1 Introduction and Overview

Supply chains are the critical infrastructure for the production, distribution, and consumption of goods as well as services in our globalized Network Economy. Supply chains, in their most fundamental realization, consist of manufacturers and suppliers, distributors, retailers, and consumers at the demand markets. Today, supply chains may span thousands of miles across the globe, involve numerous suppliers, retailers, and consumers, and be underpinned by multimodal transportation and telecommunication networks. Changes in the availability of supplies, price shocks, as well as disruptions to transportation modes or telecommunications may have effects that propagate throughout the supply chain. On the other hand, increases in demand for a product, entirely new demand markets, decreases in transaction costs, new suppliers, and even new modes of transaction, may provide new opportunities for profit maximization for manufacturers, distributors, as well as retailers, and new linkages that were not previously possible.

Supply chains are characterized by decentralized decision-making associated with the different economic agents but are, in fact, complex network systems. Hence, any formalism that seeks to model supply chains and to provide quantifiable insights and measures must be a system-wide one and network-based. Indeed, such crucial issues as the stability and resiliency of supply chains, as well as their adaptability and responsiveness to events in a global environment of increasing risk and uncertainty can only be rigorously examined from the view of supply chains as network systems.

This book builds the theoretical foundations for the formulation, analysis, and solution of supply chain problems from a network economics perspective. The approach is a natural one since it enables us to capture the optimizing behavior of the supply chain decision-makers in terms of their individual criteria (and associated weights) such as profit maximization, risk minimization, and, even, environmental emission minimization, if appropriate. In addition, the interactions of the decision-makers over space and time are revealed and the resulting material and product flows and prices, based on sound economic principles.

A network economics formalism has numerous advantages. First, one can easily visualize the supply chain structure as a network with the appropriate topology consisting of nodes and links. The identification of the network structure of the supply chain allows us to investigate the economic impacts of the addition/deletion of various decision-makers (as nodes in the network); the addition/deletion of different modes of transaction/transportation (as links in the network), and even different modes of production. In addition, the similarities/differences between the network structures of supply chains in distinct applications are graphically revealed and made more transparent since one can see the number of nodes and links and how the nodes are connected.

Indeed, by utilizing a network economics formalism we can identify, study, and exploit supply chain network structures across different applications. In this book, we do so in the context of energy supply chains, notably, electric power supply chains; environmental supply chains, including reverse supply chains in the context of electronic recycling networks; and even financial networks with intermediation, which we model and interpret in a supply chain framework.

Secondly, through a network economics framework, we can more readily bridge supply chain networks with other network systems to provide a deeper and richer understanding of supply chains at strategic as well as operational levels. This book demonstrates how supply chain networks can be reformulated and solved as transportation network equilibrium problems over appropriately constructed abstract networks or supernetworks. Transportation networks have been intensively studied by economists, engineers, as well as operations researchers/management scientists for fifty years now, beginning with the publication of the classic book *Studies in the Economics of Transportation* by Beckmann, McGuire, and Winsten in 1956. The identification of multitiered supply chains with transportation networks is obtained in this book for a variety of supply chain scenarios, with elastic demands and fixed demands, and in the context of distinct applications, from electric power supply chains to financial networks. The bridging of supply chain networks and transportation networks allows us to transfer methodologies developed for the latter to the former.

Another major innovation in this book is the treatment of supply chains in terms of dynamics. The book unveils a dynamic theory of supply chains that permits, under suitable assumptions, and starting from initial conditions, the determination of how the curves of equilibria, in terms of material and product flows, as well as prices evolve. The theory is obtained from the recent merger of projected dynamical systems and evolutionary variational inequality theory, with transportation-based applications being the principal driver behind the theory (see the papers by Cojocaru, Daniele, and Nagurney (2005a, b, c) and the books by Nagurney (1999) and Nagurney and Zhang (1996)).

In this book, the network structure of supply chains is also exploited in the presentation and description of appropriate algorithmic, that is, computational, procedures to solve the supply chain problems. In particular, this book emphasizes algorithms that are easy to understand and to implement and that exploit the underlying network structure of the problems and the applications.

This book, hence, provides not only a conceptual basis for the formulation and study of a spectrum of supply chains as network problems but also describes the necessary methodologies for the computation of the associated flows and prices.

Central to the network economics approach to supply chains is the concept of equilibrium in a supply chain, which provides a generalization of optimization, in the case of decentralized decision-making. Thus, we are able to capture both noncooperative, that is, competitive, behavior of decision-makers in a given tier of a supply chain (such as, for example, a tier of manufacturers, a tier of retailers, etc.) and also cooperative behavior between decision-makers in a supply chain network. Indeed, without cooperation, there is no supply chain network! In addition, not only are we able to determine the product flows between tiers at the equilibrium state but also the demand market prices that consumers are willing to pay. Finally, we are able to determine the prices that the individual manufacturers, retailers, distributors, should charge for the product. Clearly, it is the consumers and their demands for products that make any given supply chain viable or not.

The principal tool that we utilize for formulating (and solving) the various equilibrium problems is variational inequality theory. In order to describe the disequilibrium behavior and the associated dynamic adjustment processes, we, in turn, appeal to projected dynamical systems theory and, of course, exploit that the set of stationary points of the latter corresponds to the solutions of the former. To support the reader, we also provide two appendices. Appendix A contains the basic knowledge associated with optimization, variational inequality, and prjected dynamical systems theory. Appendix B, in turn, contains problems that accompany the chapters for self-study and/or pedagogical use. Necessary methodological tools are also reviewed and discussed in individual chapters.

The book consists of three parts. Part I has a total of five chapters, with this, the first, chapter providing an introduction and overview of the book. Chapter 2 develops the fundamental supply chain network equilibrium model, beginning with the description of the optimizing behavior of the individual economic decision-makers. The equilibrium conditions of the supply chain are then shown to satisfy a (finite-dimensional) variational inequality problem. Qualitative properties of existence and uniqueness of a solution, under reasonable assumptions, are investigated. Numerous numerical examples are given for which the solutions are determined without any algorithm. The proposed algorithm, which is accompanied by convergence results, is then applied to determine the equilibrium product flows and prices in additional supply chain network examples, which cannot be easily solved in closed form. This chapter is basic and expository.

Chapter 3 establishes that the supply chain network equilibrium model of Chapter 2 can be reformulated and solved as a transportation network equilibrium problem. A novel interpretation of supply chain equilibrium is also given in terms of path flows and path equilibrium conditions. The theoretical results in this chapter are, subsequently, utilized to suggest an alternative computational procedure, which is applied to several examples from Chapter 2 to show that, indeed, as the theory predicts, the same equilibria are obtained. The algorithm was originally proposed to compute solutions to elastic demand transportation network problems, formulated as projected dynamical systems.

Chapter 4 turns to supply chains with multicriteria decision-makers, who are concerned not only with profit maximization but also with risk minimization. The proposed model in this chapter captures both supply-side risk and demand-side risk associated with the demand markets and allows for electronic commerce. Qualitative analysis of the equilibrium is conducted and the proposed algorithm applied to several numerical examples to illustrate the usefulness of the modeling schema.

The bridges between the fundamental supply chain network model of Chapter 2 and transportation network equilibrium problems are further cemented in Chapter 5. Here not only is a fixed demand version of the supply chain network equilibrium problem of Chapter 2 presented but also a time-varying supply chain network model is constructed in which the demands vary over time, as do the flows. The latter model is formulated as an evolutionary (infinite-dimensional) variational inequality. This chapter provides further linkages between the theory of variational inequalities and projected dynamical systems, to accompany those presented in Chapter 3. This chapter also presents an evolutionary variational inequality formulation of the "extended" Braess paradox in which the demand varies over time. Solutions to several dynamic supply chain network examples in this chapter are provided, including a number of numerical examples that have closed form expressions and one that has a step-wise, time-varying demand.

Part II of this book begins with Chapter 6, and consists of four chapters. Part II focuses on energy supply chains, in the form of electric power supply chains. Electric power fuels our lights, our computers, and our homes and businesses. Its availability is essential to our everyday activities and its absence is clearly felt. Chapter 6 develops an electric power supply chain network model with electric power generators, electric power suppliers, transmission providers, as well as the consumers at the demand markets. This chapter also discusses some of the challenges posed by the restructuring in the electric power industry and how we address them in our modeling framework. The model presented in this chapter is a static one and the governing equilibrium conditions are formulated as a variational inequality problem. The structure of the electric power supply chain network differs from the supply chain network of Chapter 2.

Chapter 7 describes a dynamic electric power supply chain network model, which has the novel feature that distinct speeds of adjustment are introduced, with accompanying theory that proves that the equilibrium solutions are independent of the speeds of adjustment. This chapter takes advantage of the risk management developments of Chapter 4. Trajectories of the electric power flows as well as the prices over time are presented for an example for illustrative purposes. Numerical examples of electric power supply chain networks are solved and the profits of the various decision-makers also reported.

Chapter 8 considers a question posed fifty years ago in the Beckmann, McGuire, and Winsten (1956) book as to whether electric power generation and distribution networks can be formalized as transportation networks. Here we provide a positive answer to that question when we establish that, indeed, electric power supply chains can be reformulated and solved as transportation network equilibrium problems. Furthermore, we exploit this connection when we develop in this chapter a time-dependent electric power supply chain network model with time-varying demands. Examples are presented and solved.

Chapter 9 develops an electric power supply chain network model in which the electric power generators (or gencos) can use alternative "production processes" in terms of fuels for electric power generation. Since different fuels result in different environmental emissions, the model also includes environmental policies in the form of carbon taxes and green subsidies. The network structure of the problem is identified and then its transformation into a transportation network equilibrium problem made in order to solve the problem. The numerical examples in this chapter illustrate the efficacy of the proposed environmental policies. Chapter 9 provides an excellent transition to Part III of this book, which is on environmental supply chain networks, in which decision-makers may be explicitly concerned with the minimization of pollution emissions. Hence, in Part III of the book multicriteria decision-making plays a prominent role and we also consider financial networks with intermediation and electronic transactions.

Chapter 10 begins Part III of this book, which consists of three chapters. Chapter 10 presents the basic supply chain network equilibrium model with environmental concerns and discusses both static and dynamic versions. Companies are now being increasingly held accountable not only for their own performance in terms of environmental issues, but also for that of their suppliers, subcontractors, joint venture partners, distributors, and, ultimately, even for the disposal of their products. Hence, poor environmental performance at any stage of the supply chain may damage a company's most important asset

– its reputation. The models in this chapter handle both business-to-business (B2B) and business-to-consumer (B2C) electronic commerce.

Chapter 11 turns to a reverse supply chain management problem in the context of electronic recycling (e-cycling) networks. Electronic waste, or e-waste, is considered to be the fastest growing waste problem in the world today in terms of the quantity of electronic waste generated annually as well as the associated toxicity of its various components. On the other hand, electronic items also have components of some value and, at the same time, materials of high value, such as platinum, silver, copper, etc. The model that we describe in this chapter, unlike the preceding supply chain network models in this book, assumes a fixed amount of supply of the electronic product at the various sources of electronic waste. Decision-makers include not only sources of electronic waste, but also recyclers and processors, as well as consumers associated with the demand markets for the recycled waste. The reverse supply chain management model for electronic recycling handles the transformation of the electronic waste as the material flows down the supply chain. The model and proposed algorithm are illustrated through numerical examples.

Chapter 12 concludes the book with the development of a financial network model with intermediation and with electronic transactions. Electronic finance (see also, e.g., Nagurney (2003) and the references therein) represents one of the major success stories associated with the Internet and its numerous applications. Millions of people now use the Internet for financial transactions and their numbers are growing. The financial network model with intermediation and with sources of funds, financial intermediaries, and demand markets is developed in this chapter. It is then shown to be transformable into a transportation network equilibrium problem with fixed demands over an appropriately constructed supernetwork, which is distinct in structure from those obtained for other applications in this book. This equivalence, in turn, answers another question, outstanding for over half a century and posed by Copeland in his 1952 book, as to whether "money flows like water or electricity?" In this chapter, we show that money actually flows like transportation, but so does electricity.

Each subsequent chapter, that is, Chapter 2 through Chapter 12, ends with a sources and notes section which summarizes the contents and results obtained in the particular chapter and provides the primary sources for the results in the chapter.

It is hoped that this book will provide a useful and valuable resource for researchers, students, educators, practitioners, as well as policy-makers, and even government regulators, for the further examination, exploration, application, and solution of supply chain networks in their important and fascinating realizations, both today and in the future.