electric power production. The governing equilibrium conditions of the model were derived and showed that it satisfies a finite-dimensional variational inequality problem. Moreover, it was demonstrated that the model guarantees that the environmental standards are achieved, provided that the initial license allocation is set accordingly. Finally, it was described how the equilibrium electric power flows and the pollution permits/licenses, along with their prices could be computed. For completeness, several numerical examples were provided. Future research will include the identification of efficient computational procedures for large-scale electric power supply chains with tradable pollution permits.

Table 5.2. The Solutions to Examples 5.1, 5.2, 5.3, and 5.4

Equilibrium Solution	Example 5.1	Example 5.2	Example 5.3	Example 5.4
Equilibrium Electric Power Flows				
q_{11}^*	15.20	7.48	2.85	2.87
q_{12}^*	6.63	3.17	1.10	1.10
q_{21}^*	15.53	7.82	3.19	3.20
q_{22}^*	62.65	31.53	12.86	12.91
q_{111}^*	7.60	3.74	1.43	1.43
q_{112}^*	7.60	3.74	1.43	1.43
q_{121}^*	3.31	1.59	0.55	0.55
q_{122}^*	3.31	1.59	0.55	0.55
q_{211}^*	7.76	3.91	1.59	1.60
q_{212}^*	7.76	3.91	1.59	1.60
q_{221}^*	31.32	15.77	6.43	6.46
q_{222}^*	31.32	15.77	6.43	6.46
h_1^*	50.00	25.00	10.00	10.00
h_2^*	50.00	25.00	10.00	10.00
q_{11}^{1*}	25.00	12.50	5.00	0.00
q_{12}^{1*}	25.00	12.50	5.00	10.00
q_{21}^{1*}	25.00	12.50	5.00	0.00
q_{22}^{1*}	25.00	12.50	5.00	10.00
Equilibrium Demands				
d_1^*	50.00	25.00	10.00	0.00
d_2^*	50.00	25.00	10.00	20.00
Equilibrium Pollution Permit Price and Shadow Prices				
$\tau^* = \lambda_{11}^* = \lambda_{12}^* = \lambda_{21}^* = \lambda_{22}^*$	115.50	236.38	308.91	656.96
Equilibrium Permits/Licenses				
l_{11}^*	15.20	7.48	2.85	2.87
l_{12}^*	6.63	3.17	1.10	1.10
l_{21}^*	15.53	7.82	3.19	3.20
l_{22}^*	62.65	31.53	12.86	12.91

The research in this Chapter is the first to incorporate the substitutability and complementarity effects of multiple pollutants. This research can aid a regulatory agency in the determination of the number of permits required to achieve the reduction of emissions below a pre-determined bound. Moreover, this model focuses specifically on electric power supply chains and the effects of governmental mandates regarding environmental standards on the associated prices and quantities. The importance of environmental-energy modeling to address market failures in energy is growing as awareness of pollution effects, emission abatement technologies, and government policies are changing. A limitation of the model is the requirement of the electric power industry to report accurate and true data regarding the costs of producing electricity. A future application of this model could include the empirical implementation of a tradable permit system, such as, for example, for the electric power supply chain of New England (see Liu and Nagurney (2008)).

CHAPTER 6

ENVIRONMENTAL AND COST SYNERGY IN SUPPLY CHAIN NETWORK INTEGRATION IN MERGERS AND ACQUISITIONS

The adoption of advanced pollution abatement technologies can be the result of policy instruments (as related to Chapter 4 and Chapter 5 of this dissertation), or in an effort to increase market share by appealing to the environmentally conscious consumer. Roper Starch Worldwide (1997) noted that more than 75% of the public switch to a brand associated with the environment when price and quality are equal. Firms are increasingly realizing the importance of their environmental impacts and the return on the bottom line (Hart and Ahuja (1996)). For example, 3M saved almost $500 million by implementing over 3000 projects that have reduced emissions by over 1 billion pounds since 1975 (Walley and Whitehead (1994)). It has also been argued that sound environmental practices reduce risk to the firm (Feldman, Soyka, and Ameer (1997)).

Due to the visibility and the number of mergers/acquisitions that have been occurring it is important to understand and study the synergy results for managerial benefits from an environmental standpoint. In the first nine months of 2007 alone, according to Thomson Financial, worldwide merger activity hit $3.6 trillion, surpassing the total from all of 2006 combined (Wong (2007)). Companies merge for various reasons, some of which include such benefits as acquired technologies, and greater economies of scale that improve productivity or cut costs (Chatterjee (1986)).

Successful mergers can add tremendous value; however, with a failure rate estimated to be between 74% and 83% (Devero (2004)), it is worthwhile to develop tools to better predict the potential for creating strategic gains in the form of collusive, financial, and operational synergy (Chatterjee (1986)). Specifically, sources of operational synergy include market power (changes in market share (Brush (1996)) or cost savings effects (Chang (1988), Eccles, Lanes, and Wilson (1999)) that can be measured by evaluating the changes in the equity value of production costs of merging firms (Chatterjee (1986)). The ability of a tool to aid in managerial decisions is dependent on its proper use and deployment so that the merger meets the anticipated value. Thus, it should be noted that a successful merger depends on the ability to measure the anticipated synergy of the proposed merger, if any (cf. Chang (1988)). In particular, it has been argued that the supply chain network structure pre and post a merger is crucial in identifying the operational synergy (cf. Nagurney (2009) and the references therein) associated with mergers and acquisitions. Moreover, Chatterjee (2007) recognized that, based on a survey of academic research, interviews and anecdotal evidence that it is much easier to achieve success regarding mergers and acquisitions when the stated goal of a proposed merger is its potential for cost reduction (than its potential to increase revenue). He further emphasized that, regarding horizontal industry consolidations, there is strong academic evidence that such mergers, which are motivated by capacity reduction, are one of the few merger categories that seem to succeed.

However, with the growing investment and industrialization in developing nations, it is also important to evaluate the overall impact of merger activities at not only the operational level, but also as related to environmental impacts. There is enormous potential for developing countries to adopt cleaner production, given current technologies as well as the levels of private capital investments. For example, between 1988-1995, multinational corporations invested nearly $422 billion worth of new factories, supplies, and equipment in these countries (World Resources Institute (1998)). Through globalization, firms of industrialized nations can acquire those firms in developing nations that offer lower production costs; however, more than not, combined with inferior environmental concerns. As a result of the industrialization of developing countries, the actions taken today greatly influence the future scale of environmental and health problems.

Farrell and Shapiro (2001) study synergy effects, that is, cost savings, as related to economies of scale, competition, and consumer welfare that could only be obtained post-merger. They specifically claim that direct competition has an impact on merger-specific synergies. Soylu et al. (2006) analyzed synergy among different energy systems using a multiperiod, discrete-continuous mixed integer linear program (see also Xu (2007)). Lambertini and Mantovani (2007) conclude that horizontal mergers can contribute to reduce negative externalities related to the environment. They state that, "in the presence of a negative externality appearing in consumer surplus from merger activity, if shrinking the industry output translates into a sufficiently large reduction of the negative externality, then the overall balance may in fact be positive"; however they did not consider synergy effects or a supply chain framework. There is virtually no literature to-date that discusses the relationship between post-merger operational synergy and the effects on the environment and, thus, ultimately, society, which is addressed from a quantitative perspective in this Chapter.

As noted in the Introduction, the proponents for a system view structure of the supply chain (cf. Section 1.2.1.2), which is utilized in this Chapter, include the fostering of relationships, coordination, integration, and management in order to achieve greater consumer satisfaction and service reliability, which is necessary to be competitive in the current economic environment (Zsidisin and Siferd (2001)). Sarkis (2003) demonstrated that environmental supply chain management, also referred to as the green supply chain, is necessary to address environmental concerns. For example, the Ford Motor company demanded that all of its 5000 worldwide suppliers with manufacturing plants obtain a third party certification of environmental management system (EMS) by 2003 (Rao (2002)).

This Chapter, towards the end, develops a multicriteria decision-making optimization framework that not only minimizes costs but also minimizes emissions, as in the sustainable supply chain developed in Chapter 3. However, the main focus of this Chapter is on the system-optimized case (cf. Section 2.4), unlike Chapter 3 which addressed the user-optimized case (see Section 2.3 for a discussion on the relationship between System-Optimization and User-Optimization). This Chapter is built on the recent work of Nagurney (2009) who developed a system-optimization perspective for supply chain network integration in the case of horizontal mergers. This Chapter also focuses on the case of horizontal mergers (or acquisitions) and I extend the contributions in Nagurney (2009) to include multicriteria decision-making and environmental concerns. In particular, in this Chapter, the synergy effects associated with a merger are analyzed in terms of the operational synergy, that is, the reduction, if any, in the cost of production, storage, and distribution, as well as the environmental benefits in terms of the reduction of associated emissions (if any). This has not been done before in the literature.

This Chapter is based on Nagurney and Woolley (2009) and is organized as follows: the pre-merger supply chain network model is developed in Section 6.1 (consider, for example, such production chains as Perdue Farms vs. Tyson Foods). Section 6.1 also include the horizontally merged (or acquired) supply chain model (see also Rice and Hoppe (2001)). The method of quantification of the synergistic gains, if any, be provided in Section 6.2. In Section 6.3 numerical examples are presented and the Chapter is concluded with Section 6.4.

6.1 The Pre- and Post-Merger Supply Chain Network Models

This Section develops the pre- and post-merger supply chain network models with environmental concerns using a system-optimization approach (cf. Section 2.4). Section 6.1.1 describes the underlying network of the pre-merger related to each individual firm and their respective activities. Section 6.1.2 develops the post-merger model. Each firm is assumed to act as a multicriteria decision-maker (cf. Section 1.2.1.1) so as to not only minimize costs, but also, as per competitive and consumer pressures (Srivastara (2007), Lambertini and Mantovani (2007)), to minimize the emissions generated (see also Nagurney, Dong, and Mokhtarian (2002b) and references within).

6.1.1 The Pre-Merger Supply Chain Network Model with Environmental Concerns

I first formulate the pre-merger multicriteria decision-making optimization problem faced by Firm A and Firm B as follows and refer to this model as Case 0. Following Nagurney (2009), it is assumed that each firm is represented as a network of its economic activities, as depicted in Figure 6.1. It is also assumed that each firm produces a homogenous product. Each firm i; $i = A, B$, has n^i_M manufacturing facilities/plants; n^i_D distribution centers, and serves n^i_R retail outlets. Let $\mathcal{G}_i = [N_i, L_i]$ for $i = A, B$ denote the graph consisting of nodes and directed links representing the economic activities associated with each firm i. Also let $\mathcal{G}^0 = [N^0, L^0] \equiv \cup_{i=A,B}[N_i, L_i]$. The links from the top-tiered nodes i; $i = A, B$ in each network in Figure 6.1 are connected to the manufacturing nodes of the respective firm i, which are denoted, respectively, by: $M^i_1, \ldots, M^i_{n^i_M}$, and these links represent the manufacturing links. These models generalize the framework proposed in Nagurney (2009) to capture the environmental impacts associated with mergers (and acquisitions).

The links from the manufacturing nodes, in turn, are connected to the distribution center nodes of each firm i; $i = A, B$, which are denoted by $D^i_{1,1}, \dots, D^i_{n_D{}^i,1}$. These links correspond to the shipment links between the manufacturing plants and the distribution centers where the product is stored. The links joining nodes $D^i_{1,1}, \dots, D^i_{n^i_D,1}$ with nodes $D^i_{1,2}, \dots, D^i_{n^i_D,2}$ for $i = A, B$ correspond to the storage links. Finally, there are shipment links joining the nodes $D^i_{1,2}, \dots, D^i_{n^i_D,2}$ for $i = A, B$ with the retail outlet nodes: $R^i_1, \dots, R^i_{n^i_R}$ for each firm $i = A, B$. Each firm i has its own individual retail outlets where it sells the product, as depicted in Figure 6.1.

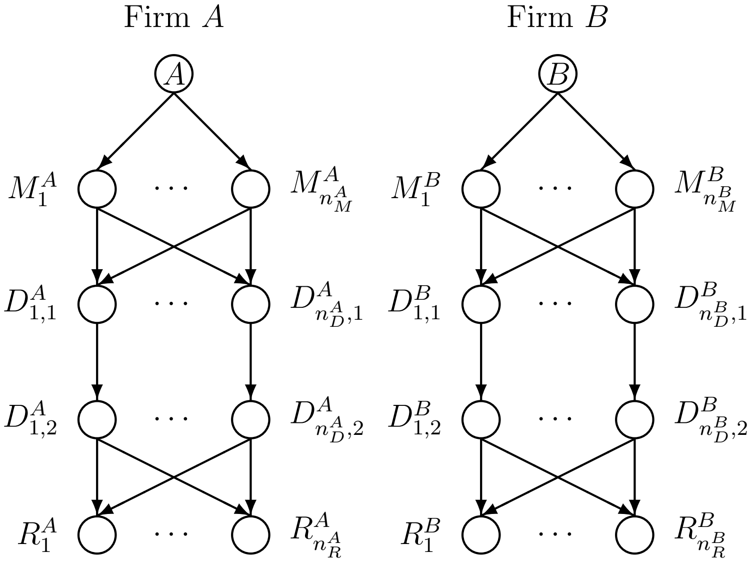

Figure 6.1. The Supply Chain Networks of Firms A and B Prior to the Merger

Assume that there is a total cost associated with each link (cf. Figure 6.1) of the network corresponding to each firm i; $i = A, B$. The links are denoted by a, b, etc., and the total cost on a link a by $\hat{c}_a$. The demands for the product are assumed as given and are associated with each firm and retailer pair. Let $d_{R^i_k}$ denote the demand for the product at retailer R^i_k associated with firm i; $i = A, B$; $k = 1, \dots, n^i_R$. A path is defined as a sequence of links joining an origin node $i = A, B$ with a destination node R^i_k. Let x_p denote the nonnegative flow of the product on path p. A path consists of a sequence of economic activities comprising manufacturing, storage, and distribution. The following conservation of flow equations must hold for each firm i:

$$\sum_{p \in P^0_{R^i_k}} x_p = d_{R^i_k}, \quad i = A, B; k = 1, \ldots, n^i_R, \tag{6.1}$$

where $P^0_{R^i_k}$ denotes the set of paths connecting (origin) node i with (destination) retail node R^i_k.

Let f_a denote the flow of the product on link a. The following conservation of flow equations must also be satisfied:

$$f_a = \sum_{p \in P^0} x_p \delta_{ap}, \quad \forall a \in L^0, \tag{6.2}$$

where $\delta_{ap} = 1$ if link a is contained in path p and $\delta_{ap} = 0$, otherwise. Here P^0 denotes the set of *all* paths in Figure 6.1, that is, $P^0 = \cup_{i=A,B;k=1,\ldots,n^i_R} P^0_{R^i_k}$. Clearly, since I am first considering the two firms prior to any merger the paths associated with a given firm have no links in common with paths of the other firm. This changes (see also Nagurney (2009)) when the mergers occur, in which case the number of paths and the sets of paths also change, as do the number of links and the sets of links, as described in Section 6.1.2.

The path flows must be nonnegative, that is,

$$x_p \geq 0, \quad \forall p \in P^0. \tag{6.3}$$

The path flows are grouped into the vector x.

The total cost on a link, be it a manufacturing/production link, a shipment/distribution link, or a storage link is assumed to be a function of the flow of the product on the link; see, for example, Nagurney (2009) and the references therein. Hence, one would have that

$$\hat{c}_a = \hat{c}_a(f_a), \quad \forall a \in L^0. \tag{6.4}$$

It is assumed that the total cost on each link is convex, is continuously differentiable, and has a bounded second order partial derivative. Assumptions of convexity and continuous differentiability are common in the economics literature regarding production cost functions (see, e.g., Gabay and Moulin (1980), Friedman (1982), Tirole (1988) and the references therein). Further more due to increasing congestion such assumptions are also reasonable regarding the transportation/shipment links (see Dafermos and Sparrow (1969)). A special case of the total cost function (6.4) that satisfies the above assumptions is a linear, separable function, such that $\hat{c}_a = h_a f_a$ for h_a nonnegative (see also Nagurney (2008)).

The units for measurement of the emissions is now discussed. I propose the use of the carbon equivalent for emissions, which is commonly used in environmental modeling and research (Nagurney (2006b), Wu et al. (2006)), as well as in practice as employed by the Kyoto Protocol (Reilly et al. (1999)), to aid in the direct comparison of environmental impacts of differing pollutants. Emissions are typically expressed in a common metric, specifically, in million metric tons of carbon equivalent (MMTCE) (USEPA (2005)).

It is also assumed that there are nonnegative capacities on the links with the capacity on link a denoted by u_a, $\forall a \in L^0$. This is very reasonable since the manufacturing plants, the shipment links, as well as the distribution centers, which serve also as the storage facilities can be expected to have capacities, in practice.

In addition, it is assumed, as given, emission functions for each economic link $a \in L^0$, and denoted by e_a, where

$$e_a = e_a(f_a), \quad \forall a \in L^0, \tag{6.5}$$

where e_a denotes the total amount of emissions generated by link a in processing an amount f_a of the product. It is reasonable to assume that the amount of emissions generated is a function of the flow on the associated economic link (see, for example, Dhanda, Nagurney, and Ramanujam (1999) and Nagurney, Qiang, and Nagurney (2009) and the references therein). It is assumed that the emission functions have the same properties as the total cost functions (6.4) above.

Since the firms, pre-merger, have no links in common (cf. Figure 6.1), their individual cost minimization problems can be formulated jointly as follows:

$$\text{Minimize} \quad \sum_{a \in L^0} \hat{c}_a(f_a) \tag{6.6}$$

subject to: constraints (6.1) – (6.3) and

$$f_a \leq u_a, \quad \forall a \in L^0. \tag{6.7}$$

In addition, since I am considering multicriteria decision-making with environmental concerns, the minimization of emissions generated can, in turn, be expressed as follows:

$$\text{Minimize} \quad \sum_{a \in L^0} e_a(f_a) \tag{6.8}$$

subject to: constraints (6.1) – (6.3) and (6.7).

One can now construct a value total cost function, which is referred to as the generalized total cost (cf. Fishburn (1970), Chankong and Haimes (1983), Yu (1985), Keeney and Raiffa (1992), Nagurney and Dong (2002)), associated with the two criteria faced by each firm. α_{ia} can be assumed the price that each firm, i, would be willing to pay for each unit of emission on link a; which represents the environmental concern for each firm, i, on link a. A higher α_{ia} represent a greater concern for the environment. Specifically, for notational convenience and simplicity, for firms $i = A, B$ and links $a \in L_i$, let $\alpha_{ia} \equiv 0$ if link $a \notin L_i$ and $\alpha_{ia} = \alpha_i$, otherwise, where α_i is decided upon by the decision-making authority of firm i. Consequently, the multicriteria decision-making problem, pre-merger, can be expressed as:

$$\text{Minimize} \quad \sum_{a \in L^0} \sum_{i=A,B} \hat{c}_a(f_a) + \alpha_{ia} e_a(f_a) \tag{6.9}$$

subject to: constraints (6.1) – (6.3) and (6.7).

Note that the optimization problem above is equivalent to each firm solving its multicriteria decision-making problem independently. Observe that this problem is, as is well-known in the transportation literature (cf. Beckmann, McGuire, and Winsten (1956), Dafermos and Sparrow (1969)), a *system-Optimization* problem but in *capacitated* form and with multicriteria decision-making; see also Patriksson (1994), Nagurney (2000, 2006b), and the references therein. Under the above imposed assumptions, the optimization problem is a convex optimization problem. If it is further assumed that the feasible set underlying the problem represented by the constraints (6.1) – (6.3) and (6.7) is non-empty, then it follows from the standard theory of nonlinear programming (cf. Bazaraa, Sherali, and Shetty (1993)) that an optimal solution exists.

Let $\mathcal{K}_6^0$ denote the set where $\mathcal{K}_6^0 \equiv \{f | \exists x \geq 0, \text{and}\,(6.1) - (6.3)\,\text{and}\,(6.7)\,\text{hold}\}$, and f is the vector of link flows. Also, associate the Lagrange multiplier β_a with constraint (6.7) for link a and denote the associated optimal Lagrange multiplier by β_a^*. This term may also be interpreted as the price or value of an additional unit of capacity on link a. The variational inequality formulation of the problem is now provided.

Theorem 6.1

The vector of link flows $f^{*0} \in \mathcal{K}_6^0$ is an optimal solution to the pre-merger problem if and only if it satisfies the following variational inequality problem with the vector of nonnegative Lagrange multipliers β^{*0}:

$$\sum_{a \in L^0} \sum_{i=A,B} [\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a} + \alpha_{ia} \frac{\partial e_a(f_a^*)}{\partial f_a} + \beta_a^*] \times [f_a - f_a^*] + \sum_{a \in L^0} [u_a - f_a^*] \times [\beta_a - \beta_a^*] \geq 0,$$

$$\forall f \in \mathcal{K}_6^0, \forall \beta_a \geq 0, \forall a \in L^0. \qquad (6.10)$$

Proof: See Bertsekas and Tsitsiklis (1989) and Nagurney (1993).

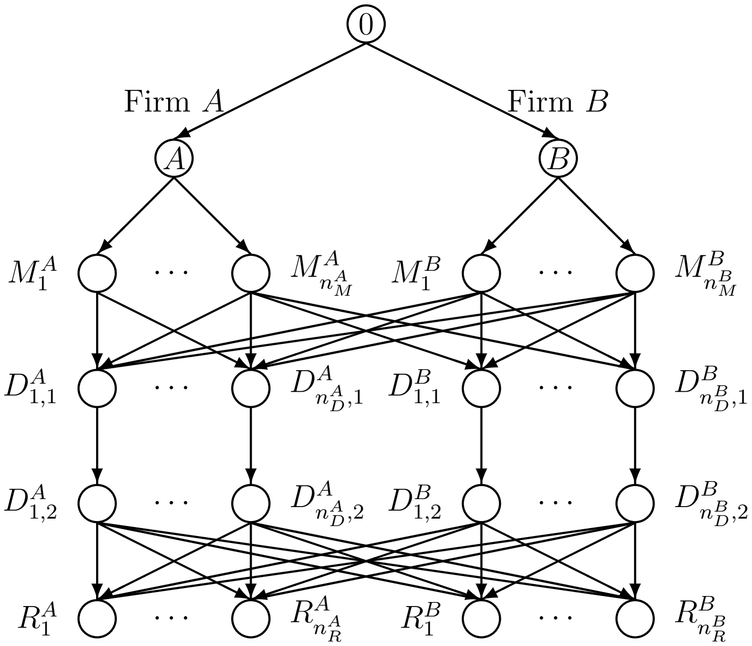

Figure 6.2. The Supply Chain Network after Firms A and B Merge

6.1.2 The Post-Merger Supply Chain Network Model with Environmental Concerns

I now formulate the post-merger case, referred to as Case 1, in which the manufacturing facilities produce the product and then ship it to any distribution center and the retailers can obtain the product from any distribution center. Since the product is assumed to be homogeneous, after the merger the retail outlets are indifferent at which manufacturing plant the product was produced. Figure 6.2 depicts the post-merger supply chain network topology. Note that there is now a supersource node 0 which represents the merger of the firms with additional links joining node 0 to nodes A and B, respectively.

The post-merger optimization problem is concerned with total cost minimization as well as the minimization of emissions. Specifically, the nodes and links associated with network $\mathcal{G}^0$ depicted in Figure 6.1 are retained but now the additional links connecting the manufacturing plants of each firm and the distribution centers and the links connecting the distribution centers and the retailers of the other firm are now added. The network underlying this merger is referred to as $\mathcal{G}^1 = [N^1, L^1]$. The total cost functions, as in (6.4), and emission functions, as in (6.5), are associated with the new links. It is assumed, for simplicity, that the corresponding functions on the links emanating from the supersource node are equal to zero.

A path p now (cf. Figure 6.2) originates at node 0 and is destined for one of the bottom retail nodes. Let x_p now in the post-merger network configuration given in Figure 6.2 denote the flow of the product on path p joining (origin) node 0 with a (destination) retailer node. Then the following conservation of flow equations must hold:

$$\sum_{p \in P^1_{R^i_k}} x_p = d_{R^i_k}, \quad i = A, B; k = 1, \ldots, n^i_R, \tag{6.11}$$

where $P^1_{R^i_k}$ denotes the set of paths connecting node 0 with retail node R^i_k in Figure 6.2. Due to the merger, the retail outlets can obtain the product from any manufacturing plant and any distributor. The set of paths $P^1 \equiv \cup_{i=A,B;k=1,\ldots,n^i_R} P^1_{R^i_k}$.

In addition, as before, let f_a denote the flow of the product on link a. Hence, the following conservation of flow equations must be satisfied:

$$f_a = \sum_{p \in P^1} x_p \delta_{ap}, \quad \forall a \in L^1. \tag{6.12}$$

Of course, one would also have that the path flows must be nonnegative, that is,

$$x_p \geq 0, \quad \forall p \in P^1. \tag{6.13}$$

It is assumed, again, that the links representing the manufacturing activities, the shipment, and the storage activities possess nonnegative capacities, denoted as u_a, $\forall a \in L^1$. This can be expressed as

$$f_a \leq u_a, \quad \forall a \in L^1. \tag{6.14}$$

It is assumed that, post-merger, the value associated with the environmental emission cost minimization criterion is denoted by α and this value is nonnegative. This is reasonable since, unlike in the pre-merger case, the firms are now merged into a single decision-making economic entity and there is now a single value associated with the emissions generated.

Hence, the following multicriteria decision-making optimization problem can be solved:

$$\text{Minimize} \quad \sum_{a \in L^1} [\hat{c}_a(f_a) + \alpha e_a(f_a)] \tag{6.15}$$

subject to constraints: (6.11) – (6.14). Note that L^1 represents all links in the post-merger network belonging to firm A and to firm B.

There are distinct options for the value of α and several are explored in Section 6.3, in concrete numerical examples. Specifically, in the case that the merger/acquisition is an environmentally hostile one, then one may set $\alpha = 0$; in the case that it is environmentally conscious, then α may be set to 1; and so on, with α being a function of the firms' pre-merger values also a possibility.

The solution to the post-merger multicriteria decision-making optimization problem (6.15) subject to constraints (6.11) through (6.14) can also be obtained as a solution to a variational inequality problem akin to (6.10) where now $a \in L^1$, α is substituted for α_i, and the vectors: f, x, and β have identical definitions as before, but are re-dimensioned/expanded accordingly. Finally, instead of the feasible set $\mathcal{K}_6^0$ one would now have $\mathcal{K}_6^1 \equiv \{f | \exists x \geq 0, \text{and}\,(6.11) - (6.14)\,\text{hold}\}$. The solution to the variational inequality problem governing Case 1 is denoted by f^{*1}, β^{*1}. For completeness, the variational inequality formulation of the Case 1 problem is now provided. The proof is immediate.

Theorem 6.2

The vector of link flows $f^{*1} \in \mathcal{K}_6^1$ is an optimal solution to the post-merger problem if and only if it satisfies the following variational inequality problem with the vector of nonnegative Lagrange multipliers β^{*1}:

$$\sum_{a \in L^1} [\frac{\partial \hat{c}_a(f_a^*)}{\partial f_a} + \alpha \frac{\partial e_a(f_a^*)}{\partial f_a} + \beta_a^*] \times [f_a - f_a^*] + \sum_{a \in L^1} [u_a - f_a^*] \times [\beta_a - \beta_a^*] \geq 0,$$

$$\forall f \in \mathcal{K}_6^1, \forall \beta_a \geq 0, \forall a \in L^1. \tag{6.16}$$

Finally, the total generalized cost TGC^0 associated with Case 0 is defined as the value of the objective function in (6.9) evaluated at its optimal solution f^{*0} and the total generalized cost TGC^1 associated with Case 1 as the value of the objective function in (6.15) evaluated at its optimal solution f^{*1}. These flow vectors are obtained from the solutions of variational ienqualities (6.10) and (6.16), respectively. In the next Section, it is discussed how one can utilize these two total generalized costs to determine the strategic advantage or synergy associated with a merger/acquisition. In addition, TE^0 is defined as the total emissions generated under solution f^{*0}; TE^1 as the total emissions generated under solution f^{*1}, and TC^0 and TC^1 the corresponding total costs. Due to the similarity of variational inequalities (6.10) and (6.16) the same computational procedure can be utilized to compute the solutions. Indeed, one can utilize the variational inequality formulations of the respective pre- and post-merger supply chain network problems to then exploit the simplicity of the underlying feasible sets, $\mathcal{K}_6^0$ and $\mathcal{K}_6^1$, which have a network structure identical to that underlying system-optimized transportation network problems. In particular, in Section 6.3, the modified projection method (cf. 2.5.2) of Korpelevich (1977) embedded with the equilibration algorithm (cf. 2.5.3) of Dafermos and Sparrow (1969) (see also Nagurney (1993)) is applied to solve all the numerical examples in Matlab and the computer system used was an IBM system at the University of Massachusetts at Amherst.

6.2 Quantifying Synergy Associated with Multicriteria Decision-Making Firms with Environmental Concerns in Mergers/Acquisitions

The synergy associated with the total generalized costs which captures both the total costs and the total emissions is denoted by $\mathcal{S}^{TGC}$ and is defined as follows:

$$\mathcal{S}^{TGC} \equiv [\frac{TGC^0 - TGC^1}{TGC^0}] \times 100\%. \tag{6.17}$$

The synergy can also be measured by analyzing the total costs pre and post the merger (cf. Eccles, Lanes, and Wilson (1999) and Nagurney (2009)), as well as the changes in emissions. For example, the synergy based on total costs and proposed by Nagurney (2009), but not in a multicriteria decision-making context, which is denoted here by $\mathcal{S}^{TC}$, can be calculated as the percentage difference between the total cost pre *vs* the total cost post merger:

$$\mathcal{S}^{TC} \equiv [\frac{TC^0 - TC^1}{TC^0}] \times 100\%. \tag{6.18}$$

The environmental impacts related to the relationship between pre and post merger emission levels can also be calculated using a similar measure as that of the total cost. Towards that end, one can also define the total emissions synergy, denoted by $\mathcal{S}^{TE}$ as:

$$\mathcal{S}^{TE} \equiv [\frac{TE^0 - TE^1}{TE^0}] \times 100\%. \tag{6.19}$$

6.3 Numerical Examples

In this Section, numerical examples are presented in which one can utilize the synergy measures defined in Section 6.2. The numerical examples are from Nagurney and Woolley (2009). Consider firm A and firm B, as depicted in Figure 6.3 for the pre-merger case. Each firm owns and operates two manufacturing plants, M_1^i and M_2^i, one distribution center, and provides the product to meet demand at two retail markets R_1^i and R_2^i for $i = A, B$. Figure 6.4 depicts the post-merger supply chain network. The total cost functions were: $\hat{c}_a(f_a) = f_a^2 + 2f_a$ for all links a pre-merger and post-merger in all the numerical examples below, except for the links post-merger that join the node 0 with nodes A and B. By convention, these merger links had associated total costs equal to 0. The definition of the links and the associated emission functions for all the examples are given in Table 6.1. The modified projection method embedded with the equilibration algorithm was implemented in Matlab, and the computer system used was an IBM system at the University of Massachusetts Amherst. The solutions to the numerical examples are given in Table 6.2 for the pre-merger case and in Table 6.3 for the post-merger case. The synergy calculations are presented in Table 6.4.

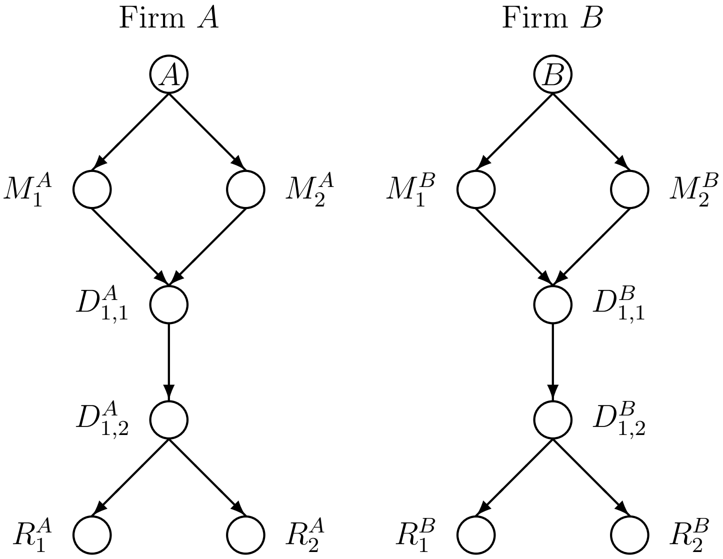

Figure 6.3. The Pre-Merger Supply Chain Network Topology for the Numerical Examples

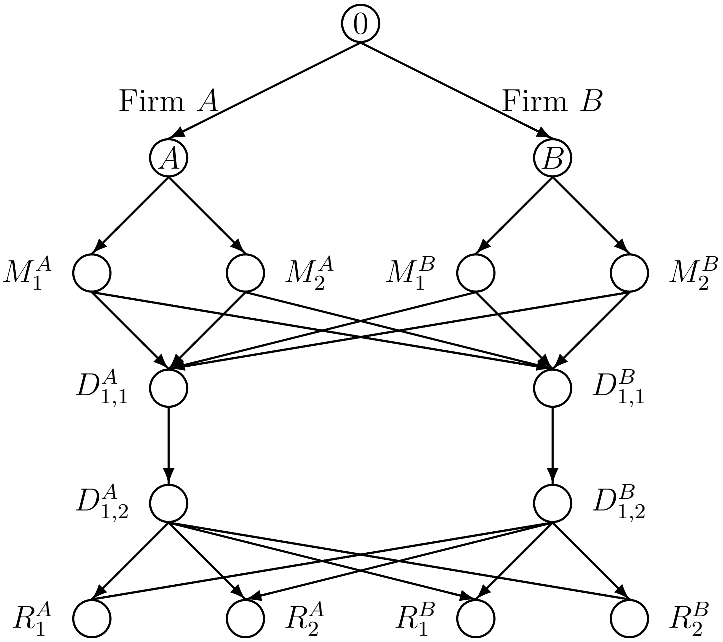

Figure 6.4. The Post-Merger Supply Chain Network Topology for the Numerical Examples

Table 6.1. The Definition of the Links and the Associated Emission Functions for the Numerical Examples

Link a	From Node	To Node	Ex. 6.1,6.4: $e_a(f_a)$	Ex. 6.2,6.3: $e_a(f_a)$
1	A	M_1^A	$10f_1$	$5f_1$
2	A	M_2^A	$10f_2$	$5f_2$
3	M_1^A	$D_{1,1}^A$	$10f_3$	$5f_3$
4	M_2^A	$D_{1,1}^A$	$10f_4$	$5f_4$
5	$D_{1,1}^A$	$D_{1,2}^A$	$10f_5$	$5f_5$
6	$D_{1,2}^A$	R_1^A	$10f_6$	$5f_6$
7	$D_{1,2}^A$	R_2^A	$10f_7$	$5f_7$
8	B	M_1^B	$10f_8$	$10f_8$
9	B	M_2^B	$10f_9$	$10f_9$
10	M_1^B	$D_{1,1}^B$	$10f_{10}$	$10f_{10}$
11	M_2^B	$D_{1,1}^B$	$10f_{11}$	$10f_{11}$
12	$D_{1,1}^B$	$D_{1,2}^B$	$10f_{12}$	$10f_{12}$
13	$D_{1,2}^B$	R_1^B	$10f_{13}$	$10f_{13}$
14	$D_{1,2}^B$	R_2^B	$10f_{14}$	$10f_{14}$
15	M_1^A	$D_{1,1}^B$	$10f_{15}$	$5f_{15}$
16	M_2^A	$D_{1,1}^B$	$10f_{16}$	$5f_{16}$
17	M_1^B	$D_{1,1}^A$	$10f_{17}$	$10f_{17}$
18	M_2^B	$D_{1,1}^A$	$10f_{18}$	$10f_{18}$
19	$D_{1,2}^A$	R_1^B	$10f_{19}$	$5f_{19}$
20	$D_{1,2}^A$	R_2^B	$10f_{20}$	$5f_{20}$
21	$D_{1,2}^B$	R_1^A	$10f_{21}$	$10f_{21}$
22	$D_{1,2}^B$	R_2^A	$10f_{22}$	$10f_{22}$

Table 6.2. The Pre-Merger Solutions to the Numerical Examples

Link a	From Node	To Node	Ex. 6.1 - 6.4: f_a^*
1	A	M_1^A	5.00
2	A	M_2^A	5.00
3	M_1^A	$D_{1,1}^A$	5.00
4	M_2^A	$D_{1,1}^A$	5.00
5	$D_{1,1}^A$	$D_{1,2}^A$	10.00
6	$D_{1,2}^A$	R_1^A	5.00
7	$D_{1,2}^A$	R_2^A	5.00
8	B	M_1^B	5.00
9	B	M_2^B	5.00
10	M_1^B	$D_{1,1}^B$	5.00
11	M_2^B	$D_{1,1}^B$	5.00
12	$D_{1,1}^B$	$D_{1,2}^B$	10.00
13	$D_{1,2}^B$	R_1^B	5.00
14	$D_{1,2}^B$	R_2^B	5.00

6.3.1 Example 6.1

The demands at the retailers for Firm A and Firm B were set to 5 and the capacity on each link was set to 15 both *pre* and *post* merger. The weights: $\alpha_{ia} = \alpha_i$ were set to 1 for both firms $i = A, B$ and for all links $a \in L^0$. Thus, I assumed that each firm is equally concerned with cost minimization and with emission minimization. The pre-merger solution f^{*0} for both firms had all components equal to 5 for all links except for the storage links, which had flows of 10. The associated β^{*0} had all components equal to 0, since the flow on any particular link did not meet capacity. The total cost was 660.00, the total emissions generated was 800.00 and the total generalized cost was 1460.00.

Post-merger, for each firm, the cost and emission functions were again set to $\hat{c}_a(f_a) = f_a^2 + 2f_a$ and $e_a(f_a) = 10f_a$, respectively, including those links formed post-merger. The demand at each retail market was kept at 5 and the capacity of each link, including those formed post-merger, was set to 15. The weight α, post-merger, was set to 1. The solution is as follows; see also Table 3. For both firms, the manufacturing link flows were 5; 2.5 was the shipment between each manufacturer and distribution center, 10 was the flow representing storage at each distribution center, and 2.5 was the flow from each distribution/storage center to each demand market. The vector of optimal multipliers, β^{*1}, post-merger, had all its components equal to 0. The total cost was 560.00, the total emissions generated were 800.00, and the total generalized cost was 1360.00. There were total cost synergistic gains, specifically, at $S^{TC} = 15.15\%$, yet no environmental gains, since $S^{TE} = 0.00\%$. Additionally, the total generalized cost synergy was: $S^{TGC} = 6.85\%$.

6.3.2 Example 6.2

Example 6.2 was constructed from Example 6.1 but with the following modifications. Pre-merger, the emission functions of Firm A were reduced from $e_a(f_a) = 10f_a$ to $e_a(f_a) = 5f_a$, $\forall a \in L^0$. Hence, Firm A now is assumed to produce fewer emissions as a function of flow on each link than Firm B. Additionally, pre-merger, the environmental concern of Firm B was reduced to zero, that is, $\alpha_{Ba} = 0$, for all links a associated with Firm B, pre-merger. Hence, not only does Firm A emit less as a function of the flow on each link, but Firm A also has a greater environmental concern than Firm B. Pre-merger, the optimal solution f^{*0} was identical to that obtained, pre-merger, for Example 6.1. The total cost was 660.00, the total emissions generated were 600.00, and the total generalized cost was 860.00. The components of β^{*0} were the same as in Example 6.1.

Post-merger, the emission functions of Firm A were as above and $e_a(f_a) = 5f_a$, on all links formed post-merger, and emanating from the original Firm A; the analogous links for Firm B had emission functions $e_a(f_a) = 10f_a$. I assumed an amicable merger. In particular, post-merger, I assumed that $\alpha = 0.5$. The optimal flow from node A to each manufacturer was 5.83, the optimal shipment from each original A's manufacturer to original A's distribution center was 3.12, while the distribution to

B's distribution center was 2.71. Storage for Firm A possessed a flow of 10.83 and A shipped from its own distribution/storage center to its own as well as the retail markets of Firm B in the amount of 2.71. For Firm B, the optimal flow from node B to its manufacturing facilities was 4.17, with a shipment to its own distribution center of 1.87, and 2.29 to A's distribution center. The flow at B's original distribution/storage center was 9.17. Finally, the flow shipped from the original B to each retail outlet from its distribution/storage center was 2.29. The total cost was now 566.22, the total emissions generated were equal to 574.98, and the total generalized cost was now 853.71.

Thus, the synergies were: $S^{TC} = 14.21\%$ for the total cost; $S^{TE} = 4.23\%$ for the total emissions, and $S^{TGC} = 0.82\%$ for the total generalized cost. I can see that, as compared to Example 6.1, that even though cost synergies decreased by 0.94%, the total emission synergies increased by 4.23%, and the total generalized cost synergy decreased by 6.12%. In the event of an amicable merger between firms that have different environmental concerns and, thus, activities to reduce emissions, there was an increase in emission synergy. There was, nevertheless, a tradeoff between operational synergy gains with environmental benefits. As environmental benefits are increased, operational synergy decreased, even though, not quite as significantly as the environmental gains to society. However, it is interesting to note that the total generalized cost synergy decreased even more drastically than the environmental gains which signifies the influential effect environmental concerns had on the objective of the firm *pre* and *post* merger.

6.3.3 Example 6.3

Example 6.3 was constructed from Example 6.2 but with the following changes. I now assumed that the merger was hostile, but with Firm B as the dominant firm, that is, the post environmental concern be like that of Firm B. Hence, $\alpha = 0$. The pre-merger results are the same as in Example 2, and now I describe the post-merger results. The flows were symmetric for each original firm, with a flow of 5 from each manufacturer, a shipment of 2.50 to each distribution center with a flow of 10 in the storage center, and a product shipment of 2.50 to each retail outlet.

The total cost was 560.00, the total emissions generated were 600.00, and the total generalized cost was 560.00. Thus, the synergy results were 15.15% for the total cost, 0.00% for the total emissions, and 34.88% for the total generalized cost. It is of notable interest that the total cost synergy and the total emission synergy are identical to those obtained for Example 6.1. However, the total generalized cost synergy in this example was significantly higher. In Example 6.1, both firms showed concern for the environment *pre* and *post* merger, with $\alpha_{Aa} = \alpha_{Ba} = 1$, for all links a associated with Firm A and Firm B pre-merger; in this example, Firm B showed no concern for the environment pre-merger, and as the dominant firm, post-merger, $\alpha = 0$. So even though there was no benefit, environmentally, and no difference in total cost, there were significant gains in terms of the total generalized cost of the merged firm.

6.3.4 Example 6.4

Example 6.4 was constructed from Example 6.1 but with the following modifications. Pre-merger, I assumed that Firm A is environmentally conscious, that is $\alpha_{Aa} = 1$ for firm $i = A$ and for all links a associated with Firm A, while Firm B does not display any concern for the environment, that is, $\alpha_{Ba} = 0$ for all its links. Additionally, I now assumed that the merger was hostile with Firm A as the dominant firm, that is, Firm A imposes its environmental concern on Firm B. I assumed that, post-merger, $\alpha = 1$. The pre-merger optimal flows are the same as in Example 1. The total cost was 660.00, the total emissions generated were 800.00, and the total generalized cost was 1060.00.

Table 6.3. Post-Merger Solutions to the Numerical Examples

Link a	From Node	To Node	Ex. 1: f_a^*	Ex. 2: f_a^*	Ex 3: f_a^*	Ex. 4: f_a^*
1	A	M_1^A	5.00	5.83	5.00	5.00
2	A	M_2^A	5.00	5.83	5.00	5.00
3	M_1^A	$D_{1,1}^A$	2.50	3.12	2.50	2.50
4	M_2^A	$D_{1,1}^A$	2.50	3.12	2.50	2.50
5	$D_{1,1}^A$	$D_{1,2}^A$	10.00	10.83	10.00	10.00
6	$D_{1,2}^A$	R_1^A	2.50	2.71	2.50	2.50
7	$D_{1,2}^A$	R_2^A	2.50	2.71	2.50	2.50
8	B	M_1^B	5.00	4.17	5.00	5.00
9	B	M_2^B	5.00	4.17	5.00	5.00
10	M_1^B	$D_{1,1}^B$	2.50	1.87	2.50	2.50
11	M_2^B	$D_{1,1}^B$	2.50	1.87	2.50	2.50
12	$D_{1,1}^B$	$D_{1,2}^B$	10.00	9.17	10.00	10.00
13	$D_{1,2}^B$	R_1^B	2.50	2.29	2.50	2.50
14	$D_{1,2}^B$	R_2^B	2.50	2.29	2.50	2.50
15	M_1^A	$D_{1,1}^B$	2.50	2.71	2.50	2.50
16	M_2^A	$D_{1,1}^B$	2.50	2.71	2.50	2.50
17	M_1^B	$D_{1,1}^A$	2.50	2.29	2.50	2.50
18	M_2^B	$D_{1,1}^A$	2.50	2.29	2.50	2.50
19	$D_{1,2}^A$	R_1^B	2.50	2.71	2.50	2.50
20	$D_{1,2}^A$	R_2^B	2.50	2.71	2.50	2.50
21	$D_{1,2}^B$	R_1^A	2.50	2.29	2.50	2.50
22	$D_{1,2}^B$	R_2^A	2.50	2.29	2.50	2.50

The post-merger results were as follows. The optimal link flows were identical to those obtained for Example 6.3, post-merger. The total cost was 560.00, the total emissions generated were 800.00, and the total generalized cost was 1360.00. The synergy results were: 15.15% for the total cost; 0.00% for the total emissions, and −28.30% for the total generalized cost. When the dominant firm in the proposed merger was more concerned with the environmental impacts, the overall total generalized cost synergy was the lowest. This example illustrates the importance of not only demonstrating concern for the environment but also to take action in order to reduce the emission functions.

Table 6.4. Synergy Values for the Numerical Examples

Example	1	2	3	4
TC^0	660.00	660.00	660.00	660.00
TC^1	560.00	566.22	560.00	560.00
S^{TC}	15.15%	14.21%	15.15%	15.15%
TE^0	800.00	600.00	600.00	800.00
TE^1	800.00	574.98	600.00	800.00
S^{TE}	0.00%	4.23%	0.00%	0.00%
TGC^0	1460.00	860.00	860.00	1060.00
TGC^1	1360.00	853.71	560.00	1360.00
S^{TGC}	6.85%	0.73%	34.88%	−28.30%

Table 6.5. Post-Merger Solutions to the Variant Numerical Examples

Link a	From Node	To Node	Ex. 1,4: f_a^*	Ex. 2: f_a^*	Ex. 3: f_a^*
1	A	M_1^A	5.00	5.62	5.00
2	A	M_2^A	5.00	5.62	5.00
3	M_1^A	$D_{1,1}^A$	0.00	2.08	2.50
4	M_2^A	$D_{1,1}^A$	0.00	2.08	2.50
5	$D_{1,1}^A$	$D_{1,2}^A$	10.00	10.83	9.99
6	$D_{1,2}^A$	R_1^A	0.00	1.77	2.50
7	$D_{1,2}^A$	R_2^A	0.00	1.77	2.50
8	B	M_1^B	5.00	4.37	5.00
9	B	M_2^B	5.00	4.37	5.00
10	M_1^B	$D_{1,1}^B$	0.00	1.04	2.50
11	M_2^B	$D_{1,1}^B$	0.00	1.04	2.50
12	$D_{1,1}^B$	$D_{1,2}^B$	10.00	9.17	9.99
13	$D_{1,2}^B$	R_1^B	0.00	1.35	2.50
14	$D_{1,2}^B$	R_2^B	0.00	1.35	2.50
15	M_1^A	$D_{1,1}^B$	5.00	3.54	2.50
16	M_2^A	$D_{1,1}^B$	5.00	3.54	2.50
17	M_1^B	$D_{1,1}^A$	5.00	3.33	2.50
18	M_2^B	$D_{1,1}^A$	5.00	3.33	2.50
19	$D_{1,2}^A$	R_1^B	5.00	3.65	2.50
20	$D_{1,2}^A$	R_2^B	5.00	3.65	2.50
21	$D_{1,2}^B$	R_1^A	5.00	3.23	2.50
22	$D_{1,2}^B$	R_2^A	5.00	3.23	2.50

Table 6.6. Synergy Values for the Variant Numerical Examples

Example	1	2	3	4
TC^0	660.00	660.00	660.00	660.00
TC^1	660.00	578.46	560.00	660.00
S^{TC}	0.00%	12.35%	15.15%	0.00%
TE^0	800.00	600.00	600.00	800.00
TE^1	400.00	376.03	450.00	400.00
S^{TE}	50.00%	37.33%	25.00%	50.00%
TGC^0	1460.00	860.00	860.00	1060.00
TGC^1	1060.00	766.47	560.00	1060.00
S^{TGC}	27.40%	10.88%	34.88%	0.00%

6.3.5 Variant Numerical Examples

In addition, in order to explore the impacts of improved technologies associated with distribution/transportation I constructed the following variants of the above numerical examples. I assumed that the pre-merger data were as in Examples 6.1 through 6.4 as were the post-merger data except that I assumed that the emission functions associated with the new "merger" links were all identically equal to 0. The post-merger link flow solutions are given in Table 6.5 and the synergy computations in Table 6.6 for these additional four examples.

The synergies computed for this variant of Examples 6.1 through 6.4 suggest an inverse relationship between total cost synergy and emission synergy. It is also interesting to compare the results for the variants of Example 6.1 and Example 6.4 in Table 6.6. Despite the fact that they both have identical total cost and total emission synergies, their respective total generalized cost synergies are, nevertheless, distinct. This can be attributed to the difference in concern for the environment pre- and post-merger.

6.4 Summary and Conclusions

In this Chapter, I presented a multicriteria decision-making framework to evaluate the environmental impacts associated with mergers and acquisitions. The framework is based on a supply chain network perspective, in a system-optimization context, that captures the economic activities of a firm such as manufacturing/production, storage, as well as distribution. I presented the pre-merger and the post-merger network models, derived their variational inequality formulations, and then defined a total generalized cost synergy measure as well as a total cost synergy measure and a total emissions synergy measure. The firms, pre-merger, assigned a weight representing their individual environmental concerns; post-merger, the weight was uniform.

Several numerical examples were provided, which, although stylized, demonstrated the generality of the approach and how the new framework can be used to assess apriori synergy associated with mergers and acquisitions and with an environmental focus. Specifically, I concluded that the operating economies (resulting from greater economies of scale that improve productivity or cut costs) may have an inverse impact on the environmental effects to society depending on the level of concern that each firm has for the environment and their joint actions taken to reduce emissions.

To the best of my knowledge, this is the first attempt to quantify the relationships associated with mergers and acquisitions and possible synergies associated with environmental emissions. With this Chapter, I can begin to further explore numerous questions associated with mergers and acquisitions, environmental synergies, as well as industrial organization. For example, I note that this chapter has focused on horizontal mergers, as was also the case in Nagurney (2009). Additional research is needed to evaluate the possible synergy associated with vertical integrations and the impacts on the environment. I expect that related issues be especially relevant to the electric power industry and the associated supply chains. Of course, application of the models and measures in this chapter to real-world practical settings is also of importance. I plan to pursue empirical applications in the future.

Finally, I emphasize that environmental emissions may have a very strong *spatial* component (see also, e.g., Dhanda, Nagurney, and Ramanujam (1999) and the references therein). Therefore, extensions of the models in this chapter to an explicit spatial dimension would also be worthwhile.

CHAPTER 7

MULTIPRODUCT SUPPLY CHAIN HORIZONTAL NETWORK INTEGRATION: MODELS, THEORY, AND COMPUTATIONAL RESULTS

Although there are numerous articles discussing multiechelon supply chains, the majority deal with a homogeneous product (see, for example, Dong et al. (2004), Nagurney (2006a), and Wang et al. (2007)). Firms are seeing the need to spread their investment risk by building multiproduct supply facilities, which also gives the advantage of flexibility to meet changing market demands. According to a study of the US supply output at the firm-product level between 1972 and 1997, on the average, two-thirds of US supply firms altered their mix of products every five years (Bernard et al. (2006)). By running a multiuse plant, costs of supply may be divided among different products, which may increase efficiencies.

While Chapter 6 studied synergistic effects from horizontal mergers with a single product, it is interesting to note the relationships between merger activity to multiproduct output. For example, according to a study of the US supply output at the firm-product level between 1972 and 1997, less than 1 percent of a firm's product additions occurred due to mergers/acquisitions. Actually, 95 percent of firms, engaging in M&A, were found to adjust their product mix, which can be associated with ownership changes (Bernard et al. (2006)). The importance of the decision as to what to offer (e.g., products and services), as well as the ability of firms to realize synergistic opportunities of the proposed merger, if any, can add tremendous value. A survey of 600 executives involved in their companies' mergers and acquisitions (M&A), conducted by Accenture and the Economist Unit (EIU), found that less than half (45%) achieved expected cost-savings synergies (Byrne (2007)).

This chapter is built on the recent work of Nagurney (2009) who developed a system-optimization perspective for supply chain network integration in the case of horizontal mergers/acquisitions. In this chapter, I also focus on the case of horizontal mergers (or acquisitions) and extend the contributions in Nagurney (2009) to the much more general and richer setting of multiple product supply chains. This approach is most closely related to that of Dafermos (1973) who proposed transportation network models with multiple modes/classes of transportation (cf. Section 2.4.1). In particular, I develop a system-optimization approach to the modeling of multiproduct supply chains and their integration and explicitly introduce capacities on the various economic activity links associated with manufacturing/production, storage, and distribution. Moreover, in this chapter, the synergy effects associated with horizontal multiproduct supply chain network integration are analyzed, in terms of the operational synergy, that is, the reduction, if any, in the cost of production, storage, and distribution. Finally, the proposed computational procedure fully exploits the underlying network structure of the supply chain optimization problems both pre and post-integration.

It can be noted that Min and Zhou (2002) provided a synopsis of supply chain modeling and the importance of planning, designing, and controlling the supply chain as a whole. Nagurney (2006b), subsequently, proved that supply chain network equilibrium problems, in which there is cooperation between tiers, but competition among decision-makers within a tier, can be reformulated and solved as transportation network equilibrium problems. Cheng and Wu (2006) proposed a multiproduct, and multicriterion, supply-demand network equilibrium model. Davis and Wilson (2006), in turn, studied differentiated product competition in an equilibrium framework. Mixed integer linear programming models have been used to study synergy in supply chains, which has been considered by Soylu et al. (2006), who focused on energy systems, and by Xu (2007).

This chapter is based on Nagurney, Woolley, and Qiang (2009) and is organized as follows. The pre-integration multiproduct supply chain network model is developed in Section 7.1. Section 7.1 also introduces the horizontally merged (or integrated) multiproduct supply chain model. The method of quantification of the synergistic gains, if any, is provided in Section 7.2, along with new theoretical results. In Section 7.3 numerical examples are presented, which not only illustrate the richness of the framework proposed in this chapter, but which also demonstrate quantitatively how the costs associated with horizontal integration affect the possible synergies. The chapter is concluded with Section 7.4, in which the results are summarized and presented along with suggestions for future research.

7.1 The Pre- and Post-Integration Multiproduct Supply Chain Network Models

This Section develops the pre- and post-integration supply chain network multiproduct models using a system-optimization approach (based on the Dafermos (1973) multiclass model) but with the inclusion of explicit capacities on the various links. Moreover, here, a variational inequality formulation of multiproduct supply chains and their integration is provided, which enables a computational approach which fully exploits the underlying network structure. I also identify the supply chain network structures both pre and post the merger and construct a synergy measure.

Section 7.1.1 describes the underlying pre-integration supply chain network associated with an individual firm and its respective economic activities of manufacturing, storage, distribution, and retailing. Section 7.1.2 develops the post-integration model. The models are extensions of the Nagurney (2009) models to the more complex, and richer, multiproduct domain.

7.1.1 The Pre-Integration Multiproduct Supply Chain Network Model

First, the pre-integration multiproduct decision-making optimization problem faced by firms A and B is formulated and I refer to this model as Case 0. It is assumed that each firm is represented as a network of its supply chain activities, as depicted in Figure 7.1. Each firm i; $i = A, B$, has n^i_M manufacturing facilities; n^i_D distribution centers, and serves n^i_R retail outlets. Let $G_i = [N_i, L_i]$ denote the graph consisting of nodes $[N_i]$ and directed links $[L_i]$ representing the supply chain activities associated with each firm i; $i = A, B$. Let L^0 denote the links: $L_A \cup L_B$ as in Figure 7.1. It is assumed that each firm is involved in the production, storage, and distribution of J products, with a typical product denoted by j.

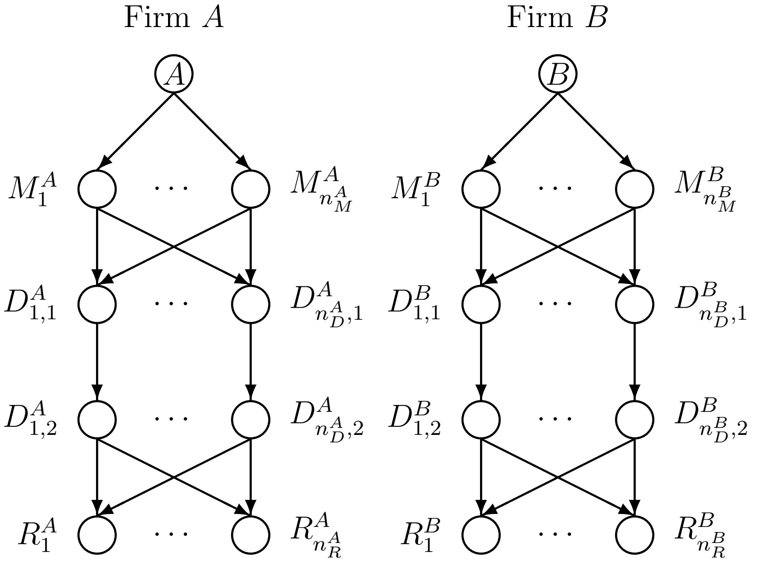

Figure 7.1. Supply Chains of Firms A and B Prior to the Integration

The links from the top-tiered nodes i; $i = A, B$ in each network in Figure 7.1 are connected to the manufacturing nodes of the respective firm i, which are denoted, respectively, by: $M^i_1, \ldots, M^i_{n^i_M}$. These links represent the manufacturing links. The links from the manufacturing nodes, in turn, are connected to the distribution center nodes of each firm i; $i = A, B$, which are denoted by $D^i_{1,1}, \ldots, D^i_{n_{D^i},1}$. These links correspond to the shipment links between the manufacturing facilities and the distribution centers where the products are stored. The links joining nodes $D^i_{1,1}, \ldots, D^i_{n^i_D,1}$ with nodes $D^i_{1,2}, \ldots, D^i_{n^i_D,2}$ for $i = A, B$, correspond to the storage links for the products. Finally, there are shipment links joining the nodes $D^i_{1,2}, \ldots, D^i_{n^i_D,2}$ for $i = A, B$ with the retail nodes: $R^i_1, \ldots, R^i_{n^i_R}$ for each firm $i = A, B$. Each firm i, for simplicity, and, without loss of generality, is assumed to have its own individual retail outlets for delivery of the products, as depicted in Figure 7.1, prior to the integration.

The demands for the products are assumed as given and are associated with each product, and each firm and retail pair. Let $d^j_{R^i_k}$ denote the demand for product j; $j = 1, \ldots, J$, at retail outlet R^i_k associated with firm i; $i = A, B$; $k = 1, \ldots, n^i_R$. A path consists of a sequence of links originating at a node i; $i = A, B$ and denotes supply chain activities comprising manufacturing, storage, and distribution of the products to the retail nodes. Let x^j_p denote the nonnegative flow of product j, on path p. Let $P^0_{R^i_k}$ denote the set of all paths joining an origin node i with (destination) retail node R^i_k. Clearly, since I am first considering the two firms prior to any integration, the paths associated with a given firm have no links in common with paths of the other firm. This changes (see also Nagurney (2009)) when the integration occurs, in which case the number of paths and the sets of paths also change, as do the number of links and the sets of links, as described in Section 7.1.2. The following conservation of flow equations must hold for each firm i, each product j, and each retail outlet R^i_k:

$$\sum_{p \in P^0_{R^i_k}} x^j_p = d^j_{R^i_k}, \quad i = A, B; \quad j = 1, \ldots, J; \quad k = 1, \ldots, n^i_R, \tag{7.1}$$

that is, the demand for each product must be satisfied at each retail outlet.

Links are denoted by a, b, etc. Let f^j_a denote the flow of product j on link a. The following conservation of flow equations must be satisfied:

$$f^j_a = \sum_{p \in P^0} x^j_p \delta_{ap}, \quad j = 1 \ldots, J; \quad \forall a \in L^0, \tag{7.2}$$

where $\delta_{ap} = 1$ if link a is contained in path p and $\delta_{ap} = 0$, otherwise. Here P^0 denotes the set of *all* paths in Figure 7.1, that is, $P^0 = \cup_{i=A,B;k=1,\ldots,n^i_R} P^0_{R^i_k}$. The path flows must be nonnegative, that is,

$$x^j_p \geq 0, \quad j = 1, \ldots, J; \quad \forall p \in P^0. \tag{7.3}$$

The path flows are grouped into the vector x.

Note that the different products flow on the supply chain networks depicted in Figure 7.1 and share resources with one another. To capture the costs, I proceed as follows. There is a total cost associated with each product j; $j = 1, \ldots, J$, and each link (cf. Figure 7.1) of the network corresponding to each firm i; $i = A, B$. The total cost on a link a associated with product j is denoted by $\hat{c}^j_a$. The total cost of a link associated with a product, be it a manufacturing link, a shipment/distribution link, or a storage link is assumed to be a function of the flow of all the products on the link; see, for example, Dafermos (1973). Hence, one would have that

$$\hat{c}^j_a = \hat{c}^j_a(f^1_a, \ldots, f^J_a), \quad j = 1, \ldots, J; \quad \forall a \in L^0. \tag{7.4}$$

The top tier links in Figure 7.1 have total cost functions associated with them that capture the manufacturing costs of the products; the second tier links have multiproduct total cost functions associated with them that correspond to the total costs associated with the subsequent distribution/shipment to the storage facilities, and the third tier links, since they are the storage links, have associated with them multiproduct total cost functions that correspond to storage. Finally, the bottom-tiered links, since they correspond to the shipment links to the retailers, have total cost functions associated with them that capture the costs of shipment of the products.

It is assumed that the total cost function for each product on each link is convex, continuously differentiable, and has a bounded third order partial derivative. Since the firms' supply chain networks, pre-integration, have no links in common (cf. Figure 7.1), their individual cost minimization problems can be formulated jointly as follows:

$$\text{Minimize} \quad \sum_{j=1}^{J} \sum_{a \in L^0} \hat{c}_a^j(f_a^1, \ldots, f_a^J) \tag{7.5}$$

subject to: constraints (7.1) – (7.3) and the following capacity constraints:

$$\sum_{j=1}^{J} \alpha_j f_a^j \leq u_a, \quad \forall a \in L^0. \tag{7.6}$$

The term α_j denotes the volume taken up by product j, whereas u_a denotes the nonnegative capacity of link a.

Observe that this problem is, as is well-known in the transportation literature (cf. Beckmann, McGuire, and Winsten (1956), Dafermos and Sparrow (1969), and Dafermos (1973)), a *system-optimization* problem but in *capacitated* form. Under the above imposed assumptions, the optimization problem is a convex optimization problem. If it is further assumed that the feasible set underlying the problem represented by the constraints (7.1) – (7.3) and (7.6) is non-empty, then it follows from the standard theory of nonlinear programming (cf. Bazaraa, Sherali, and Shetty (1993)) that an optimal solution exists.

Let $\mathcal{K}_7^0$ denote the set where $\mathcal{K}_7^0 \equiv \{f | \exists x \, \text{such that} \, (7.1) - (7.3) \, \text{and} \, (7.6) \, \text{hold}\}$, where f is the vector of link flows. It is assumed that the feasible set $\mathcal{K}_7^0$ is non-empty. Lagrange multiplier β_a is associated with constraint (7.6) for each $a \in L^0$. The associated optimal Lagrange multiplier is denoted by β_a^*. This term may be interpreted as the price or value of an additional unit of capacity on link a; it is also sometimes refered to as the *shadow price*. The variational inequality formulation of the problem is now provided. For convenience, and since I am considering Case 0, the solution of variational inequality (7.7) below is denoted as (f^{0*}, β^{0*}) and I refer to the corresponding vectors of variables with superscripts of 0.

Theorem 7.1

The vector of link flows $f^{0*} \in \mathcal{K}^0_7$ *is an optimal solution to the pre-integration problem if and only if it satisfies the following variational inequality problem with the vector of nonnegative Lagrange multipliers* β^{0*}:

$$\sum_{j=1}^{J}\sum_{l=1}^{J}\sum_{a\in L^0}\left[\frac{\partial \hat{c}^l_a(f^{1*}_a,\ldots,f^{J*}_a)}{\partial f^j_a}+\alpha_j\beta^*_a\right]\times[f^j_a-f^{j*}_a]+\sum_{a\in L^0}[u_a-\sum_{j=1}^{J}\alpha_j f^{j*}_a]\times[\beta_a-\beta^*_a]\geq 0,$$

$$\forall f^0 \in \mathcal{K}^0_7, \forall \beta^0 \geq 0. \quad (7.7)$$

Proof: See Bertsekas and Tsitsiklis (1989) and Nagurney (1999).

7.1.2 The Post-Integration Multiproduct Supply Chain Network Model

The post-integration case, referred to as Case 1, is now formulated. Figure 7.2 depicts the post-integration supply chain network topology. Note that there is now a *supersource* node 0 which represents the integration of the firms in terms of their supply chain networks with additional links joining node 0 to nodes A and B, respectively.

As in the pre-integration case, the post-integration optimization problem is also concerned with total cost minimization. Specifically, the nodes and links associated with the network depicted in Figure 7.1 are retained but now the additional links connecting the manufacturing facilities of each firm and the distribution centers of the other firm as well as the links connecting the distribution centers of each firm and the retail outlets of the other firm are added. The network in Figure 7.2, underlying this integration, is referred to as $G^1 = [N^1, L^1]$ where $N^1 \equiv N^0 \cup$ node 0 and $L^1 \equiv L^0 \cup$ the additional links as in Figure 7.2. Total cost functions as in (7.4) are associated with the new links, for each product j. Note that if the total cost functions associated with the integration/merger links connecting node 0 to node A and node 0 to node B are set equal to zero, this means that the supply chain integration is *costless* in terms of the supply chain integration/merger of the two firms. Of course, non-zero total cost functions associated with these links may be utilized to also capture the risk associated with the integration. Such issues are explored numerically in Section 7.3.

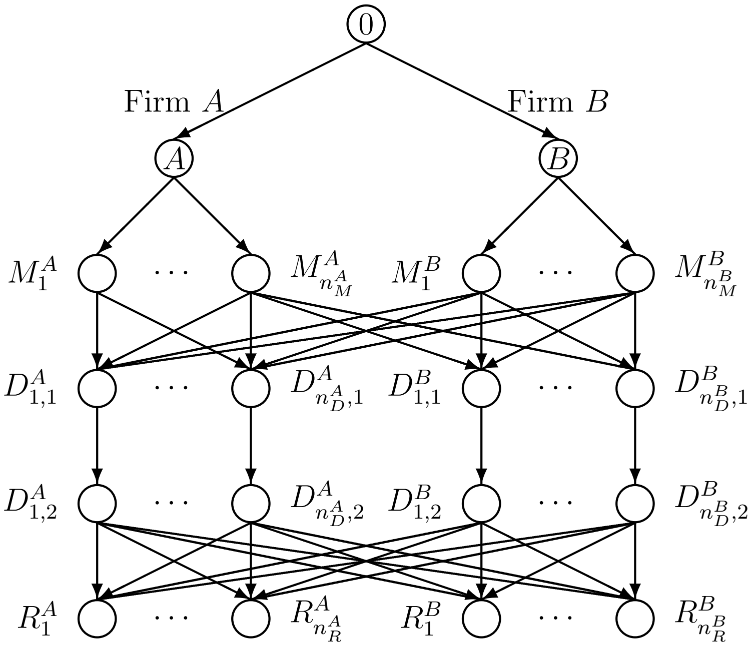

Figure 7.2. Supply Chain Network after Firms A and B Merge

A path p now (cf. Figure 7.2) originates at the node 0 and is destined for one of the bottom retail nodes. Let x_p^j, in the post-integrated network configuration given in Figure 7.2, denote the flow of product j on path p joining (origin) node 0 with a (destination) retail node. Then, the following conservation of flow equations must hold:

$$\sum_{p \in P^1_{R^i_k}} x_p^j = d^j_{R^i_k}, \quad i = A, B; \quad j = 1, \ldots, J; \quad k = 1, \ldots, n^i_R, \tag{7.8}$$

where $P^1_{R^i_k}$ denotes the set of paths connecting node 0 with retail node R^i_k in Figure 7.2. Due to the integration, the retail outlets can obtain each product j from any manufacturing facility, and any distributor. The set of paths $P^1 \equiv \cup_{i=A,B;k=1,\ldots,n^i_R} P^1_{R^i_k}$.

In addition, as before, let f_a^j denote the flow of product j on link a. Hence, one must also have the following conservation of flow equations satisfied:

$$f_a^j = \sum_{p \in P^1} x_p^j \delta_{ap}, \quad j = 1, \ldots, J; \quad \forall a \in L^1. \tag{7.9}$$

Of course, I also have that the path flows must be nonnegative for each product j, that is,

$$x_p^j \geq 0, \quad j = 1, \ldots, J; \quad \forall p \in P^1. \tag{7.10}$$

It is assumed, again, that the supply chain network activities have nonnegative capacities, denoted as u_a, $\forall a \in L^1$, with α_j representing the volume factor for product j. Hence, the following constraints must be satisfied:

$$\sum_{j=1}^{J} \alpha_j f_a^j \leq u_a, \quad \forall a \in L^1. \tag{7.11}$$

Consequently, the optimization problem for the integrated supply chain network is:

$$\text{Minimize} \quad \sum_{j=1}^{J} \sum_{a \in L^1} \hat{c}_a^j(f_a^1, \ldots, f_a^J) \tag{7.12}$$

subject to constraints: (7.8) – (7.11).

The solution to the optimization problem (7.12) subject to constraints (7.8) through (7.11) can also be obtained as a solution to a variational inequality problem akin to (7.7) where now $a \in L^1$. The vectors f and β have identical definitions as before, but are re-dimensioned/expanded accordingly and superscripted with a 1. Finally, instead of the feasible set $\mathcal{K}_7^0$ one would now have $\mathcal{K}_7^1 \equiv \{f | \exists x \text{ such that } (7.8)-(7.11) \text{ hold}\}$. It is assumed that $\mathcal{K}_7^1$ is non-empty. The solution to the variational inequality problem (7.13) below governing Case 1 is denoted by (f^{1*}, β^{1*}) and the vectors of corresponding variables are denoted as (f^1, β^1). I now, for completeness, provide the variational inequality formulation of the Case 1 problem. The proof is immediate.

Theorem 7.2

The vector of link flows $f^{1*} \in \mathcal{K}^1_7$ is an optimal solution to the post-integration problem if and only if it satisfies the following variational inequality problem with the vector of nonnegative Lagrange multipliers β^{1*}:

$$\sum_{j=1}^{J}\sum_{l=1}^{J}\sum_{a\in L^1}[\frac{\partial \hat{c}^l_a(f^{1*}_a,\ldots,f^{J*}_a)}{\partial f^j_a}+\alpha_j\beta^*_a]\times[f^j_a-f^{j*}_a]+\sum_{a\in L^1}[u_a-\sum_{j=1}^{J}\alpha_j f^{j*}_a]\times[\beta_a-\beta^*_a]\geq 0,$$

$$\forall f^1 \in \mathcal{K}^1_7, \forall \beta^1 \geq 0. \tag{7.13}$$

Let TC^0 denote the total cost, $\sum_{j=1}^J \sum_{a\in L^0} \hat{c}^j_a(f^1_a,\ldots,f^J_a)$, evaluated under the solution f^{0*} to (7.7) and let TC^1, $\sum_{j=1}^J \sum_{a\in L^1} \hat{c}^j_a(f^1_a,\ldots,f^J_a)$ denote the total cost evaluated under the solution f^{1*} to (7.13). Due to the similarity of variational inequalities (7.7) and (7.13) the same computational procedure can be utilized to compute the solutions. Indeed, the variational inequality formulations of the respective pre- and post-integration supply chain network problems are utilized since one can then exploit the simplicity of the underlying feasible sets $\mathcal{K}^0_7$ and $\mathcal{K}^1_7$ which include constraints with a network structure identical to that underlying multimodal system-optimized transportation network problems.

It is worthwhile to distinguish the multiproduct supply chain network models developed above from the single product models in Nagurney (2009). First, note that the total cost functions in the objective functions (7.5) and (7.12) are not separable as they were, respectively, in the single product models in Nagurney (2009). In addition, since I am dealing now with multiple products, which can be of different physical dimensions, the corresponding capacity constraints (cf. (7.6) and (7.11)) are also more complex than was the case for their single product counterparts. It should also be emphasized that the above multiproduct framework contains, as a special case, the merger of firms that produce (pre-merger) distinct products, which is captured by assigning a demand of zero to those products at the respective demand markets. Of course, in such a case, the total cost functions would also be adapted accordingly.

Finally, the multiproduct models developed in this chapter allow for non-zero total costs associated with the top-most merger links (cf. Figure 7.2), which join node 0 to nodes A and B. In Nagurney (2009) it was assume that the corresponding total costs, in the single product case, were zero. Of course, it would also be interesting to explore the issue of "retooling" a manufacturing facility, post-merger, for it to be able to produce the other firm's product(s) in its original manufacturing facilities.

7.2 Quantifying Synergy Associated with Multiproduct Supply Chain Network Integration

The synergy is measured by analyzing the total costs prior to and post the supply chain network integration (cf. Eccles et al. (1999) and Nagurney (2009)). For example, the synergy based on total costs and proposed by Nagurney (2009), but now in a multiproduct context, which is denoted here by $\mathcal{S}^{TC}$, can be calculated as the percentage difference between the total cost pre *vs* the total cost post the integration:

$$\mathcal{S}^{TC} \equiv [\frac{TC^0 - TC^1}{TC^0}] \times 100\%. \tag{7.14}$$

From (7.14), one can see that the lower the total cost TC^1, the higher the synergy associated with the supply chain network integration. Of course, in specific firm operations one may wish to evaluate the integration of supply chain networks with only a subset of the links joining the original two supply chain networks. In that case, Figure 7.2 would be modified accordingly and the synergy as in (7.14) computed with TC^1 corresponding to that new supply chain network topology.

One can now provide a theorem which shows that if the total costs associated with the integration of the supply chain networks of the two firms are identically equal to zero, then the associated synergy can never be negative.

Theorem 7.3

If the total cost functions associated with the integration/merger links from node 0 *to nodes A and B for each product are identically equal to zero, then the associated synergy,* $\mathcal{S}^{TC}$*, can never be negative.*

Proof: It is first noted that the pre-integration supply chain optimization problem can be defined over the same expanded network as in Figure 7.2 but with the cross-shipment links extracted and with the paths defined from node 0 to the retail nodes. In addition, the total costs from node 0 to nodes A and B must all be equal to zero. Clearly, the total cost minimization solution to this problem yields the same total cost value as obtained for TC^0. One must now show that $TC^0 - TC^1 \geq 0$.

Assume not, that is, that $TC^0 - TC^1 < 0$, then, clearly, one would have not obtained an optimal solution to the post-integration problem, since, the new links need not be used, which would imply that $TC^0 = TC^1$, which is a contradiction.

Another interpretation of this theorem is that, in the system-optimization context (assuming that the total cost functions remain the same as do the demands), the addition of new links can never make the total cost increase; this is in contrast to what may occur in the context of user-optimized networks, where the addition of a new link may make everyone worse-off in terms of user cost. This is the well-known Braess paradox (1968); see, also, Braess et al. (2005).

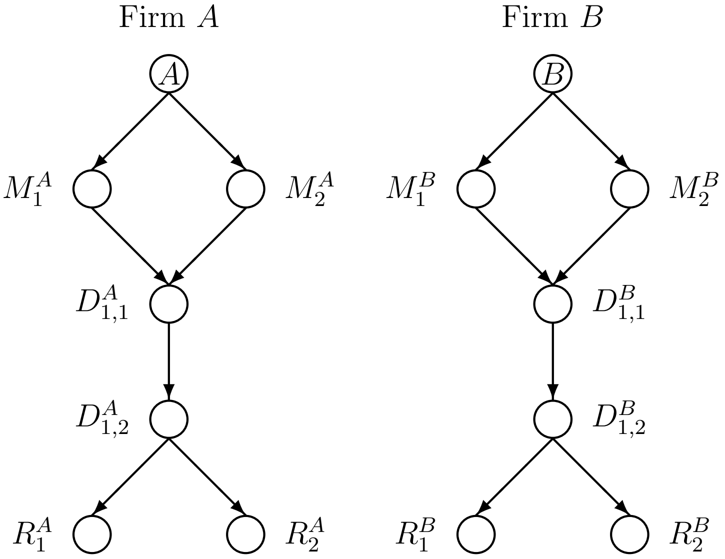

Figure 7.3. Pre-Integration Supply Chain Network Topology for the Numerical Examples

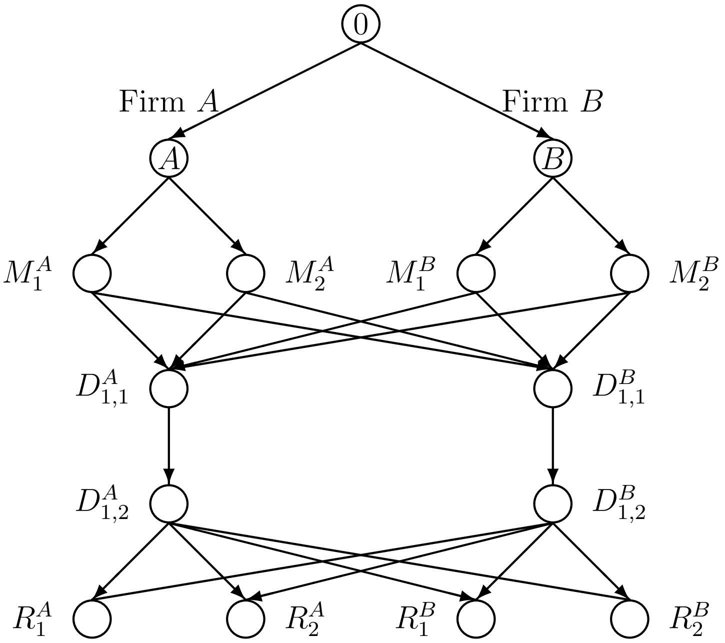

Figure 7.4. Post-Integration Supply Chain Network Topology for the Examples

7.3 Numerical Examples

In this Section, numerical examples are presented for which the solutions to the supply chains both pre and post the integration are computed, along with the associated total costs and synergies as defined in Section 7.2. The examples were solved using the modified projection method (see Section 2.5.2, cf. Korpelevich (1977) and Nagurney (2009)) embedded with the equilibration algorithm (see Section 2.5.3, cf. Dafermos and Sparrow (1969) and Nagurney (1984)). As discussed in Section 2.5.2, the modified projection method is guaranteed to converge if the function that enters the variational inequality is monotone and Lipschitz continuous (provided that a solution exists). Both these assumptions are satisfied under the conditions imposed on the multiproduct total cost functions in Section 7.1 as well as by the total cost functions underlying the numerical examples below. Since it also assumed that the feasible sets are non-empty, one can be guaranteed that the modified projection method converge to a solution of variational inequalities (7.7) and (7.13).

The computational procedure was implemented in FORTRAN and utilized a Unix system at the University of Massachusetts Amherst for the computations. The algorithm was considered to have converged when the absolute value of the difference between the computed values of the variables (the link flows; respectively, the Lagrange multipliers) at two successive iterations differed by no more than 10^{-5}. In order to fully exploit the underlying network structure, the multiproduct supply chain networks were first converted into single-product "extended" ones, as discussed in Dafermos (1973) for multimodal/multiclass traffic networks. The link capacity constraints, which do not explicitly appear in the original traffic network models, were adapted accordingly. The modified projecion method yielded subproblems, at each iteration, in flow variables and in price variables. The former were computed using the equilibration algorithm of Dafermos and Sparrow (1969) and the latter were computed explicitly and in closed form.

For all the numerical examples, it was assumed that each firm i; $i = A, B$, was involved in the production, storage, and distribution of two products, and each firm had, prior to the integration/merger, two manufacturing plants, one distribution center, and supplied the products to two retail outlets.

After the integration of the two firms' supply chain networks, each retailer was indifferent as to which firm supplied the products and the integrated/merged firms could store the products at any of the two distribution centers and could supply any of the four retailers. Figure 7.3 depicts the pre-integration supply chain network(s), whereas Figure 7.4 depicts the post-integration supply chain network for the numerical examples.

For all the examples, it was assumed that the pre-integration total cost functions and the post-integration total cost functions were nonlinear (quadratic), of the form:

$$\hat{c}_a^j(f_a^1, f_a^2) = \sum_{l=1}^{2} g_a^{jl} f_a^j f_a^l + h_a^j f_a^j, \quad \forall a \in L^0, \forall a \in L^1; \quad j = 1, 2, \tag{7.15}$$

with convexity of the total cost functions being satisfied (except, where noted, for the top-most merger links from node 0).

Table 7.1. Definition of Links and Associated Total Cost Functions for Example 7.1

Link a	From	To	$\hat{c}_a^1(f_a^1, f_a^2)$	$\hat{c}_a^2(f_a^1, f_a^2)$
1	A	M_1^A	$1(f_1^1)^2 + 2f_1^2 f_1^1 + 11f_1^1$	$2(f_1^2)^2 + 2f_1^1 f_1^2 + 8f_1^2$
2	A	M_2^A	$2(f_2^1)^2 + 2f_2^2 f_2^1 + 8f_2^1$	$1(f_2^2)^2 + 2f_2^1 f_2^2 + 6f_2^2$
3	M_1^A	$D_{1,1}^A$	$3(f_3^1)^2 + 2.5f_3^2 f_3^1 + 7f_3^1$	$4(f_3^2)^2 + 2.5f_3^1 f_3^2 + 7f_3^2$
4	M_2^A	$D_{1,1}^A$	$4(f_4^1)^2 + 1.5f_4^2 f_4^1 + 3f_4^1$	$3(f_4^2)^2 + 1.5f_4^1 f_4^2 + 11f_4^2$
5	$D_{1,1}^A$	$D_{1,2}^A$	$1(f_5^1)^2 + f_5^2 f_5^1 + 6f_5^1$	$4(f_5^2)^2 + f_5^1 f_5^2 + 11f_5^2$
6	$D_{1,2}^A$	R_1^A	$3(f_6^1)^2 + 1.5f_6^2 f_6^1 + 4f_6^1$	$4(f_6^2)^2 + 1.5f_6^1 f_6^2 + 10f_6^2$
7	$D_{1,2}^A$	R_2^A	$4(f_7^1)^2 + 2f_7^2 f_7^1 + 7f_7^1$	$2(f_7^2)^2 + 2f_7^1 f_7^2 + 8f_7^2$
8	B	M_1^B	$4(f_8^1)^2 + 3f_8^2 f_8^1 + 5f_8^1$	$4(f_8^2)^2 + 3f_8^1 f_8^2 + 6f_8^2$
9	B	M_2^B	$1(f_9^1)^2 + 1.5f_9^2 f_9^1 + 4f_9^1$	$4(f_9^2)^2 + 1.5f_9^1 f_9^2 + 6f_9^2$
10	M_1^B	$D_{1,1}^B$	$2(f_{10}^1)^2 + 3f_{10}^2 f_{10}^1 + 3.5f_{10}^1$	$3(f_{10}^2)^2 + 3f_{10}^1 f_{10}^2 + 4f_{10}^2$
11	M_2^B	$D_{1,1}^B$	$1(f_{11}^1)^2 + 2.5f_{11}^2 f_{11}^1 + 4f_{11}^1$	$4(f_{11}^2)^2 + 2.5f_{11}^1 f_{11}^2 + 5f_{11}^2$
12	$D_{1,1}^B$	$D_{1,2}^B$	$4(f_{12}^1)^2 + 3f_{12}^2 f_{12}^1 + 6f_{12}^1$	$2(f_{12}^2)^2 + 3f_{12}^1 f_{12}^2 + 5f_{12}^2$
13	$D_{1,2}^B$	R_1^B	$3(f_{13}^1)^2 + 3f_{13}^2 f_{13}^1 + 7f_{13}^1$	$4(f_{13}^2)^2 + 3f_{13}^1 f_{13}^2 + 10f_{13}^2$
14	$D_{1,2}^B$	R_2^B	$4(f_{14}^1)^2 + .5f_{14}^2 f_{14}^1 + 4f_{14}^1$	$4(f_{14}^2)^2 + .5f_{14}^1 f_{14}^2 + 12f_{14}^2$
15	M_1^A	$D_{1,1}^B$	$4(f_{15}^1)^2 + 2f_{15}^2 f_{15}^1 + 6f_{15}^1$	$4(f_{15}^2)^2 + 2f_{15}^1 f_{15}^2 + 7f_{15}^2$
16	M_2^A	$D_{1,1}^B$	$4(f_{16}^1)^2 + 2f_{16}^2 f_{16}^1 + 6f_{16}^1$	$3(f_{16}^2)^2 + 2f_{16}^1 f_{16}^2 + 7f_{16}^2$
17	M_1^B	$D_{1,1}^A$	$1(f_{17}^1)^2 + 3.5f_{17}^2 f_{17}^1 + 4f_{17}^1$	$4(f_{17}^2)^2 + 3.5f_{17}^1 f_{17}^2 + 5f_{17}^2$
18	M_2^B	$D_{1,1}^A$	$4(f_{18}^1)^2 + 3f_{18}^2 f_{18}^1 + 9f_{18}^1$	$4(f_{18}^2)^2 + 3f_{18}^1 f_{18}^2 + 7f_{18}^2$
19	$D_{1,2}^A$	R_1^B	$4(f_{19}^1)^2 + 3.5f_{19}^2 f_{19}^1 + 7f_{19}^1$	$1(f_{19}^2)^2 + 3.5f_{19}^1 f_{19}^2 + 9f_{19}^2$
20	$D_{1,2}^A$	R_2^B	$2(f_{20}^1)^2 + 3f_{20}^2 f_{20}^1 + 5f_{20}^1$	$4(f_{20}^2)^2 + 3f_{20}^1 f_{20}^2 + 6f_{20}^2$
21	$D_{1,2}^B$	R_1^A	$4(f_{21}^1)^2 + 2.5f_{21}^2 f_{21}^1 + 3f_{21}^1$	$3(f_{21}^2)^2 + 2.5f_{21}^1 f_{21}^2 + 9f_{21}^2$
22	$D_{1,2}^B$	R_2^A	$3(f_{22}^1)^2 + 2f_{22}^2 f_{22}^1 + 4f_{22}^1$	$4(f_{22}^2)^2 + 2f_{22}^1 f_{22}^2 + 3f_{22}^2$

Table 7.2. Pre-Integration Optimal Product Flow Solutions to Examples 7.1, 7.2, and 7.3

Link a	From Node	To Node	f_a^{1*}	f_a^{2*}
1	A	M_1^A	8.50	.80
2	A	M_2^A	1.50	9.20
3	M_1^A	$D_{1,1}^A$	8.50	.80
4	M_2^A	$D_{1,1}^A$	1.50	9.20
5	$D_{1,1}^A$	$D_{1,2}^A$	10.00	10.00
6	$D_{1,2}^A$	R_1^A	5.00	5.00
7	$D_{1,2}^A$	R_2^A	5.00	5.00
8	B	M_1^B	0.00	8.03
9	B	M_2^B	10.00	1.97
10	M_1^B	$D_{1,1}^B$	0.00	8.03
11	M_2^B	$D_{1,1}^B$	10.00	1.97
12	$D_{1,1}^B$	$D_{1,2}^B$	10.00	10.00
13	$D_{1,2}^B$	R_1^B	5.00	5.00
14	$D_{1,2}^B$	R_2^B	5.00	5.00

7.3.1 Example 7.1

Example 7.1 served as the baseline for the computations. The Example 7.1 data are now described. The pre and post-integration total cost functions for products 1 and 2 are listed in Table 7.1. The links post-integration that join the node 0 with nodes A and B had associated total costs equal to zero for each product $j = 1, 2$, for Examples 7.1 through 7.3. The demands at the retail outlets for Firm A and Firm B were set to 5 for each product. Hence, $d^j_{R^i_k} = 5$ for $i = A, B$; $j = 1, 2$, and $k = 1, 2$. The capacity on each link was set to 25 both *pre* and *post* integration, so that: $u_a = 25$ for all links $a \in L^0$; $a \in L^1$. The weights: $\alpha_j = 1$ were set to 1 for both products $j = 1, 2$, both pre and post-integration; thus, it was assumed that the products are equal in volume.

The pre-integration optimal solutions for the product flows for each product for Examples 7.1 through 7.3 are given in Table 7.2. Note that Example 7.1, pre-integration, was used as the basis from which variants post-integration were constructed, yielding Examples 7.2 and 7.3, as described below.

The post-integration optimal solutions are reported in Table 7.3 for product 1 and in Table 7.4 for product 2.

Since none of the link flow capacities were reached, either pre- or post-integration, the vectors β^{0*} and β^{1*} had all their components equal to zero. The total cost, pre-merger, $TC^0 = 5,702.58$. The total cost, post-merger, $TC^1 = 4,240.86$. Please also refer to Table 7.5 for the total cost and synergy values for this example as well as for the next two examples. The synergy $\mathcal{S}^{TC}$ for the supply chain network integration for Example 7.1 was equal to 25.63%.

It is interesting to note that, since the distribution center associated with the original Firm A has total storage costs that are lower for product 1, whereas Firm B's distribution center has lower costs associated with the storage of product 2, that Firm A's original distribution center, after the integration/merger, stores the majority of the volume of product 1, while the majority of the volume of product 2 is stored, post-integration, at Firm B's original distribution center. It is also interesting to note that, post-integration, the majority of the production of product 1 takes place in Firm B's original manufacturing plants, whereas the converse holds true for product 2. This example, hence, vividly illustrates the types of supply chain cost gains that can be achieved in the integration of multiproduct supply chains.

7.3.2 Example 7.2

Example 7.2 was constructed from Example 7.1 but with the following modifications. An idealized situation is now considered in which it is assumed that the total costs associated with the new integration links; see Table 7.1 (links 15 through 22) for each product were identically equal to zero.

Post-integration, the optimal flow for each product, for each firm, has now changed; see Table 7.3 and Table 7.4. It is interesting to note that now the second manufacturing plant associated with the original Firm B produces the majority of product 1 but the majority of product 1 is still stored at the original distribution center of Firm A. Indeed, the zero costs associated with distribution between the original supply chain networks lead to further synergies as compared to those obtained for Example 7.1.

Since, again, none of the link flow capacities were reached, either pre- or post-integration, the vectors β^{0*} and β^{1*} had all their components equal to zero. The total cost, post-merger, $TC^1 = 2,570.27$. The synergy $\mathcal{S}^{TC}$ for the supply chain network integration for Example 7.2 was equal to 54.93%. Observe that this obtained synergy is, in a sense, the maximum possible for this example since the total costs for both products on all the new links are all equal to zero.

7.3.3 Example 7.3

Example 7.3 was constructed from Example 7.2 but with the following modifications. It is now assumed that the capacities associated with the links that had zero costs between the two original firms had their capacities reduced from 25 to 5. The computed optimal flow solutions are given in Table 7.3 for product 1 and in Table 7.4 for product 2.

The computed vector of Lagrange multipliers β^{1*} is now provided. All terms were equal to zero except those for links 15 through 20 since the sum of the corresponding product flows on each of these links was equal to the imposed capacity of 5. In particular, now: $\beta^*_{15} = 40.82$, $\beta^*_{16} = 59.79$, $\beta^*_{17} = 14.35$, $\beta^*_{18} = 53.59$, $\beta^*_{19} = 79.95$, and $\beta^*_{20} = 68.39$.

The total cost, post-merger, was now $TC^1 = 3,452.34$. The synergy $\mathcal{S}^{TC}$ for the supply chain network integration for Example 7.3 was equal to 39.46%. Hence, even with substantially lower capacities on the new links, given the zero costs, the synergy associated with the supply chain network integration in Example 7.3 was quite high, although not as high as obtained in Example 7.2.

Table 7.3. Post-Integration Optimal Flow Solutions to the Examples for Product 1

Link a	From	To	Ex. 1 f_a^{1*}	Ex. 2 f_a^{1*}	Ex. 3 f_a^{1*}
1	A	M_1^A	5.94	0.76	5.36
2	A	M_2^A	0.53	0.00	1.98
3	M_1^A	$D_{1,1}^A$	5.94	0.00	5.36
4	M_2^A	$D_{1,1}^A$	0.53	0.00	1.98
5	$D_{1,1}^A$	$D_{1,2}^A$	18.27	19.24	17.34
6	$D_{1,2}^A$	R_1^A	5.00	5.00	5.00
7	$D_{1,2}^A$	R_2^A	3.27	4.24	4.27
8	B	M_1^B	6.25	1.67	5.00
9	B	M_2^B	7.29	17.57	7.66
10	M_1^B	$D_{1,1}^B$	0.00	0.00	0.00
11	M_2^B	$D_{1,1}^B$	1.73	0.00	2.66
12	$D_{1,1}^B$	$D_{1,2}^B$	1.73	0.76	2.66
13	$D_{1,2}^B$	R_1^B	0.00	0.00	0.00
14	$D_{1,2}^B$	R_2^B	0.00	0.00	1.93
15	M_1^A	$D_{1,1}^B$	0.00	0.76	0.00
16	M_2^A	$D_{1,1}^B$	0.00	0.00	0.00
17	M_1^B	$D_{1,1}^A$	6.25	1.67	5.00
18	M_2^B	$D_{1,1}^A$	5.55	17.57	5.00
19	$D_{1,2}^A$	R_1^B	5.00	5.00	5.00
20	$D_{1,2}^A$	R_2^B	5.00	5.00	3.07
21	$D_{1,2}^B$	R_1^A	0.00	0.00	0.00
22	$D_{1,2}^B$	R_2^A	1.73	0.76	0.73

Firm B's original distribution center now stores more of product 1 and 2 than it did in Example 7.2 (post-integration). Also, because of capacity reductions associated with the cross-shipment links there is a notable reduction in the volume of shipment of product 1 from the second manufacturing plant of Firm B to Firm A's original distribution center and in the shipment of product 2 from Firm A's original second manufacturing plant to Firm B's original distribution center.

7.3.4 Variant Numerical Examples

I then proceeded to ask the following question: assuming that the links, post-merger, joining node 0 to nodes A and B no longer had zero associated total cost for each product but, rather, reflected a cost associated with merging the two firms.

Table 7.4. Post-Integration Optimal Flow Solutions to the Examples for Product 2

Link a	From	To	Ex. 1 f_a^{2*}	Ex. 2 f_a^{2*}	Ex. 3 f_a^{2*}
1	A	M_1^A	3.44	4.66	5.00
2	A	M_2^A	11.81	11.88	8.74
3	M_1^A	$D_{1,1}^A$	0.00	0.88	0.00
4	M_2^A	$D_{1,1}^A$	4.91	0.48	3.74
5	$D_{1,1}^A$	$D_{1,2}^A$	4.91	4.82	3.74
6	$D_{1,2}^A$	R_1^A	1.52	0.00	0.61
7	$D_{1,2}^A$	R_2^A	2.58	0.00	1.20
8	B	M_1^B	2.34	3.46	3.58
9	B	M_2^B	2.42	0.00	2.68
10	M_1^B	$D_{1,1}^B$	2.34	0.00	3.58
11	M_2^B	$D_{1,1}^B$	2.42	0.00	2.68
12	$D_{1,1}^B$	$D_{1,2}^B$	15.09	15.18	16.26
13	$D_{1,2}^B$	R_1^B	4.88	2.72	5.00
14	$D_{1,2}^B$	R_2^B	4.30	2.46	3.07
15	M_1^A	$D_{1,1}^B$	3.44	3.78	5.00
16	M_2^A	$D_{1,1}^B$	6.89	11.40	5.00
17	M_1^B	$D_{1,1}^A$	0.00	3.46	0.00
18	M_2^B	$D_{1,1}^A$	0.00	0.00	0.00
19	$D_{1,2}^A$	R_1^B	0.12	2.28	0.00
20	$D_{1,2}^A$	R_2^B	0.70	2.54	1.93
21	$D_{1,2}^B$	R_1^A	3.48	5.00	4.39
22	$D_{1,2}^B$	R_2^A	2.42	5.00	3.80

Table 7.5. Total Costs and Synergy Values for the Examples

Measure	Example 7.1	Example 7.2	Example 7.3
Pre-Integration TC^0	5,702.58	5,702.58	5,702.58
Post-Integration TC^1	4,240.86	2,570.27	3,452.34
Synergy Calculations $\mathcal{S}^{TC}$	25.63%	54.93%	39.46%

It was further assumed that the cost (cf. (7.15)) was linear and of the specific form given by

$$\hat{c}_a^j = h_a^j f_a^j = h f_a^j, \quad j = 1, 2$$

for the upper-most links (cf. Figure 7.4). Hence, it was assumed that all the h_a^j terms were identical and equal to an h. At what value would the synergy then for Examples 7.1, 7.2, and 7.3 become negative? Through computational experiments these values were determined. In the case of Example 7.1, if $h = 36.52$, then the synergy value would be approximately equal to zero since the new total cost would be approximately equal to $TC^0 = 5,702.58$. For any value larger than the above h, one would obtain negative synergy. This has clear implications for mergers in terms of supply chain network integration and demonstrates that the total costs associated with the integration/merger itself have to be carefully weighed against the cost benefits associated with the integrated supply chain activities. In the case of Example 7.2, the h value was approximately equal to 78.3. A higher value than this h for each such merger link would result in the total cost exceeding TC^0 and, hence, negative synergy would result.

Finally, for completeness, the corresponding h in the case of Example 7.3 is determined which found the value to be $h = 78.3$, as in Example 7.2.

7.4 Summary and Conclusions

In this chapter, I developed multiproduct supply chain network models, which allow one to evaluate the total costs associated with manufacturing/production, storage, and distribution of firms' supply chains both pre and post-integration. Such horizontal integrations can take place, for example, in the context of mergers and acquisitions, an activity which has garnered much interest and momentum recently. The model(s) utilize a system-optimization perspective and allow for explicit upper bounds on the various links associated with manufacturing, storage, and distribution. The models are formulated and solved as variational inequality problems.

In addition, a proposed multiproduct synergy measure is utilized to identify the potential cost gains associated with such horizontal supply chain network integrations. It is proved that, in the case of zero "merging" costs, that the associated synergy can never be negative. Solutions to several numerical examples were computed for which the optimal product flows and Lagrange multipliers/shadow prices associated with the capacity constraints both before and after the integration were determined. The computational approach allows one to explore many issues regarding supply chain network integration and to effectively ascertain the synergies prior to any implementation of a potential merger. In addition, it was determined, computationally, for several examples, what identical linear costs would yield zero synergy, with higher values resulting in negative synergy.

There are numerous questions that remain and that be considered for future research. It would be interesting to develop competitive variants of the models in a game theoretic context and to also explore elastic demands. Also, this chapter does consider the time dimension in that it models the supply chain networks before and after the proposed merger and, hence, it considers two distinct points in time. For certain applications it may be useful to have a more detailed time discretization with accompanying network structure. Finally, it would be very interesting to explicitly incorporate the risks associated with supply chain network integration within this framework.

CHAPTER 8

CONCLUSIONS AND FUTURE RESEARCH

This dissertation focuses on supply chain issues including sustainability, policy analysis, merger and integration, while incorporating multicriteria decision-making of the key players throughout the supply chain with their associated interaction. Models were presented for multitiered supply chain networks where the multiple decision-makers face conflicting objectives in a competitive economic environment. I provide new theoretical interpretations between a sustainable supply chain network with distinct environmental criteria and an electric power supply chain model with a taxation scheme. With the focus on a specific supply chain application, the electric power industry, the association between a taxation and tradable permit scheme can be realized. Moreover, I examined the relationship between environmental and cost synergies through pre and post horizontal integration of supply chain networks as well as provided the more general and richer multiproduct domain regarding supply chain integration. The methodology utilized throughout the dissertation was variational inequality theory.

Specifically, in Chapter 3, I built on the work of Nagurney and Toyasaki (2003), which introduced environmental concerns into a supply chain network equilibrium framework (see also Nagurney, Dong, and Mokhtarian (2002b)) to develop the multitiered, multicriteria supply chain network model with distinct manufacturing plants for each manufacturer with associated environmental emissions. This network modeling framework is capable of identifying the equilibrium supply chain transaction flows and the demands (along with the associated prices). This new supply chain network model with environmental concerns was then transformed into a transportation network equilibrium model with elastic demands over an appropriately constructed abstract network or supernetwork. The benefits including a new interpretation of the equilibrium conditions governing sustainable supply chains in terms of path flows has been recently shown by Nagurney (2006a) (see also Nagurney (2000), Nagurney and Liu (2005), Nagurney (2006b), and Wu et al. (2006)). The contributions of this Chapter further demonstrated the generality of the concepts of transportation network equilibrium, originally proposed in the seminal book of Beckmann, McGuire, and Winsten (1956) (see also Boyce, Mahmassani, and Nagurney (2005)).

Additionally, numerical examples were conducted to illustrate the usefulness of the model. Specifically, it was shown that environmentally conscious consumers could significantly reduce the environmental emissions through the economics and the underlying decision-making behavior in the supply chain network. Interestingly, I establish that the prices associated with the environmental criteria of the various decision-makers can be interpreted as taxes, which is addressed in Chapter 4. However, Chapter 4 addresses a taxation scheme on a specific supply chain network application, the electric power industry, but those taxes are determined endogenously, while the prices associated with the environmental criteria in Chapter 3 are set exogenously. Chapter 3 is based on Nagurney, Liu, and Woolley (2007) but includes the generalization of emission functions which aids in the numerous applications of the model.

In Chapter 4, I developed a general modeling and computational framework in a specific supply chain network application as I just mentioned, the electric power generation industry, that may help policymakers to determine the optimal carbon taxes on the power plants, the equilibrium electric power transaction flows and the demands for electric power (along with the associated prices). There were three distinct carbon taxation environmental policies and models presented. The first model was a completely decentralized scheme, allowing the policy-makers to determine the optimal tax for each individual electric power plant which guarantees that the emission bound or quota of each plant is not exceeded. The second and third models, on the other hand, both enforce a "global" emission bound on the entire industry by imposing a uniform tax rate on the generating plants. However, the second policy assumes that the global emission bound is fixed while the third policy allows the bound to be a function of the tax. The numerical examples illustrate the impacts of the distinct carbon taxation policies on the electric power supply chain networks and demonstrate how policy-makers can determine the optimal taxes in order to achieve the environmental objectives. As the bound was tightened in the numerical examples, it was noted that the permit price and demand market price increased while emissions and demand decreased. Chapter 4 is based on Nagurney, Liu, and Woolley (2006) but, as in Chapter 3, includes the generalization of emission functions which aids in the numerous applications of the model.

While pollution by electric power entities can be controlled by price, in the form, for example, of a carbon tax that is imposed for emissions that exceed a predetermined bound as is modeled in Chapter 4 of the dissertation (see also Wu et al. (2006)), it can also be controlled by quantity, as was addressed in Chapter 5 of the dissertation, in the case of an emission trading scheme. Specifically, in Chapter 5, a multipollutant permit trading model was developed in the case of electric power supply chains in which there are different technologies associated with electric power production. The equilibrium electric power flows and the pollution permits/licenses, along with their prices could be computed with several numerical examples provided. Interestingly, assuming the same cost and emission functions, a single centralized carbon taxation scheme with a fixed bound on carbon emissions had the same result on electricity price and demand as an initial tradable permit license allocation that totaled the taxation scheme bound used in Chapter 4. It was also noted that the equilibrium price of the permits increases, as expected, as the environmental standard was tightened. The research in this Chapter is the first to incorporate the substitutability and complementarity effects of multiple pollutants. This research can aid a regulatory agency in the determination of the number of permits required to achieve the reduction of emissions below a pre-determined bound. Chapter 5 is based on Woolley, Nagurney, and Stranlund (2009) but, as in Chapter 3 and Chapter 4, includes the generalization of emission functions which aids in the numerous applications of the model.

While Chapter 4 and Chapter 5 focused on the impact of policy instruments on the behavior of the decision-makers throughout the supply chain, Chapter 6 and Chapter 7 study the impact of supply chain merger/integration in an effort to create synergistic gains and appeal to the environmentally conscious consumer, built on the work of Nagurney (2009). Specifically, in Chapter 6, I present a multicriteria supply chain network decision-making framework, in a system-optimization context, to evaluate the environmental impacts associated with mergers and acquisitions that captures the economic activities of a firm pre- and post-merger. The firms, pre-merger, were assigned a weight representing their individual environmental concerns; post-merger, the weight was uniform. The product flows along with the cost and resulting emissions could be computed pre and post-merger with several numerical examples provided to calculate synergistic gains, if any.

The numerical examples demonstrated that the operating economies may have an inverse impact on the environmental effects to society depending on the level of concern that each firm has for the environment and their joint actions taken to reduce emissions. There was a tradeoff between operational synergy gains with environmental benefits. As environmental benefits are increased, operational synergy decreased, even though, not quite as significantly as the environmental gains to society. I also explored the impacts of improved technologies associated with distribution/transportation. To the best of my knowledge, this is the first attempt to quantify the relationships associated with mergers and acquisitions and possible synergies associated with environmental emissions. Chapter 6 is based on Nagurney and Woolley (2009).

In Chapter 7, I considered the multiproduct dimension of supply chains with distinct firms and their horizontal integration. I developed the multiproduct supply chain network models prior to and post their horizontal integration with explicit capacities associated with the economic activities of production, storage, and distribution; an approach that is closely related to that of Dafermos (1973) who proposed transportation network models with multiple classes of transportation. I build on the novel work of Nagurney (2009) to also focus on the case of horizontal mergers (or acquisitions) and I extend the contributions in Nagurney (2009) to the much more general and richer setting of multiple product supply chains. I utilize a system-optimization perspective for the model development and I propose a measure, which allows one to quantify and assess, from a supply chain network perspective, the synergy benefits associated with the integration of multiproduct firms through mergers/acquisitions. The flows and prices of the various commodities could be computed with several numerical examples provided. Chapter 7 is based on Nagurney, Woolley, and Qiang (2009).

8.1 Future Research

I will continue my research in complex supply chain decision-making on network systems. First, I would like to build on my recent work in Chapter 7 and extend upon this framework to also consider the multiproduct case with environmental concerns. I will study the impact of environmental concerns through merger/acquisions of supply chain networks that include manufacturers, distribution outlets, and the final demand at the retail markets. To my knowledge, there is currently no literature to date that incorporates the study of the merger/integration of multiproduction firms and their respective supply chains and the resulting impact on the quality of the environment.

Additionally, I will study supply chain integration though vertical integration versus separation and the resulting effects on anticipated operational synergy. This work can then be extended to incorporate associated environmental emissions and aid in the study of the relationship of cost synergistic effects to the environmental impact of the proposed merger/integration.

Finally, the work on supply chain mergers/integration could also be extended to include regulatory requirements regarding environmental practices as it is important to understand not only the environmental and cost relationship, but the policy implications on resulting emissions. Additional issues related to mergers/integration of supply chains include risk and uncertainty and the associated effect on the success rate of proposed mergers.

Moreover, I will combine the work in Chapter 4 and Chapter 5 regarding a taxation and tradable permit scheme for the electric power supply chain generation, distribution, and consumption network to include the empirical implementation for the electric power supply chain of New England (see Liu and Nagurney (2009)).

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