GAME THEORY ANALYSIS OF GREEN PROCUREMENT IN SUSTAINABLE SUPPLY CHAIN MANAGEMENT

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_______________________________(Signed)

________Xin MA________(Name of student)

Dedicated

with love

to my family.

Abstract

With the rapid increase of fossil energy consumption, climate change and environmental problems are receiving closer attention. Starting from the perspective of sustainable supply chain management, besides procurement costs, a manufacturer (or a buyer) has to pay great attention to the cost of emitting greenhouse gases, which is directly influenced by the green degree of the raw materials from its suppliers. Therefore, there exists a conflict in a supply chain. That is, suppliers pass on the greenhouse gas emissions to the manufacturer to avoid the environmental cost. To study the coordination behaviors in a supply chain from sustainable perspective, this research focuses on how a manufacturer can adopt reasonable procurement strategies under the carbon emission regulations to achieve simultaneously the goals of profit maximization and pollution minimization. Three specific topics on green procurement are studied.

In the first topic, the competition between two independent manufacturers is analyzed under two types of carbon emission regulations. Several boundary conditions are derived to assist the manufacturer to make the optimal procurement decision. In addition, how to select appropriate locations for the manufacturer to set up factories are analyzed by comparison of the influences of carbon emission regulations. With respect to the asymmetric information of suppliers, the second topic firstly focuses on the procurement contract design issue between a manufacturer and a single supplier. The green degree of a supplier is private and known only by the supplier itself. This factor predominately determines the emission volumes of the manufacturer. Under the emissions trading mechanism, the procurement contract between the profit-maximization manufacturer and the supplier is analyzed under different types of auctions, and a scenario of competitive procurement with

multiple suppliers is discussed. From the dynamic viewpoint, the third topic aims to analyze the impact of carbon tax schemes on the pricing issue in a decentralized supply chain with a profit-maximization manufacturer and multiple suppliers. Two types of pricing strategies are derived respectively for both suppliers and the manufacturer. In addition, to observe a more general outcome, the scenario for the manufacturer sourcing from an n-suppliers' oligopoly is studied. The comparative statics analysis is conducted for the pricing strategies under different situations and parameter settings.

Regarding each specific model, research outcomes provide meaningful managerial implications for both manufacturers and suppliers. Manufacturers benefit from the findings by adopting flexible strategies (e.g., ordering strategy, contract design, pricing strategy) when they comply with different carbon emissions regulations. The suppliers can have a better understanding of methods for maintaining or increasing their market share and the mutual effects of the strategies on the manufacturer and suppliers.

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Chapter 1

Introduction

1.1 Background

Fossil fuel, as a primary energy source, has played a dominant role in society since the Industrial Revolution. The consumption of fossil fuel, such as coal, oil, and natural gas, emits a series of greenhouse gases (GHG), including Carbon Dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFC's), Perfluorocarbons (PFC's), and, Sulfur Hexafluoride (SF_6). These GHG lead to the phenomenon of global warming. Supported by fossil fuel-based technologies, individual business firms have provided a global scale of goods and services. However, this triggers serious environmental problems. For example, air pollution particulates in Bejing in November 2015 reached more than 20 times of that the World Health Organization considers to be safe [Fri15]; in the same year, NASA reported that "*El Niño has caused the warm water layer that is normally piled up around Australia and Indonesia to thin dramatically, while in the eastern tropical Pacific, the normally cool surface waters are blanketed with a thick layer of warm water.*

This massive redistribution of heat causes ocean temperatures to rise from the central Pacific to the Americas. It has sapped Southeast Asias rain in the process, reducing rainfall over Indonesia and contributing to the growth of massive wildfires that have blanketed the region in choking smoke" [Nat15]. All these evidences show that the human being is facing a big threat and a great challenge.

In the recent years, sustainable operations management has been booming, and also brought scholars' attention to the challenges of global warming and reduction of carbon emissions. From the micro-perspective, the operational decisions of a firm, such as procurement strategy, production technology, and product design, can directly determine emission volumes. As a potential means, sustainable operations management plays a significant role in providing effective solutions to deal with today's drastic climate change. For example, in 2013, the Carbon Disclosure Project (CDP) conducted its annual investigation for managing carbon emissions. In that project, more than 6,000 suppliers participated in the survey. According to the results of the investigation, an increasing number of suppliers realized the benefits in both monetary savings and emissions reduction. In addition, the results show that 29% of suppliers reported emissions reduction in 2012, while one year earlier, it was only 19%. In 2013, 69% of CDP members made investments in reducing GHG emissions while this figure was only 39% in 2011 [Car13]. In the business world, the Hewlett Packard Enterprise (HP) has executed a product return and recycling program for particular products since 2013, all over the world. After expiry of the product life, HP provides the additional services (i.e., free delivery) to motivate the environmental protection and consumer awareness. From the perspective of climate change and manufacturing operations, Cachon et al. [Cac12] pointed out that (1) a week with six or more days of heat exceeding 90F (32.2°C) reduces production in that week by 8% on average; (2) severe weather reduces production on average by 1.5%. Plambeck [Pla12] provided examples of how companies make profits by reducing GHG emissions under their direct and indirect control. In addition, by analyzing the literature on operations and supply chain management, Plambeck [Pla12] provided insights on additional means for companies to reduce GHG emissions and to establish new supply chains for renewable energy and other zero-emission products, and on the potential impacts of climate change on supply chains.

From the viewpoint of sustainable supply chain management, this research project aims to figure out reasonable solutions to cope with the challenges of carbon emissions in sustainable supply chain management, involving information asymmetry, dynamically coordinated strategies analysis, and the comparison of competitive strategies, which can enhance environmental benefits to firms. In the following section, two types of carbon emission regulations, which have been implemented all over the world, are briefly introduced.

1.2 Carbon Emission Regulations

A historic international agreement on climate change, i.e., The Paris Agreement, was adopted by 195 countries on December 12, 2015. According to the French COP21 President, Laurent Fabius, *"This text, which we have built together, [...] is the best balance possible, a balance which is both powerful and fragile, which will enable each delegation, each group of countries, to return home with their heads held high, having gained a lot"*. This project confirmed the goal of *"holding the increase in average temperature to well below 2° C and pursuing efforts to limit this increase to 1.5° C, which would significantly reduce the risks and impacts of climate change"*. In addition, the Paris agreement stressed the urgency of accelerating the implementation of the Convention and the Kyoto Protocol in order to enhance pre-2020 ambitions [Uni15b].

The Kyoto Protocol, as an effective convention addressing global climate change, provides three mechanisms to curb global carbon emissions, including Joint Implementation, Clean Development Mechanisms, and International Emissions Trade. On the basis of the above mechanisms, some countries and regions have established trading markets for carbon emissions, which were set out in Article 17 of the Kyoto Protocol, such as the Chicago Climate Exchange and New South Wales Greenhouse Gas Abatement Scheme. In 2005, the world's largest cap-and-trade (emissions trading) market was officially established in Europe, i.e., the European Union Emissions Trading Scheme (EU ETS). The cap-and-trade mechanism is essentially an economic incentive mechanism to encourage agents to adjust their operational decisions and/or strategies for simultaneously reducing emissions and to achieving their goal of profit-maximization. Since 2013, several regions in China, including Beijing, Shanghai, Shenzhen, Tianjin, Chongqing, Guangdong, and Hubei, have successfully implemented the emissions trading scheme. The first inter-regional emissions trading market was tested in Beijing-Chengde for one year. Based on this mechanism, carbon-intensive firms not only have realized their implementation plan but also have begun to turn a profit [Heb15]. For example, Bejing Eastern Petrochemical Co. Ltd earned 0.5 million RMB in profit during 2015 [Bei15]. In addition, the Chinese government will initiate the national carbon emissions trading market comprehensively in 2017 [Chi15].

A carbon tax scheme, as an alternative incentive mechanism, is a government-determined, cost-effective means to curb carbon emissions from burning fossil fuels. This economic instrument focuses on encouraging decision-makers to adopt new or green technologies to reduce carbon emissions. For instance, carbon capture and storage (CCS) has been endorsed by global development organizations as a new way to reduce approximately 1/5 of the emissions increase predicted under a “business-as-usual” global economic development scenario by 2050 [Kin11]. As a typical case, a carbon tax has been successfully implemented in Australia. The initial price of the carbon tax was fixed, then, it was replaced by a flexible price on July 1, 2015 [Ora15]. However, a carbon tax scheme becomes fully effective only if it is accompanied by synergistic actions. Therefore, with respect to manufacturers, the ways to adjust the operational strategy under the carbon tax scheme are worth studying. Are there any boundary conditions that can assist manufacturers in making better decisions?

Based on the aforementioned introduce, these two types of carbon emission regulations addressed uncertainty from different aspects. The carbon tax scheme aims to control the price of emissions, while the uncertainty of the aggregate emissions level is neglected. The cap-and-trade mechanism focuses on aggregate emissions, while leaving the price uncertain [Gou13].

However, from the perspective of the micro-firm level, both the trading prices and emission allowances are uncertain. First, with respect to a firm, the cost of emissions (e.g., a carbon tax or emissions trading prices) is exogenously varied. Second, the emissions allowances of a firm are predominantly determined by its uncertain demand. Therefore, motived by the uncertainties of these two aspects, this research project is dedicated to study how a firm makes reasonable procurement decisions under carbon emissions regulations. The research objectives are illustrated in the following section.

1.3 Research Objectives

The main objective is to determine how carbon emissions regulations impact on the operational strategies of firms in a supply chain consisting of a manufacturing and multiple suppliers. That is, this research project is an intersection of procurement management and the application of the carbon emissions regulations. In order to achieve this objective, three specific topics are studied in each chapter based on the viewpoint of sustainable operations management. In the following chapters, from the game theoretical modeling perspective, this research focuses on solving three specific questions under the aforementioned carbon emissions regulations, respectively.

(1) *What is the optimal sourcing strategy for the manufacturer (or the buyer)?* From the firms' perspective, the competition behaviors of profit-maximization manufacturers by adopting different sourcing strategies are explored. In addition, under the influences of the carbon emission regulations, how to choose appropriate locations for manufacturing factories is analyzed.

(2) *How is an appropriate sourcing mechanism designed for the manufacturer?* Facing information asymmetry, the manufacturer needs to deal with private information, i.e., the unit emission rates of suppliers, by designing a reasonable sourcing mechanism. How to choose the optimal bidding strategy for suppliers under different auction types is also studied.

(3) *What is the optimal pricing strategy for the manufacturer in a dynamic scenario?* Starting from the viewpoint of dynamic coordination for the operational strategies, the manufacturer could adopt flexible pricing strategies in consideration of the impact of the carbon tax scheme.

The above three research questions are sub-topics of sustainable supply chain management. The related literature is analyzed in the next chapter.

1.4 Dissertation Overview

The structure of this dissertation is organized as follows. Chapter 2 discusses the related literature including sustainable supply chain management, green procurement in operations research, and applications of carbon emissions regulations in operations management.

Chapter 3 studies the impact of carbon emissions on the sourcing problems from the firms' perspective. A game model between two independent competitive manufacturers under carbon emission regulations, including the emissions trading mechanism and the carbon tax scheme is proposed. In a loose supply market, the manufacturer can cooperate with a traditional supplier (e.g., cost-effective strategy) or a greener supplier (e.g., environment-friendly strategy). A cost-effective strategy has a competitive advantage in terms of cost, whereas an environment-friendly strategy can reduce a manufacturer's total GHG emissions. Given the certain demand and emission allowances, the equilibrium strategy is analyzed with the basic model, which is then extended to study uncertainty. By characterizing the existence and the uniqueness of the equilibrium strategy, the structural properties of the sourcing game are derived under the emissions trading mechanism. With respect to the uncertainty of trading prices, two separate conditions regarding how trading prices have an impact on the equilibrium strategies of manufacturers is analyzed. In addition, the sourcing game is extended to study three other scenarios. First, the sourcing game with multiple competitors affected by the emissions trading mechanism is studied. Second, how manufacturers can make appropriate sourcing decisions under the carbon tax scheme is analyzed. Third, the emissions trading mechanism and the carbon tax scheme are compared. In particular, the boundary conditions are identified to analyze and compare the dominance of the emissions trading mechanism and that of the carbon tax scheme. Overall, the purpose of this chapter is to identify reasonable and flexible sourcing strategies for manufacturers in an uncertain environment.

In Chapter 4, this research project aims to design an appropriate sourcing mechanism with information asymmetry in a supply chain with one manufacturer and multiple suppliers subject to an emissions trading scheme. The manufacturer purchases raw materials from suppliers, who hold private information regarding the green degree i.e., the unit emission rates of their raw materials. An appropriate strategy must be adopted by the manufacturer for the contract design, including a series of payments and the order quantities; the suppliers are subsequently invited to bid for the contracts. The basic model is formulated to assist the manufacturer in designing a reasonable contract for a single supplier, and the optimal contract structure will be identified. The characteristics of the optimal order quantity and payoff functions of both the manufacturer and supplier are analyzed. A competitive procurement scenario with multiple suppliers is discussed. In addition, the robustness and properties of the contract are derived. With respect to the diversity of auctions, three different auction types are analyzed, including a green degree auction, a price auction with emissions targets, and a performance-based auction. In addition, an efficient emissions trading policy is established to guide manufacturers regarding how to trade their emission allowances based on the optimal order quantities.

The carbon tax is a cost-efficient scheme to curb emissions, and it has been implemented in Australia, British Columbia, and other places worldwide. Chapter 5 aims to analyze its effect on dynamic pricing in a supply chain with one manufacturer and two suppliers. A profit-maximizing manufacturer makes final products using raw materials from suppliers with heterogeneous prices and emission rates. A two-stage game model is built over an infinite time horizon for this issue. In the first stage, suppliers face a price-dependent demand to set their prices and production rates under the constraint of inventory capacity. In response to the carbon tax scheme, the manufacturer evaluates the procurement prices and emission rates of suppliers to control its emission volumes and sets the sales price of its product. This chapter predominately focuses on the optimal pricing strategies in a decentralized supply chain. The open-loop equilibrium and Markovian Nash equilibrium for the dynamic pricing game models of both suppliers and the manufacturer are derived. The equilibrium prices of suppliers and the manufacturer can be solved based on both irreversible actions and real-time states. These two types of equilibria can be regarded as the solutions of two different models in specific situations. To analyze the effect of sourcing diversity on pricing strategies and emissions control for the manufacturer, this chapter extends the equilibrium prices to a multiple suppliers oligopoly. Numerical examples are presented to illustrate the equilibrium and its monotonicity with various parameter settings.

Chapter 6 concludes the dissertation and proposes a future research plan.

Chapter 2

Literature Review

Based on the research objectives in Chapter 1, this chapter predominantly aims to introduce the intersection of related literature including sustainable supply chain management, green procurement in operations research, and the applications of carbon emission regulations. With respect to three specific sub-topics or research questions, a brief review will be conducted within each individual chapter.

2.1 Sustainable Supply Chain Management

The concept of sustainable supply chain management (or green supply chain management, GSCM) has been widely discussed by researchers from different perspectives in the past five years. In reality, the motivation for the introduction of GSCM could be for ethical and commercial reasons [Tse13a]. Starting from the view point of supply chain management (SCM), Seuring and Mller [Seu08] suggested that sustainable SCM could not only affect the management of material, information and capital flows, but could also achieve the goals of the triple bottom line (environmental, social and economic). Ramudhin et al. [Ram10] built a multi-objective mixed integer linear programming model, which considered two aspects: carbon emissions and total logistics costs, to study the design of supply chains. This model effectively evaluated the GHG footprint of the supply chain and provided better suggestions to managers in implementing GSCM. Gavronski et al. [Gav11] proposed that GSCM was complex and implemented at the cooperation and plant level to assess or improve the environmental performance of a supplier base. Sarkis et al. [Sar11] defined GSCM as integrating environmental concerns into the inter-organizational practices of SCM, for instance, reverse logistics. In addition, they also introduced a brief history of GSCM. Given the characteristics of GSCM, Kim and Rhee [Kim12] integrated four aspects, including green purchasing, green manufacturing/materials management, green distribution/marketing, and reverse logistics, into GSCM. Similarly, Srivastava [Sri07] put forward a more detailed framework which also integrated environmental criteria into SCM, including product design, material sourcing and selection, manufacturing processes, delivery of final products to consumers, and the end-of-life management of the product. More recently, Barari et al. [Bar12] discussed GSCM from the viewpoint of economy and ecology; they also suggested that making profits and achieving an ecological balance were the objectives of GSCM. Around the same time, Zhu et al. [Zhu12] described GSCM from another viewpoint, in which GSCM could be defined as an emergent environmentally sustainable organizational technological innovation. Tseng et al. [Tse13b] proposed a similar concept for GSCM with the triple bottom line, from different aspects, and stated that ethics were also important through the whole supply chain. From the micro-operations aspect, GSCM not only focuses on products and production processes but also includes materials sourcing (Tseng and Chiu [Tse13a]).

In addition, many journal papers reviewed particular topics in GSCM. Srivastava [Sri07] analyzed the GSCM from three aspects: the importance of GSCM, green design, and green operations. With respect to green operations, Srivastava [Sri07] reviewed green manufacturing and remanufacturing, reverse logistics and network design, and waste management. Shang et al. [Sha10] suggested six critical GSCM dimensions, including green manufacturing and packaging, environmental participation, green marketing, green supplier, green stocking, and green eco-design. Their results, from cluster analysis, showed that a green marketing oriented group was the best choice, based on a resource-based view (RBV). Dekker et al. [Dek12] introduced green logistics from the operations aspect, which included three decision phases: design, planning, and control. With the view of product life-cycle management, Chen et al. [Che12] reviewed five topics: green design, green purchasing, green manufacturing, green marketing and service, and GSCM strategy. Genovese and Koh [Gen13] explored green supplier selection with empirical studies such as questionnaire surveys and in-depth interviews. Their research work provided evidences that some theoretical studies could be applied to the real world.

With respect to the applications of GSCM, Neto et al. [Net08] developed a multi-objective programming (MOP) model to study sustainable supply chains in the European pulp and paper industry. They discussed four scenarios in Germany which had different mandatory recycling percentages (free, 20%, 50%, and 100%). The results indicated that (1) mandatory recycling 20% pulp weakly influenced the Pareto-efficient frontier, however, it also restricted environmental replacements; (2) 50% mandatory recycling pulp in the EU and 100% in Germany had similar results: restricted environmental replacements and degraded Pareto frontier. Regarding LCA standards, Chaabane et al. [Cha12] developed a mixed-integer linear programming model to study the issue of designing a sustainable supply chain. According to an analysis of strategic planning, they converted the results into a mathematical programming model which had two objectives: environmental and economic, including location costs, supply costs, production costs, distribution costs, reverse logistics costs, transportation costs, LCA-based costs and the carbon credit component. Considering the important characteristics of aluminum, which can be 100% recycled, the model was applied to study planning for a sustainable supply chain in the aluminum industry. The experimental results indicated that effective environmental protection strategies might improve the cost management.

Recently, Fahimnia et al. [Fah15] presented a structured review of GSCM by using bibliometric and network analysis. Research clusters were identified for topological analysis, identification of key research topics, interrelations, and collaboration patterns. Their analysis results indicated that modeling has started to take on greater importance, especially by using the practical real data.

2.2 Green Procurement in Operations Research

In supply chain management, procurement is a significant issue which has attracted many researchers since the 1950's. This section discusses the issue of green procurement from an operations research (OR) modeling aspect.

As a pioneer, Noci [Noc97] proposed green supplier ranking systems for evaluating the environmental performance of suppliers. A three-phase selection procedure was established for selecting green suppliers including identification of green strategies, the definition of environmental performance of the key suppliers, and selection of the most appropriate method.

Lu et al. [Lul07] integrated the analytical hierarchy process (AHP) and fuzzy set theory to select a green supplier. The evaluation framework mainly focused on two parts: the development of the structure criteria and criteria weights calculation. The evaluation structure was built based on the current environmental regulations, company environmental policies, and environmental guidelines from non-governmental organizations. In order to overcome the subjective bias, fuzzy logic was adopted to update the AHP approach. Similarly, Lee et al. [Lee09] applied fuzzy AHP to select green suppliers for high-tech industries. Considering the interrelationships among different criteria, Hsu [Hsu09] adopted an effective method, the analytic network process (ANP) to evaluate green suppliers instead of AHP. In this evaluation framework, the requirements of green purchasing, green materials coding and recording, environmental management and hazardous substance management (HSM) were taken into account.

In the mean time, Kuo et al. [Kuo10] built an integrated model which considered artificial neural networks (ANN), ANP, and data envelopment analysis (DEA) for green supplier selection. In a case study on a camera manufacturer, they compared integrated methods: ANN-DEA and ANP-DEA, and found that ANN-DEA had a better capability to evaluate supplier performance. Bai [Bai10] adopted rough set theory to effectively manage the development of green suppliers. The advantage of rough set theory is that it can deal with 'incomplete' information in poor environments. Latterly, Yeh [Yeh11] developed an MOP model which included four aspects (cost, time, product quality, and green appraisal score) to select an appropriate green supplier. To improve the efficiency of the model, a genetic algorithm (GA) was employed to obtain the Pareto optimal solutions. Büyüközkan et al.

[Buy12] proposed a novel hybrid green supplier evaluation framework which integrated the fuzzy decision-making trial and evaluation laboratory model (DEMATEL), fuzzy ANP and fuzzy TOPSIS. In addition, Shaw et al. [Sha12] presented a model which integrated fuzzy-AHP with fuzzy multi-objective linear programming. In the first selection stage, fuzzy-AHP was used to calculate the weights of cost, quality rejection percentage, late delivery percentage, greenhouse gas emissions, and demand. Then, these weights formed part of the input data of a linear programming model which was used to select the best green supplier.

Starting from the carbon management perspective, Hsu et al. [Hsu13] suggested an evaluation framework from three dimensions: planning, implementation, and management. Thirteen sub-criteria were identified based on the above dimensions. In addition, the Decision-making Trial and Evaluation Laboratory (DEMATEL) method was applied to check the interrelationships among sub-criteria. Training related to carbon management was identified as the key criterion of green supplier selection.

In addition, Dou et al. [Dou14] developed a green supplier selection model based a grey ANP-based model, in consideration of the complexity of the evaluation process. This two-stage integrated model improved the effectiveness of assessment capability for the performances of green suppliers. Shen et al. [She13] applied a fuzzy multi-criteria decision-making method to study the issue of green suppliers performance evaluation. Nine environmental criteria were summarized for green supplier evaluation. The highlight of this paper was that the linguistic preferences were combined through fuzzy TOPSIS to obtain the ranking. Similarly, Kannan et al. [Kan14] also applied fuzzy TOPSIS to select green suppliers. A real case study was analyzed in a Brazilian electronics company. Meanwhile, Kumar et al. [Kum14] proposed a comprehensive model, a DEA model with carbon footprint monitoring, to select green suppliers. The missing data in this model were provided by using the series mean and the AHP technique, which translates the DEA model into a Chance Constrained DEA model.

2.3 Carbon Emission Regulations in Operations Management

From the perspective of sustainable operations management, this section focuses on applications of carbon emission regulations, i.e., the emissions trading mechanism and the carbon tax scheme. Various researchers have been carried out a series of quantitative analysis for complicated production management issues under the emissions trading mechanism. For example, both Hua et al. [Hua11] and Chen et al. [Che13] studied the impact of carbon emissions on economic order quantity (EOQ). Hua et al. [Hua11] focused on how firms manage carbon footprints in inventory management under the emissions trading mechanism. The difference is that Chen et al. [Che13] considered the constraint on the amount of carbon emitted. Gong and Zhou [Gon13] developed a stochastic dynamic programming model to fully analyze the production planning under the emissions trading mechanism. The optimal production policy and the optimal trading policy have been proposed to minimize the total cost based on two types of production technologies. Zhao et al. [Zha10b] built a nonlinear complementarity model to analyze the long-run equilibrium for electric power markets under the allowance trading systems. Drake et al. [Dra16] studied the impacts of carbon emission regulations and production technology choice on production decisions and capacity portfolio.

The implications based on the aforementioned decisions were further analyzed for the expected profit and emission allowances of a firm.

With respect to the carbon tax scheme, Gemechu et al. [Gem12] studied an environmental tax based on the carbon footprint of products for the pulp and paper sector. Two individual methods, life cycle analysis (LCA) and environmentally extended input-output analysis (EIO), were established to identify the emission intensities for the product. For the scenario of multiple suppliers in the market, Choi [Cho13] adopted the multi-stage stochastic dynamic programming based on the classical newsvendor model to study the issue of supplier selection under the carbon tax scheme. The impacts of the linear and quadratic structure of the carbon tax were discussed. Krass et al. [Kra13] studied the economic impacts of different types of technologies on consumer prices, production quantities, profit of firms, pollution amount, etc. A Stackelberg game model was developed to analyze the above research issues between a firm (the follower) and a regulator (the leader). Chung et al. [Chu13] analyzed how manufacturing firms make strategic responses to pollution taxes in supply chain networks. A key implication of their research result showed that the tax depends on the oligopolistic game structure. In addition, there are other aspects of research which focus on the coordination of operation patterns and optimization of production strategies. Subramanian [Sub07] characterized a three-stage game model to analyze how firms coordinate production planning, bidding for permits of emissions, and abatement behavior. A linear emissions cost was considered. Two market operation scenarios, involving independent demands and Cournot competition, were analyzed. Caro et al. [Car15] proposed a general model of joint production of GHG emissions in a supply chain. Two scenarios were studied. In the first scenario, the social planner imposed a carbon tax on firms in proportion to the emissions allocated. For the second scenario, the leader offsets emissions and cooperates with individual firms to withdraw the costs of the offsets. With respect to both cases, the optimal offset level indicated that the emissions need to be over-allocated, even if the carbon tax is the social cost of carbon emissions. Cachon [Cac14] studied how the layout of retail facilities impacts on the emission tradeoffs. Following the modeling approach in Cachon [Cac14], Park et al. [Par15] investigated the impact of carbon emissions on the supply chain structure and social welfare. Their research results indicated that imposing carbon costs can lead to a significant increase in social welfare when the retailer's profit is low.

2.4 Game Theory Models

Game theory is a powerful methodology deals with interactive optimization problems in which the decisions of multiple agents affect each agents's payoff [Cac03]. In the past few centuries, several scholars have made contributions to the development of game theory. John von Neumann and Oskar Morgenstern are credited as the fathers of modern game theory. Later on, game theory has been widely studied and exploited, including the concept of equilibrium (Nash, 1950; Harsanyi, 1968), games with imperfect information (Kuhn 1953), cooperative games (Aumann, 1959; Shubik, 1962), and auctions (Vickrey, 1961). This section aims to provide a brief introduce regarding game theoretical models, including non-cooperative static games and differential games, applied in this research project.

2.4.1 Non-cooperative Static Games

In non-cooperative static games, each player chooses their strategies simultaneously. Non-cooperative static games aim to seek a rational analysis regarding how the game will be played. A game in the normal form consists of *players* (indexed by $i = 1, ..., n$), *strategies* ($x_i,\ i = 1, ..., n$), and *payoffs*, $\pi_i(x_1, x_2, ..., x_n),\ i = 1, ..., n$. The solution concept for the non-cooperative games was formally introduced by John Nash (1950). As a pioneer, Parlar (1988) [Par88] analyzed the newsvendor problem using a game theory framework. Next, we briefly introduce several basic definitions based on the research work of Cachon [Cac03].

Definition 1. *Given an n-player game, player i's best response to strategies x_{-i} of the other players is the strategy x_i^* that maximizes player i's payoff $\pi_i(x_i, x_{-i})$:*

$$x_i^*(x_{-i}) = \arg\max_{x_i} \pi_i(x_i, x_{-i}). \tag{2.1}$$

Definition 2. *An outcome $(x_1^*, x_2^*, ..., x_n^*)$ is a Nash equilibrium of the game if x_i^* is a best response to x_{-i}^* for all $i = 1, 2, ..., n$.*

A Nash equilibrium is as a *fixed point* of the best response mapping. The Nash equilibrium indicates that no player is willing to deviate from their strategy. Moreover, the Nash equilibrium must satisfy the system of equations $\partial\pi_i/\partial x_i = 0$, all i. Fixed point theorems (e.g., Brouwer, Kakutani and Tarski) can be used to identify the existence of an equilibrium.

Definition 3. *A twice continuously differentiable payoff function $\pi_i(x_1, ..., x_n)$ is supermodular (submodular) iff $\partial^2\pi_i/\partial x_i \partial x_j \geqslant 0$ ($\leqslant 0$) for all x and all $j \neq i$. The game is called supermodular iff the players' payoffs are supermodular.*

The theory of supermodular games is introduced by Topkis [Top98]. Supermodularity indicates complementarity between two strategies. In a supermodular game, there exists at least one Nash equilibrium. In addition, the uniqueness of equilibrium is worthy studying to avoid ambiguity. Several alternative methods can be applied to solve this issue, including algebraic argument, contraction mapping argument, univalent mapping argument and index theory approach. In game models analysis, especially the non-cooperative supply chain models, meaningful managerial implications can be obtained by comparative statics, which is concerned with the dependence of equilibrium strategies on some parameters. Supermodular games approach is a more convenient method for comparative.

2.4.2 Differential Games

As the branch of dynamic games, the development of differential games is based on the Optimal Control Theory (Pontryagin et al. [Pon62]) and Dynamic Programming (Bellman [Bel57]) by incorporating strategic behavior. Differential games aim to investigate interactive decisions over time. Dockner et al. [Doc00] surveyed applications of noncooperative differential games in economics and management science. The open-loop equilibria in nonzero-sum deterministic differential games were firstly studied by Berkovitz [Ber64] and Ho et al. [Hoy65]. Later on, The open-loop and feedback Nash equilibria in nonzero-sum deterministic differential games were first analyzed by Case [Cas67, Cas69] and Starr and Ho [Sta69a, Sta69b]. Basar [Bas77a, Bas77b, Bas80] was a pioneer to study explicit results for stochastic quadratic differential games. Regarding cooperative stochastic differential games in recent work, Yeung and Petrosyan [Yeu04] developed a generalized theorem focusing on subgame-consistent solutions. Yeung and Petrosyan

[Yeu06] dealed with the theory and applications of cooperative stochastic differential games. Next, the main concepts regarding differential games are introduced based on the research work of Yeung and Petrosyan [Yeu06].

In a differential game with two players with its control $\mu_i(t)$, the objective of a supplier is to maximize its payoff function π_i

$$\max_{\mu_i(t)} \pi_i(\mu_i, \mu_j) = \max_{\mu_i(t)} \int_0^T f_i(t, x_i(t), x_j(t), \mu_i(t), \mu_j(t))dt, \tag{2.2}$$

where $x_i(t)$ is a state variable to describe the state of the system. The state of system is formulated as the differential equation

$$\dot{x}_i(t) = g_i(t, x_i(t), x_j(t), \mu_i(t), \mu_j(t)), \tag{2.3}$$

and the initial condition is assumed as $x_i(t_0) = x_{i0}$.

Definition 4. *The 2-tuple (ϕ_1, ϕ_2) of functions $\phi_i : [0, T\rangle \longmapsto \mathbb{R}^2$, $i \in 1, 2$, is called an open-loop Nash equilibrium if, for each $i \in 1, 2$, an optimal control path $\mu_i(\cdot)$ of the Equations (2.2) and (2.3) exists and is given by the open-loop strategy $\mu_i(t) = \phi(t)$.*

Definition 5. *The 2-tuple (ϕ_1, ϕ_2) of functions $\phi_i : [0, T\rangle \longmapsto \mathbb{R}^2$, $i \in 1, 2$, is called a Markovian Nash equilibrium if, for each $i \in 1, 2$, an optimal control path $\mu_i(\cdot)$ of the Equations (2.2) and (2.3) exists and is given by the Markovian strategy $\mu_i(t) = \phi(x_i(t), x_j(t), t)$.*

Based on the definitions 4 and 5, the open-loop Nash equilibrium indicates that the control of each player is only a function a time, whereas a Markovian Nash equilibrium indicates that the control of each player is a function of state variables and time.

2.5 Summary

On the basis of the research background of this project, this chapter elucidated the related literature review from three aspects, involving (i) sustainable supply chain management, (ii) green procurement in operations research, (iii) carbon emissions in operations management. Some noteworthy remarks concerning the aforementioned reviews can be summarized as follows.

1. By investigating relationships amongst the higher impact papers, Fahimnia et al. [Fah15] addressed the current situation of GSCM. First, the geographic dispersion of papers showed that Europe has the greatest output followed by North America. Currently, the growth trend of research work have occurred in the Asia area. Second, sub-supplier management and behavioral/individual issues in sustainable supply chains, and barriers and enablers evaluation of sustainable supply chain implementations are new research trends. In addition, some weaknesses in this field have also been identified. This field is dominated by teams of academic scholars. A stagnant view of the sustainable supply chain management discipline was provided by a small number of scholars. Overall, the GSCM field is still growing and the opportunities for future research focusing on modeling perspectives based on the practical applications are apparent.

2. With respect to the OR models which are applied to analyze the issue of green procurement, the aforementioned analyses show that integrated models from the current research trend in green supplier evaluation and selection. The main reasons are as follows. Firstly, the traditional individual multi-criteria decision models, such as MOP, AHP, ANP, have the characteristic of subjective preference. Thus, some additional methods need to be integrated to revise or overcome the subjective preference. Secondly, the computation processes of OR models, such

as ANP, mathematical programming models, are very complicated. The artificial intelligence methods, such as ANN, GA, and Tabu-Search-based algorithm, can effectively integrate with these OR models to get optimal solutions.

3. Most of the literature describes the issue of sustainable operations management, only starting from the viewpoint of a single firm level, that is, the behavior/strategies of competitors are neglected. This is the fundamental reason why the non-cooperative game theory models are applied in this project to analyze operations management issues under carbon emission regulations. By contrast, the advantages of game theory include (1) the interaction behaviors between players can be perfectly presented, (2) the general decisions can be determined for two or multiple players. By adopting non-cooperative game models, this project not only focuses on optimizing the payoff of a profit-maximization firm, but also aims to analyze how to select reasonable procurement strategies in response to its competitors under the carbon emission regulations and the constraint of uncertainty.

In the following chapters, non-cooperative game models will be developed to illustrate three issues under carbon emission regulations. The Nash equilibrium outcomes of game models will be analyzed based on two static game models and a dynamic game model with complete information and asymmetric information.

Chapter 3

Sourcing Strategy Analysis under Carbon Emission Regulations

3.1 Introduction

In this chapter, the research work focuses on modeling and analyzing decisions that can guide manufacturers into adopting flexible profit-maximization strategies under two types of carbon emission regulations, i.e., the emissions trading mechanism and the carbon tax scheme. That is, in the face of these two types of the regulations, how do manufacturers adopt appropriate sourcing strategies by characterizing the equilibrium outcome from the perspective of sustainable operations management? In addition, the decision of relocation for the manufacturers to comply with global differences in carbon emissions regulations is analyzed.

A significant problem in the current business world is to establish a sustainable development mode to improve companies' social responsibility. From the environmental protection perspective, reducing carbon emissions is a critical goal, especially for the manufacturing industry in general, the electrical and electronics industries in particular. Therefore, a series of regulations have been designed and implemented to curb GHG emissions. For example, in 2013, to address the increasing pressures of GHG emissions from the electrical and electronics industries, the International Organization for Standardization (ISO) established standard ISO 14067, which addressed the details of the requirements and guidelines for quantifying the carbon footprint of products based on life cycle assessment [Int13]. To enhance products' competitive ability, in Asian regions, electronic manufacturers have developed and implemented carbon footprint and labeling schemes for their products. In this way, Samsung and LG have developed private databases to collect emissions information from their suppliers and manufacturing processes; this is a better way to implement supply chain carbon management [Gre15]. At present, an increasing number of manufacturing companies have begun to realize the importance of the environmental level of products in China, particularly in Hong Kong and Shenzhen. These firms cooperate with universities or consulting companies in evaluating products' carbon footprint. For example, Shenzhen Sunshine Circuit Technology Co., Ltd. received the verification statement for their products' carbon footprint in November 2014 [Pro14].

However, a manufacturer with a carbon footprint certificate may still fail to compete with its competitors. In addition to the environmental factor, procurement cost is another critical part of manufacturers' total cost. Should a manufacturer cooperate with a greener supplier with eco-products or a traditional supplier with a lower price? To simultaneously achieve the goals of both profit maximization and GHG emissions minimization, manufacturers must adjust their procurement strategies under different carbon emission regulations and market-oriented competition, which is the motivation of this research project. In addition, the research work in this chapter aims to analyze the competition and coordination issues between manufacturers at the peer level. That is, the research work focuses on studying how strategies adopted by manufacturers are constrained by different carbon emissions regulations.

The cap-and-trade mechanism is essentially an economic incentive method to encourage agents to adjust their operational decisions and strategies for simultaneously reducing GHG emissions and achieving their goal of profit-maximization. Under the cap-and-trade mechanism, a manufacturer should balance its emission allowances before production. That is, if the amounts of emissions from production processes exceed emission allowances, the manufacturer needs to buy quotas from the market; if the manufacturer has abundant allowances, the manufacturer can then sell these quotas to the market or to other firms. This scenario is more complicated for manufacturers to make decisions in an oligopoly market.

With respect to the analysis of sourcing strategies, from an empirical study viewpoint, Hoetker et al. [Hoe07] analyzed how three aspects of a supplier's relationship with its customers affect the supplier's survival. Zhang et al. [Zha10] studied a dynamic adverse selection model for a scenario in which the supplier sells to a downstream retailer under asymmetric inventory information. Beginning from the cooperation viewpoint, Yin [Yin10] studied the case of alliance among perfectly complementary suppliers in a price-sensitive assembly system. Li et al. [Lih13] studied a repeated game between a manufacturer and two competing suppliers. A novel fixed-point analysis method was developed to characterize the structure of the optimal contract. Wu and Zhang [Wux14] examined sourcing from overseas or from the home country and how it can affect the trade-off of a single firm's decision. The Basyesian Nash equilibrium concept was applied to analyze the result of the game model because firms can observe only private signals of demand.

This chapter is at the intersection of three research streams, including green procurement, applications of carbon emission regulations in operations management, and analysis of sourcing strategies. The game model in this chapter is based on Cournot competition analysis on the equilibrium strategy and optimal sourcing quantity adopted by a manufacturer constrained by carbon emission regulations and with uncertainty information. First, this chapter describes competition between manufacturers at the peer-level under the constraint of carbon emission regulations. Second, how the two types of regulations, including the emissions trading mechanism and carbon tax scheme, affect the equilibrium outcome of the sourcing game is analyzed in detail. Third, this chapter analyzes the relocation issue for manufacturers or company(or factories) acquisitions with better production technologies when facing global differences in carbon emission regulations.

The main objective of this chapter is to attain a comprehensive understanding on how carbon emission regulations affect the operational strategies of agents in a manufacturing industry. We develop a game model with two manufacturers who can select two types of suppliers. One of the suppliers is called the traditional supplier who provides a lower cost but higher emissions; the other is called the greener supplier who provides a higher cost but lower emissions. The model focuses on the analysis of the sourcing order quantities of competing manufacturers from the two types of suppliers.

In this chapter, based on the emissions trading mechanism, the payoff of manufacturers involve emissions trading cost, production cost, and sales revenue. First, a base case of the model with deterministic demand and emission allowances is analyzed. Then, this issue under the uncertainty scenario is further examined. The structural properties of the payoff functions, the existence, and the uniqueness of equilibrium analysis of the game model are discussed in detail. Based on the equilibrium conditions of the sourcing game, the optimal ordering quantity and the optimal market clearing price are derived. The issue of how the interaction of trading prices and the emissions-related cost affects the equilibrium outcome of manufacturers, including cost-effective and environmental trade-offs, is further analyzed. Boundary conditions of the equilibrium that can assist manufacturers in selecting the appropriate sourcing strategy and deciding the optimal sourcing order quantity are discussed.

In addition, three possible extensions of the sourcing game model are studied. In the first,the basic model is extended to include multiple competitors. The equilibrium outcome for the scenario with multiple competitors is analyzed. In the second extension, how the carbon tax scheme affects the equilibrium of the sourcing game is studied. Two types of model structures of the carbon tax are analyzed, and the boundary conditions are derived. Finally, the conditions of manufacturers' relocation issue are analyzed, which is constrained by the two types of carbon emissions regulations.

The remainder of this chapter is organized as follows. Under the emissions trading mechanism, in Section 3.2, the basic model setting and the payoff matrix for both scenarios of certainty and uncertainty are described. In addition, the structural properties of the payoff functions are analyzed. The existence and uniqueness of the equilibrium outcome for the sourcing game are derived. For the uncertainty scenario, how trading prices and emissions-related cost affect equilibrium outcomes are characterized. Section 3.3 extends the analysis to (i) multiple competitors; (ii) the impact of the carbon tax scheme; and (iii) the comparison of carbon emissions regulations. Section 3.4 illustrates managerial implications. Section 3.5 gives the summary of this chapter.

3.2 Model Setup

3.2.1 General Description

We consider two manufacturers (1 and 2) that provide substitutable products in the same market. Both manufacturers need to design and produce products to satisfy different types of consumer demands (i.e., greener products or less-green products). Thus, the manufacturers must adopt appropriate technologies to produce and cooperate with reliable suppliers. For the model analysis, we focus on the supplier rather than on the technological decision. There exist two types of suppliers: greener and traditional. A greener supplier can provide raw materials with a lower carbon footprint and a high unit price; a traditional supplier provides raw materials with high carbon emissions and a low unit price. Manufacturers can adopt a greener strategy (i.e., sourcing from a greener supplier) or a traditional strategy (i.e., sourcing from a traditional supplier).

The manufacturers must make procurement decisions before the beginning of the next operation period to satisfy the random market demand. We employ a Cournot competition game model that can be applied to help the manufacturers in analyzing procurement decisions under random demand. Let q_i $(i = 1, 2)$ be the ordering quantities of the two manufacturers and the market clearing price be $p = a - (q_1 + q_2)$, where a is the intercept of the inverse demand function. In this chapter, we focus on a one-short Cournot game, while several papers studied long-term relationships, e.g., Ji et al. [Jip15].

The two types of suppliers, a greener supplier and a traditional supplier, are denoted by S_g and S_t, where the subscripts g and t stand for greener and traditional suppliers, respectively. Let c_g and c_t be the procurement costs (or prices) which are offered by suppliers S_g and S_t with e_g and e_t, the unit of emissions (e.g., CO_2) rate of raw materials from S_g and S_t. Without loss of generality, assume $c_g > c_t$ and $e_g < e_t$ such that neither supplier dominates the other with respect to either the procurement price or the emissions amount. In addition, manufacturers are constrained by the carbon emissions regulations; therefore, we first aim to analyze the game model under the emissions trading scheme (or the cap-and-trade scheme). Under the emissions trading scheme, manufacturers can buy or sell the emission allowances in the carbon trading market. Therefore, manufacturers should balance expenditures between the procurement cost and the emissions cost (to buy or sell emission allowances).

Taking EU ETS as a practical example, the buying and selling price of the emissions allowances are denoted by p_b and p_s, where $0 < p_s \leqslant p_b$. For a certain period, let C_i be the level of emissions allowances of manufacturer i, for $i = 1,\ 2$. The value of C_i is determined by the trading prices and the emissions amount incurred during the manufacturing processes. If C_i is greater than the production emissions, then the manufacturers can sell the surplus of emissions allowances to the carbon-trading market; otherwise, the manufacturers must buy deficits as emission allowances from the market. In addition, assume the trading prices are exogenous.

TABLE 3.1: Payoff matrix of manufacturers

		Manufacturer 1	
		S_g	S_t
Manufacturer 2	S_g	$(\Pi_{1,gg}, \Pi_{2,gg})$	$(\Pi_{1,tg}, \Pi_{2,tg})$
	S_t	$(\Pi_{1,gt}, \Pi_{2,gt})$	$(\Pi_{1,tt}, \Pi_{2,tt})$

Based on the above analysis, the payoff matrix of the game model between the two manufacturers can be characterized as in Table 3.1. There are four possible equilibrium combinations for the game model: (S_g, S_g), (S_g, S_t), (S_t, S_g), and, (S_t, S_t). The competitor of manufacturer i in this model is denoted by using subscript $-i$, the strategy space of manufacturer $-i$ is denoted by $k \in \{g, t\}$. The expected profit function, e.g., $\Pi_{i,gt}$, means the expected profit of manufacturer i who purchases from the greener supplier S_g, when manufacturer $-i$ sources from the traditional supplier S_t. Without considering demand uncertainty, the expected profit function of manufacturer i sourcing from supplier j can be formulated as

$$\Pi_{i,jk} = pq_i - p_b(e_j q_i - C_i)^+ + p_s(C_i - e_j q_i)^+ - c_j q_i, \tag{3.1}$$

where $(x)^+ := \max\{0, x\}, i = 1, 2,$ and $j, k \in \{g, t\}$.

Proposition 3.1. *Given the demand and emission allowances available,*
(i) if emission allowances are abundant, (S_t, S_t) *is the unique equilibrium and* $q_1^* = q_2^* = (a - p_s e_t - c_t)/3$, *and* $\Pi_{1,tt}^* = \Pi_{2,tt}^* = [(a - p_s e_t - c_t) + 9p_s C_i]/9$, $i = 1, 2$*;*
(ii) if emission allowances are inadequate, (S_g, S_g) *is the unique equilibrium and* $q_1^* = q_2^* = (a - p_b e_g - c_g)/3$, *and* $\Pi_{1,gg}^* = \Pi_{2,gg}^* = [(a - p_b e_g - c_g) + 9p_b C_i]/9, i = 1, 2.$

Proof of Proposition 3.1.
(i) Taking the first order derivative of manufacturer i's payoff function (3.1) with respect to q_i when emission allowances are abundant, we can observe

$$\frac{\partial \Pi_{i,tt}}{\partial q_i} = a - q_{-i} - p_s e_t - c_t - 2q_i. \tag{A.1}$$

If manufacturer $-i$ keeps its sourcing quantity q_{-i}, then the optimal solution for manufacturer i is

$$q_i = \frac{a - p_s e_t - q_{-i} - c_t}{2} \tag{A.2}$$

Similarly, if manufacturer i keeps its sourcing quantity q_i, then the optimal solution for the manufacturer $-i$ is

$$q_{-i} = \frac{a - p_s e_t - q_i - c_t}{2} \tag{A.3}$$

Let q_i^* and q_{-i}^* maximize $\Pi_{i,tt}$ and $\Pi_{-i,tt}$, respectively, then (q_i^*, q_{-i}^*) must be the equilibrium solution.

$$q_i^* = q_{-i}^* = \frac{a - p_s e_t - c_t}{3} \tag{A.4}$$

The profit of manufacturer i is

$$\Pi_{i,tt}^* = \frac{(a - p_s e_t - c_t)^2 + 9 p_s C_i}{9} \tag{A.5}$$

(ii) The proof for the second item of Proposition 3.1. is similar with the aforementioned part, therefore, the proof is omitted.

Q.E.D

When demand is available, the two manufacturers source from a single type of supplier. With respect to cost efficiency, if the manufacturers have sufficient emission allowances, (S_t, S_t) is the unique sourcing equilibrium; otherwise, the manufacturers will purchase emission allowances, and (S_g, S_g) is the unique sourcing equilibrium. We are also interested in understanding the impacts of the uncertain market demand and emission allowances of the manufacturers under different trading conditions. Therefore, in the following sections, the uncertainty scenario is analyzed in detail.

3.2.2 The Model under Uncertainty

With respect to the sales market for manufacturers, let D_i denote the random demand of manufacturer i, F_i and f_i be the cumulative distribution function (cdf) and the probability density function (pdf) of D_i, respectively. Under the emissions trading scheme, each manufacturer is constrained by the rules of the carbon market because, to obtain emissions permits, manufacturers need to determine their emissions allowances dynamically based on the variance in trading prices. In this section, C_i is a random variable to describe the random values of the emission allowances of manufacturer i. Let G_i and g_i be the cdf and the pdf of C_i, respectively.

Manufacturers play a competition game under both uncertainty of demand and emission allowances. Therefore, the expected profit function of manufacturer i can be formulated as

$$\Pi^U_{i,jk}(q_i|q_{-i}, C_i) = \mathbb{E}[p(D_i \wedge q_i) - p_b(e_j q_i - C_i)^+ + p_s(C_i - e_j q_i)^+ - c_j q_i], \quad (3.2)$$

where $(x \wedge y) := \min\{x, y\}$, $i = 1, 2$, $j, k \in \{g, t\}$, and $\mathbb{E}(\cdot)$ is the expectation operator. In Equation (3.2), denoting the superscript $'U'$ be the expected payoff function of manufacturer i, who adopts strategy jk under the uncertainty scenario. The sales revenue, the first term in Equation (3.2), is given by $p(D_i \wedge q_i)$, the next two terms are the expected emissions trading costs, and the last part is the production cost. The manufacturers are willing to adopt the optimal strategy to maximize their payoff; that is, the manufacturers will cooperate with appropriate types of suppliers that can minimize their operation cost in a competitive environment.

3.2.3 Equilibrium Analysis

In this section, the equilibrium for the sourcing game under uncertain demand and emission allowances is analyzed. To unveil the structural properties of payoff function (3.2), concavity and modularity analyses are the main technical approach used in this chapter. The following propositions disclose the significant properties of payoff function (3.2), which can provide the fundamental conditions of equilibrium analysis.

Proposition 3.2. *Given uncertain demand and emission allowances,*

(i) the payoff function of manufacturer i*,* $\Pi^U_{i,jk}(q_i|q_{-i}, C_i)$*, is a strictly concave function in* q_i*;*

(ii) a positive order quantity will be chosen by manufacturer i *if and only if* $a > q_{-i} + c_j - p_s e_j$*; Otherwise,* $q_i = 0$*.*

Proof of Proposition 3.2.

(i) Taking the second order derivate of manufacturer i's payoff function (3.2) with respect to q_i, we get

$$\frac{\partial^2 \Pi^U_{i,jk}(q_i \mid q_{-i}, C_i)}{\partial q_i^2} = -2[1 - F_i(q_i)] - (a - q_i - q_{-i}) f_i(q_i) - (p_b - p_s) e_j^2 g_i(e_j q_i) < 0. \tag{A.6}$$

Thus, $\Pi^U_{i,jk}(q_i \mid q_{-i}, C_i)$ is concave in q_i.

(ii) Taking the first order derivative of manufacturer i's payoff function (3.2) with respect to q_i, we get

$$\begin{aligned} \frac{\partial \Pi^U_{i,jk}(q_i \mid q_{-i}, C_i)}{\partial q_i} =& (a - q_i - q_{-i})[1 - F_i(q_i)] - \mathbb{E}(D_i \wedge q_i) \\ & - e_j(p_b - p_s) G_i(e_j q_i) - p_s e_j - c_j. \end{aligned} \tag{A.7}$$

Following the above result in Proposition 3.2 (i), $\Pi^U_{i,jk}(q_i \mid q_{-i}, C_i)$ can be maximized with a positive order quantity q_i if and only if (A.7) is a positive number when $q_i = 0$. Thus, plugging $q_i = 0$ into Equation (A.7), we can get the condition $a > q_{-i} + c_j - p_s e_j$.

Q.E.D

Proposition 3.2 (i) demonstrates that there exists a maximal point of the expected payoff function (3.2) with respect to the order quantity q_i. In addition, Proposition 3.2 (ii) indicates that $q_i + c_j - p_s e_j$ is the lowest level (the threshold) for manufacturer i to play the game with its competitor (or to enter the product market). An interesting result can be observed; that is, while the threshold is independent of any parameter of manufacturer i's competitor, it is determined predominantly by the supplier's type. The closed form of the optimal order quantities (or the equilibrium) is derived in the following propositions. Manufacturer i prefers to select supplier S_g rather than supplier S_t if manufacturer i prepares to enter the product market with a fixed production capacity because $c_g > c_t$ and $e_g < e_t$. That is, the threshold of entering the product market will be greater if manufacturer i cooperates with supplier S_g. In addition, manufacturer i will produce nothing (or avoid entering the product market) if the threshold cannot be satisfied.

Proposition 3.3. *The characteristic of the payoff function and the equilibrium of the game are given as follows:*

(i) the payoff function of manufacturer i is submodular in (q_i, q_{-i});

(ii) there exists a pure Nash equilibrium strategy for the souring game. The equilibrium point (q_i^*, q_{-i}^*) satisfies

$$(a - q_i^* - q_{-i}^*)[1 - F_i(q_i^*)] + e_j p_s = \mathbb{E}(D_i \wedge q_i^*) + e_j(p_s + p_b)G_i(e_j q_i^*) + c_j. \quad (3.3)$$

Proof of Proposition 3.3.

In view of Topkis [Top98], it is equivalent to verify that the cross partials of $\Pi_{i,jk}$ is non-positive.

(i) The cross partial derivative of $\Pi_{i,jk}$ with respect to q_i^* and q_{-i}^* is

$$\frac{\partial^2 \Pi_{i,jk}^U(q_i \mid q_{3-i}, C_i)}{\partial q_i \partial q_{-i}} = F_i(q_i) - 1 \leq 0. \tag{A.8}$$

Thus, $\Pi_{i,jk}^U(q_i \mid q_{-i}, C_i)$ is submodular in $(q_i,\, q_{-i})$.

(ii) The result in Proposition 3.3 (i) shows that this game model is a submodular game. Therefore, the existence of the equilibrium can be satisfied. In addition, with respect to the concave characteristic of the payoff function $\Pi_{i,jk}^U(q_i \mid q_{-i}, C_i)$, the equilibrium point (q_i^*, q_{-i}^*) can be solved by letting the first order derivative of the payoff function (3.2) be zero. That is, $(q_i^*,\, q_{-i}^*)$ should satisfy Equation (A.9).

$$(a - q_i - q_{-i})[1 - F_i(q_i)] = e_j(p_b - p_s)G_i(e_j q_i) + \mathbb{E}(D_i \wedge q_i) + p_s e_j + c_j. \tag{A.9}$$

Q.E.D

Proposition 3.3 (i) shows the submodularity of the payoff function (3.2), and this property can also hold with given deterministic demand and emission allowances. It is easy to see that the cross partial derivative of the payoff function (3.1) with respect to q_i and q_{-i} is negative. The submodularity of $\Pi_{i,jk}^U(q_i|q_{-i}, C_j)$ demonstrates that manufacturer i should increase the sourcing order quantity when its competitor $-i$ decreases the order quantity. Following the results of Milgrom and Roberts [Mil90], the pure Nash equilibrium of the sourcing game under the emissions trading scheme can be observed. In addition, any pure Nash equilibrium is also a mixed Nash equilibrium and a correlated equilibrium. Considering the concavity and submodularity of the payoff function (3.2), the equilibrium point

(q_i^*, q_{-i}^*) can be derived by the first order derivative of the payoff function (3.2). However, the characteristic of the uncertainties of both the demand and emission allowances will generate multiple equilibria for the sourcing game under the two different emissions trading scheme.

Regarding the aforementioned characteristics of the payoff function (3.2), the existence of equilibrium in the game model is proven. Therefore, the following subsections analyze the details of the equilibrium outcome and the optimal order quantity of the game model under the two different trading scenarios.

3.2.4 Decisions with $p_s = p_b = \overline{p}$

This section first analyzes whether the buying and the selling prices of emission allowances will become equal, i.e., $p_s = p_b = \overline{p}$, when the bid-ask price spreads and the transaction costs are ignored (Gong and Zhou [Gon13]). The result of Proposition 3.2 shows that manufacturer i prefers to select supplier S_g rather than supplier S_t when (s)he prepares to enter the product market. This result intuitively implies that strategy S_g dominates strategy S_t. However, this result does not always hold true, as the analysis shows that the equilibrium is changing with respect to the trading price $\overline{p}$.

For this emissions trading scenario, only one trading price is considered; therefore, the payoff function of manufacturer i can be simplified as follows.

$$\Pi_{i,jk}^0(q_i|q_{-i}, C_i) = \mathbb{E}[p(D_i \wedge q_i) - \overline{p}(e_j q_i - C_i) - c_j q_i]. \tag{3.4}$$

Proposition 3.4. *If* $p[1-F_i(q_i^*)]-\mathbb{E}(D_i \wedge q_i^*)-c_g > 0$, *and* $c_g/c_t > G_i(e_t q_i)/G_i(e_g q_i)$, *the characteristics of thresholds of the boundary conditions for the equilibrium of* *the sourcing game are given as follows:*

(i) the threshold δ_j is submodular in $(-c_j, e_j)$, where

$$\delta_j = \frac{p[1 - F_i(q_i^*)] - \mathbb{E}(D_i \wedge q_i^*) - c_j}{G_i(e_j q_i^*)}, j \in t, g; \tag{3.5}$$

(ii) the additional production cost per allowance saved ε is supermodular in (c_g, e_g), and ε is submodular in (c_t, e_t).

Proof of Proposition 3.4.

(i) Based on Equation (3.4), we can get its first order derivative as

$$\frac{\partial \Pi_{i,jk}^0(q_i \mid q_{-i}, C_i)}{\partial q_i} = (a - q_i - q_{-i})[1 - F_i(q_i)] - (\mathbb{E}(D_i \wedge q_i) - \overline{p} G_i(e_j q_i) - c_j. \tag{A.10}$$

Then, by checking the second order derivate,

$$\frac{\partial^2 \Pi_{i,jk}^0(q_i \mid q_{-i}, C_i)}{\partial {q_i}^2} = -p f_i(q_i) - 2[1 - F_i(q_i)] - \overline{p} e_j g_i(e_j q_i) \leq 0. \tag{A.11}$$

The concavity of the payoff function (3.4) implies that $q_i^* (q_i^* \geqslant 0)$ can maximize $\Pi_{i,jk}^0(q_i \mid q_{-i}, C_i)$ if and only if (A.9) is a positive number when $q_i^* = 0$. Then, $\overline{p}$ can be observed as

$$\overline{p} < \delta_j, \tag{A.12}$$

where

$$\delta_j = \frac{p[1 - F_i(q_i^*)] - \mathbb{E}(D_i \wedge q_i^*) - c_j}{G_i(e_j q_i^*)} \tag{A.13}$$

Since $e_t > e_g$ and the cumulative distribution function of the carbon allowances, $G()$, is non-decreasing, then $G(e_t q_i^*) \geqslant G(e_g q_i^*)$.

Taking the cross partial derivative of Equation (A.13) with respect to $-c_j$ and e_j, respectively, we can get

$$\frac{\partial^2 \delta_j}{\partial(-c_j)\partial e_j} = -\frac{q_i g_i(e_j q_i)}{G_i^2(e_j q_i)} < 0. \tag{A.14}$$

In addition,

$$\begin{aligned}\delta_t - \delta_g &= \frac{p[1-F_i(q_i^*)] - \mathbb{E}(D_i \wedge q_i^*) - c_t}{G_i(e_t q_i^*)} - \frac{p[1-F_i(q_i^*)] - \mathbb{E}(D_i \wedge q_i^*) - c_g}{G_i(e_g q_i^*)} \\ &= \frac{[p[1-F_i(q_i^*)] - \mathbb{E}(D_i \wedge q_i^*)][G_i(e_g q_i) - G_i(e_t q_i)] + c_g G_i(e_t q_i) - c_t G_i(e_g q_i)}{G_i(e_t q_i^*) G_i(e_g q_i^*)} \\ &< 0.\end{aligned} \tag{A.15}$$

(ii) Define $\varepsilon = \frac{c_g - c_t}{e_t - e_g}$.

Taking the cross partial derivative of ε with respect to c_g and e_g, we can get

$$\frac{\partial^2 \varepsilon}{\partial c_g \partial e_g} = \frac{1}{(e_t - e_g)^2} > 0. \tag{A.16}$$

Taking the cross partial derivative of ε with respect to c_t and e_t, we can get

$$\frac{\partial^2 \varepsilon}{\partial c_t \partial e_t} = -\frac{1}{(e_t - e_g)^2} < 0. \tag{A.17}$$

Q.E.D

Proposition 3.4 aims to analyze how the unit procurement cost (c_j) and the unit emissions rate (e_j) influence δ_j and ε. The first item of Proposition 3.4 indicates that δ_t is no larger than δ_g because $-c_t > -c_g$ and $e_t > e_g$. The second item implies that ε is smaller than δ_t. Therefore, the entire boundary's impacts on $\overline{p}$ can be established; that is, $\varepsilon < \delta_t < \delta_g$, which is the precondition to identify the equilibrium outcome for the sourcing game with the same trading price.

Proposition 3.5. *On the basis of Proposition 3.4, the equilibrium of the sourcing game can be observed as follow:*

(i) if $\delta_t \leqslant \overline{p} \leqslant \delta_g$*, manufacturer* i *only cooperates with supplier* S_g*, the unique equilibrium strategy of the game model is* (S_g, S_g) *and the equilibrium outcome is* (q_i^*, q_{-i}^*)*, where*

$$q_{-i,S_g}^* = a - q_{i,S_g}^* - \frac{\mathbb{E}(D_i \wedge q_{i,S_g}^*) + \overline{p}G_i(e_g q_{i,S_g}^*) + c_g}{1 - F_i(q_{i,S_g}^*)}; \tag{3.6}$$

(ii) if $\varepsilon < \overline{p} < \delta_t$*, manufacturer* i *can cooperate with both supplier* S_t *and supplier* S_g*, but the unique equilibrium strategy of the game model is* (S_g, S_g) *and the equilibrium outcome is* $(q_{i,S_g}^*, q_{-i,S_g}^*)$*;*

(iii) if $\overline{p} < \varepsilon < \delta_t$*, manufacturer* i *can cooperate with both supplier* S_t *and supplier* S_g*, but the unique equilibrium strategy of the game model is* (S_t, S_t) *and the equilibrium outcome is* $(q_{i,S_t}^*, q_{-i,S_t}^*)$*, where*

$$q_{-i,S_t}^* = a - q_{i,S_t}^* - \frac{\mathbb{E}(D_i \wedge q_{i,S_t}^*) + \overline{p}G_i(e_t q_{i,S_t}^*) + c_t}{1 - F_i(q_{i,S_t}^*)}; \tag{3.7}$$

(iv) if $\overline{p} > \delta_g$*, manufacturer* i *will not select or cooperate with any suppliers;*

(v) on the basis of the equilibrium outcome (q_i^*, q_{-i}^*)*, the optimal market clearing price* (p^*) *is a supermodular function in* $\overline{p}$ *and* q_i^**, where*

$$p^* = \frac{\mathbb{E}(D_i \wedge q_i^*) + \overline{p}G_i(e_j q_i^*) + c_j}{1 - F_i(q_i)}. \tag{3.8}$$

Proof of Proposition 3.5.

In this proposition, we need to examine the equilibrium strategy by checking the different value of the profit function when manufacturer i fixes the strategy and manufacturer $-i$ adopts strategies S_t and S_g, respectively. In the following discussion, we take it that manufacturer i fixes its strategy as S_g as an example. When manufacturer i adopts strategy S_t, we just need to adjust the subscript of payoff function. The proof for manufacturer i's adopting S_t is similar to the following proof, therefore, we omit the proof for this part.

$$\begin{aligned}\Pi^0_{-i,gt} - \Pi^0_{-i,gg} =& \mathbb{E}[p(D_{-i} \wedge q_{-i}) - \overline{p}(e_t q_{-i} - C_{-i}) - c_t q_{-i}] \\ &- \mathbb{E}[p(D_{-i} \wedge q_{-i}) - \overline{p}(e_g q_{-i} - C_{-i}) - c_g q_{-i}] \\ =& \overline{p}(e_g - e_t)q_{-i} + (c_g - c_t)q_{-i}\end{aligned} \tag{A.18}$$

(i) If $\delta_t \leqslant \overline{p} \leqslant \delta_g$, then the concavity of the payoff function cannot be satisfied when manufacturer i selects supplier S_g. In this case, manufacturer i can only cooperate with supplier S_g, because Equation (A.12) should be satisfied when j is only equal to g. In addition, because $p[1 - F_i(q_i)] - \mathbb{E}(D_i \wedge q_i) > c_g$, $c_g > c_t$, $e_t - e_g > 1$, and, $G(\cdot) \in (0, 1)$, we can get $\varepsilon < \delta_t$. That is, $\varepsilon < \delta_t \leqslant \overline{p}$, where $\varepsilon = \frac{c_g - c_t}{e_t - e_g}$, and, $\Pi^0_{-i,gt} - \Pi^0_{-i,gg} < 0$, manufacturer $-i$ will adopt strategy S_g. Therefore, the equilibrium of the game model is (S_g, S_g), and the equilibrium point is $(q^*_{i,S_t}, q^*_{-i,S_g})$, where

$$q^*_{-i,S_g} = a - q^*_{i,S_t} - \frac{\mathbb{E}(D_i \wedge q^*_{i,S_t}) + \overline{p}G_i(e_g q^*_{i,S_t}) + c_g}{1 - F_i(q^*_{i,S_t})} \tag{A.19}$$

(ii) If $\varepsilon < \overline{p} \leqslant \delta_g$, then the concavity of the payoff function cannot be satisfied when manufacturer i cooperates with both supplier S_t and supplier S_g. Because $\overline{p}$ is larger than ε, then $\Pi^0_{-i,gt} - \Pi^0_{-i,gg} < 0$, thus manufacturer $-i$ will still adopt strategy S_g. If manufacturer $-i$ fixes strategy S_g, similarly, we can get $\Pi^0_{i,tg} - \Pi^0_{i,gg} < 0$. Therefore, the unique equilibrium strategy of the game model is (S_g, S_g), and the equilibrium points are $(q^*_{i,S_g}, q^*_{-i,S_g})$, where

$$q^*_{-i,S_g} = a - q^*_{i,S_g} - \frac{\mathbb{E}(D_i \wedge q^*_{i,S_g}) + \overline{p}G_i(e_g q^*_{i,S_g}) + c_g}{1 - F_i(q^*_{i,S_g})} \tag{A.20}$$

(iii) If $\overline{p} < \varepsilon < \delta_g$, then the concavity of the payoff function cannot be satisfied when manufacturer i cooperates with both supplier S_t and supplier S_g. Because $\overline{p}$ is smaller than ε, then $\Pi^0_{-i,gt} - \Pi^0_{-i,gg} > 0$, thus manufacturer $-i$ will adopt strategy S_t. If manufacturer $-i$ fixes strategy S_t, we can get $\Pi^0_{i,tt} - \Pi^0_{i,gt} > 0$. Therefore, the unique equilibrium strategy of the game model is (S_t, S_t), and the equilibrium points are $(q^*_{i,S_t}, q^*_{-i,S_t})$, where

$$q^*_{-i,S_t} = a - q^*_{i,S_t} - \frac{\mathbb{E}(D_i \wedge q^*_{i,S_t}) + \overline{p}G_i(e_t q^*_{i,S_t}) + c_t}{1 - F_i(q^*_{i,S_t})} \tag{A.21}$$

(iv) If $\overline{p} > \delta_g$, the concavity of the payoff function cannot be satisfied, so manufacturer i will not select or cooperate with any suppliers.

(v) Based on the above results of (q^*_i, q^*_{-i}), and $p = a - q_i - q_{-i}$, then, the optimal price of the product,

$$p^* = \frac{\mathbb{E}(D_i \wedge q^*_i) + \overline{p}G_i(e_t q^*_i) + c_t}{1 - F_i(q^*_i)} \tag{A.22}$$

We prove Proposition 3.5 (v) by examining the cross partial derivative of p^* with respect to $\overline{p}$ and q^*_i,

$$\frac{\partial^2 p^*}{\partial \overline{p} \partial q^*_i} = \frac{e_j g_i(e_j q_i) + f_i(q_i) G_i(e_j q_i)}{[1 - F_i(q_i)]^2} > 0. \tag{A.23}$$

Therefore, p^* is supermodular in $(\overline{p}, q_i^*)$.

Q.E.D

Based on the results of Proposition 3.4, Proposition 3.5 further discloses the optimal sourcing quantity and the corresponding equilibrium in response to the emissions trading scheme. We present an explanation for Proposition 3.5 as shown in Figure 3.1. The blue line and the dashed blue line in Figure 3.1 describe the profit of manufacturer 1 who adopts strategy S_g and S_t, respectively. The red line and the dashed red line indicate the profit of manufacturer 2 who adopts strategy S_g and S_t, respectively. In general, the equilibrium outcome and the sourcing strategy are determined by the boundary of $\overline{p}$ and the additional production cost per allowance saved (ε). In zone III, where $\overline{p}$ is in the boundary of (δ_t, δ_g), the unique equilibrium strategy is (S_g, S_g), and the mixed strategies (S_g, S_t) or (S_t, S_g) are not the equilibria. In zone II, although manufacturer i can select both suppliers S_t and S_g, parameter ε generates an impact on the equilibrium of the sourcing game when $\overline{p}$ is smaller than δ_t. If $\overline{p}$ is larger than ε, then both manufacturers will accept the strategy profile (S_g, S_g) because trading under this strategy profile can gain more profit; otherwise, if $\overline{p}$ is smaller than ε (in zone I), then (S_t, S_t) will be the unique equilibrium strategy of the game model. In addition, manufacturer i will not cooperate with any suppliers if $\overline{p}$ is out of the upper bound (δ_g). Proposition 3.5 (ii) and (iii) investigate predominantly how $\overline{p}$ and ε affect the unique equilibrium of the sourcing game when the buying and selling prices of the emission allowances are equal. In addition, Proposition 3.5 (v) implies that there exists an optimal matching between $\overline{p}$ and q_i^*. That is, this result can assist manufacturers in making appropriate pricing decisions, particularly for new product introduction, based on the trading price and production quantity of new products.

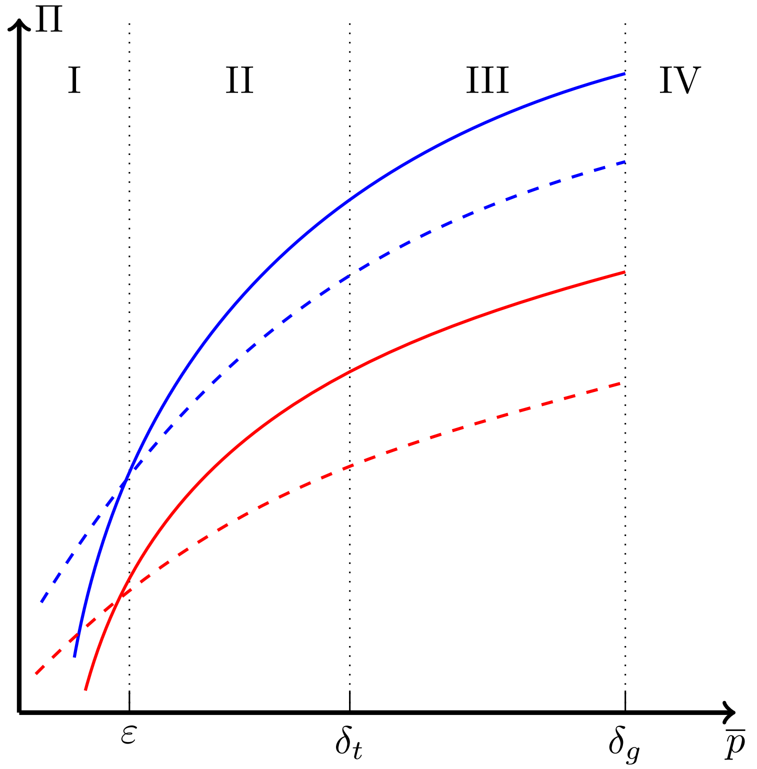


FIGURE 3.1: Diagram for the decision rule if $p_s = p_b = \overline{p}$

3.2.5 Decisions with $p_s < p_b$

In this subsection, the equilibrium outcome of the sourcing game under the scenario with $p_s < p_b$ is analyzed. The payoff function for this scenario is the same as Equation (3.2).

Proposition 3.6. *Given any $p_s < p_b$, the characteristics of the payoff function and the optimal sourcing strategy of manufacturer i are shown as follows:*

(i) $\Pi^U_{i,jk}(q_i, q_{-i}, C_i)$ is a submodular function in q_i and e_j;

(ii) if $\varepsilon < p_s < p_b$, the optimal strategy of manufacturer i is sourcing from supplier S_g and the unique equilibrium of the game model is (S_g, S_g);

(iii) if $p_s < p_b < \varepsilon$, the optimal strategy of manufacturer i is sourcing from supplier S_t, and the unique equilibrium of the game model is (S_t, S_t);

(iv) if $p_s \leqslant \varepsilon \leqslant p_b$, the optimal strategy of manufacturer i is S_t when manufacturer i has sufficient emission allowances, and the unique equilibrium of the game model

is (S_t, S_t); the optimal strategy of manufacturer i is S_g when manufacturer i's emission allowances are inadequate, and the unique equilibrium of the game model is (S_g, S_g);

(v) if manufacturers adopt strategy S_j, the equilibrium point is $(q^*_{i,S_j}, q^*_{-i,S_j})$, and the optimal market clearing price, p^*, is increasing in (p_b, p_s, e_j), where

$$q^*_{-i,s_j} = a - a^*_{i,S_j} - \frac{\mathbb{E}(D_i \wedge q^*_{i,S_j}) + (p_b - p_s)e_j G_i(e_j q^*_{i,S_j}) + p_s e_g + c_j}{1 - F_i(q^*_{i,S_j})}, \tag{3.9}$$

$$p^* = \frac{\mathbb{E}(D_i \wedge q^*_{i,S_j}) + (p_b - p_s)e_j G_i(e_j q^*_{i,S_j}) + p_s e_g + c_j}{1 - F_i(q^*_{i,S_j})}. \tag{3.10}$$

Proof of Proposition 3.6.

(i) We prove the submodularity by examining the cross partial derivative of the payoff function $\Pi^U_{i,jk}$ with respect to q_i and e_j, respectively.

$$\frac{\partial^2 \Pi^U_{i,jk}(q_i \mid q_{-i}, C_i)}{\partial q_i \partial e_j} = -(p_b - p_s)G_i(e_j q_i) - e_j q_i (p_b - p_s) g_i(e_j q_i) - p_s < 0. \tag{A.24}$$

Thus, the payoff function $\Pi^U_{i,jk}$ is submodular in (q_i, e_j).

For the following proof, we take it that manufacturer $-i$ fixes strategy S_g as an example. The optimal strategy of manufacturer i can be determined by comparing the profit functions.

$$\begin{aligned}\Pi^U_{i,tg} - \Pi^U_{i,gg} =& \mathbb{E}[p(D_i \wedge q_i) - p_b(e_t q_i - C_i)^+ + p_s(C_i - e_t q_i)^+ - c_t q_i] \\ &- \mathbb{E}[p(D_i \wedge q_i) - p_b(e_g q_i - C_i)^+ + p_s(C_i - e_g q_i)^+ - c_g q_i] \\ =& p_b \mathbb{E}[(e_g q_i - C_i)^+ - (e_t q_i - C_i)^+] + p_s \mathbb{E}[(C_i - e_t q_i)^+ \\ &- (C_i - e_g q_i)^+] + (c_g - c_t) q_i\end{aligned} \tag{A.25}$$

(ii) Case 1: $\varepsilon < p_s < p_b$.

If $p_b > \varepsilon$, then we can get $p_b(e_g - e_t)q_i + (c_g - c_t)q_i) < 0$. That is, $\Pi^U_{i,tg} < \Pi^U_{i,gg}$, and manufacturer i will adopt an optimal strategy S_g when the emission allowances of manufacturer i are inadequate. If $p_s > \varepsilon$, then the strategy S_g of manufacturer i will still be optimal when manufacturer i has sufficient emission allowances. When manufacturer i fixes the strategy as S_g, manufacturer $-i$ also adopts strategy S_g whether the emission allowances are sufficient or not. Therefore, (S_g, S_g) is an unique equilibrium of the game model under this condition.

(iii) Case 2: $p_s < p_b < \varepsilon$.

If $p_s < \varepsilon$, then we can get $p_s(e_g - e_t)q_i + (c_g - c_t)q_i) > 0$. That is, $\Pi^U_{i,tg} > \Pi^U_{i,gg}$, and manufacturer i will adopt the optimal strategy S_t when manufacturer i has sufficient emission allowances. If $p_b < \varepsilon$, then we can get the same result when the emission allowances of manufacturer i are inadequate, that is, manufacturer i will still cooperate with supplier S_t. When manufacturer i fixes the strategy S_t, manufacturer $-i$'s optimal strategy is S_g whether the emission allowances are sufficient or not. Thus, (S_t, S_t) is an equilibrium of the game model for this case.

(iv) Case 3: $p_s \leqslant \varepsilon \leqslant p_b$.

If $p_s \leqslant \varepsilon$, then we can get $p_s(e_g - e_t)q_i + (c_g - c_t)q_i) \geqslant 0$, that is, $\Pi^U_{i,tg} \geqslant \Pi^U_{i,gg}$, and the optimal strategy of manufacturer i is S_t when manufacturer i has sufficient emission allowances. We can get the symmetric result for manufacturer $-i$. Therefore, the strategy profile (S_t, S_t) is the unique equilibirum for this condition. If $\varepsilon \leqslant p_b$, then we can get $p_b(e_g - e_t)q_i + (c_g - c_t)q_i) \leqslant 0$, that is, S_g is the optimal strategy of manufacturer i when the emission allowances are inadequate. Manufacturer $-i$ will also adopt the strategy S_g in the same situation. Therefore, (S_g, S_g) is the unique equilibirum for this condition.

(v) Taking the first order derivative of manufacturer i's payoff function (2) with respect to q_i when strategy S_j is adopted, we can get

$$\frac{\partial \Pi^U_{i,jk}(q_i \mid q_{-i}, C_i)}{\partial q_i} = p[1-F_i(q_i)]-\mathbb{E}(D_i \wedge q_i)-(p_b-p_s)e_g G_i(e_g q_i)-p_s e_g-c_g. \quad \text{(A.26)}$$

Then, (q_i^*, q_{-i}^*) can be obtained by solving Equation (A.26) when it equals to zero, where

$$q_{-i}^* = a - q_i^* - \frac{\mathbb{E}(D_i \wedge q_i) + (p_b - p_s)e_g G_i(e_g q_i) + p_s e_g + c_g}{1 - F_i(q_i)} \quad \text{(A.27)}$$

$$p^* = \frac{\mathbb{E}(D_i \wedge q_i) + (p_b - p_s)e_g G_i(e_g q_i) + p_s e_g + c_g}{1 - F_i(q_i)} \quad \text{(A.28)}$$

Taking the first order derivative of p^* with respect to p_b, p_s, and e_j, respectively.

$$\frac{\partial p^*}{\partial p_b} = \frac{e_g G_i(e_g q_i)}{1 - F_i(q_i)} \geqslant 0, \quad \text{(A.29)}$$

$$\frac{\partial p^*}{\partial p_s} = \frac{e_g[1 - G_i(e_g q_i)]}{1 - F_i(q_i)} \geqslant 0, \quad \text{(A.30)}$$

$$\frac{\partial p^*}{\partial e_j} = \frac{p_s + (p_b - p_s)G_i(e_g q_i) + e_g q_i(p_b - p_s)g_i(e_g q_i)}{1 - F_i(q_i)} > 0. \quad \text{(A.31)}$$

Q.E.D

Proposition 3.6 shows the structural property of the payoff function (Equation 3.2) and the equilibrium outcome of the sourcing game under the scenario with $p_s < p_b$. Proposition 3.6 (i) indicates that manufacturer i can increase the order quantity if cooperating with a greener supplier. The following three results disclose the relationship between two trading prices and the additional production cost per allowance saved (ε), which plays a critical role in determining the optimal trading policy and the equilibrium outcome of the game model. Figure 3.2 presents a diagram illustrating the decision rule based on the equilibrium outcome for this scenario. The meaning of the lines in Figure 3.2 is the same as the meaning of those in Figure 3.1. In Figure 3.2, (a) and (b) illustrate the decision rule with different carbon emission capacities. We observe the following interesting results. First, if ε is the smallest number, then, manufacturers will adopt strategy profile (S_g, S_g) because the trading cost incurred by buying or selling, is higher than the cost of emission allowances saved. In zone I of both (a) and (b), S_g is the optimal strategy for both manufacturers. Second, if both p_s and p_b are smaller than ε, the unique equilibrium is (S_t, S_t) because such a trading can produce more profit than saving emission allowances. In zone III of both (a) and (b), S_t is the optimal strategy for both manufacturers. Third, if ε is in the interval (p_s, p_b), then the decisions will be determined by the emission allowances of manufacturer i. That is, (S_t, S_t) is the unique equilibrium of the sourcing game model when manufacturer i has sufficient allowances, as shown in Figure 3.2 (a); however, if the emission allowances are inadequate, then (S_g, S_g) is the unique equilibrium strategy of the sourcing game, as shown in Figure 3.2 (b). Proposition 3.6 (v) implies another interesting result. The market clearing price will increase when manufacturers cooperate with traditional suppliers rather than with greener suppliers. The increasing of the market clearing price also indicates the decreasing of the supply quantity. Regarding the market clearing price is increasing in e_j and $e_g < e_t$, the traditional supplier can occupy a larger market share than the greener supplier. However, with changes in ε, manufacturers have to adjust their strategies to cope with the emissions capacity constraints and the variance in trading prices.

3.3 Model Extensions

In this section, we study three possible extensions of the sourcing game model. The first extension focuses on the sourcing game with multiple competitors under

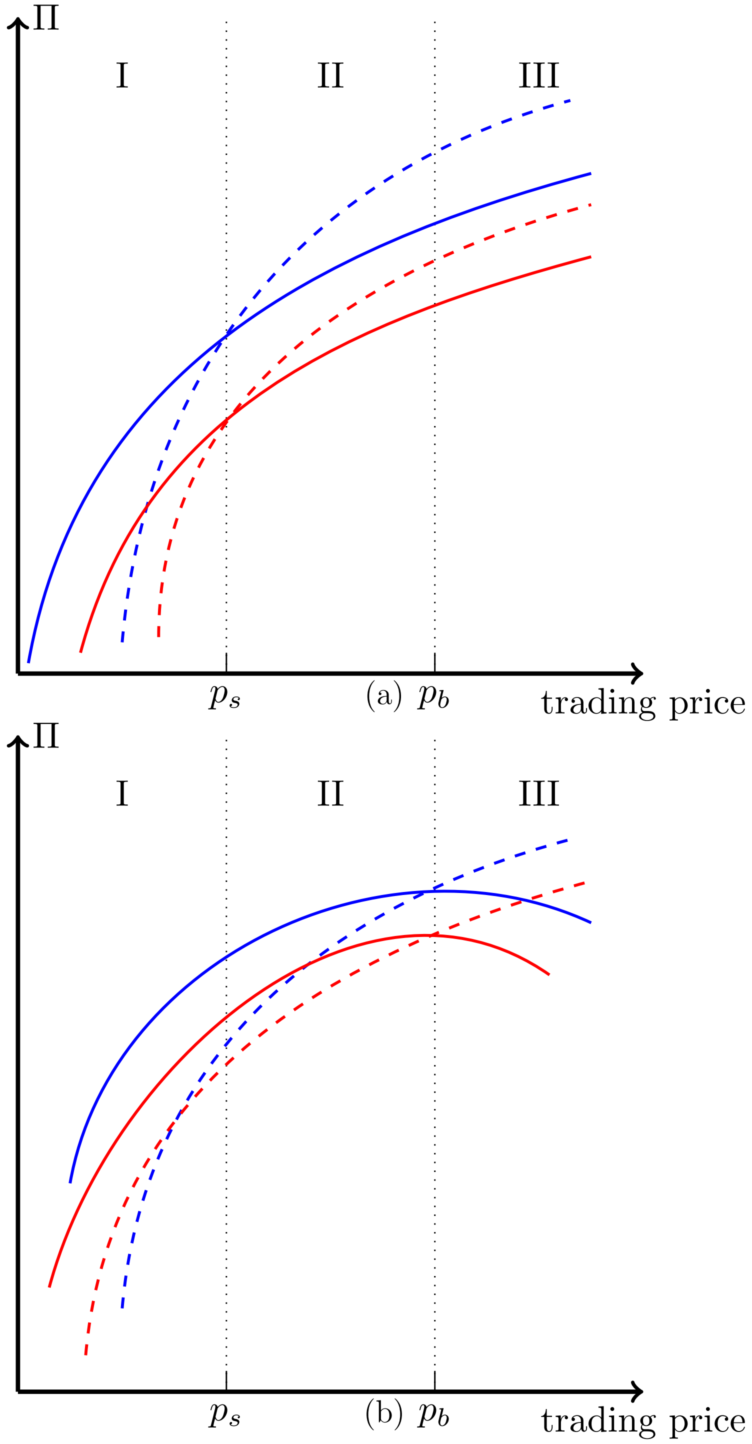


FIGURE 3.2: Diagram for the decision rule if $p_s < p_b$

the emissions trading mechanism. The second further analyzes the sourcing game under the carbon tax scheme. Finally, the emissions trading mechanism and the carbon tax scheme are compared.

3.3.1 Multiple Competitors

In this part, we extend the basic model in Section 3.2 to multiple competitors (manufacturers), i.e. $i > 2$. The property of the optimal order quantity and the equilibrium strategy are examined in a more general setting. With respect to the parameter setting, we denote N as the total number of players in this game model and let N_t and N_g be the numbers of manufacturers who cooperate with the traditional supplier and the greener supplier, respectively.

Proposition 3.7. *Considering multiple competitors,*

(i) the unique equilibrium of the game is (N_t, N_g)*;*

(ii) the optimal order quantity of manufacturer i*,* q_i^**, is decreasing in* N*.*

Proof of Proposition 3.7.

Under the condition of multiple competitors, the payoff function of manufacturer i can be given by

$$\begin{aligned}\Pi_{i,S_j}^U =&[a-(q_1+q_2+\cdots+q_N)]\mathbb{E}(D_i \wedge q_i) - p_b(e_j q_i - C_i)^+ \\ &+ p_s(C_i - e_j q_i)^+ - c_j q_i\end{aligned} \tag{A.32}$$

(i) The cross partial derivative of Π_{i,S_j}^U with respect to q_i and q_{-i} is

$$\frac{\partial \Pi_{i,S_j}^U}{\partial q_i \partial q_{-i}} = F_i(q_i) - 1 < 0. \tag{A.33}$$

Thus, the game model with multiple competitors is also submodular. (N_t, N_g) is the unique equilibrium if and only if $\Pi^U_{i,S_tj}(N_t, N_g) \geqslant \Pi^U_{i,S_t}(N_t + 1, N_g - 1)$ and $\Pi^U_{i,S_g}(N_t, N_g) \geqslant \Pi^U_{i,S_g}(N_t - 1, N_g + 1)$, where the first condition satisfies the number of traditional suppliers that can be selected, and the second condition satisfies the number of greener suppliers that can be selected.

(ii) Taking the first order derivative of manufacturer i's payoff function (A.32) with respect to q_i, we can get

$$\begin{aligned}\frac{\partial \Pi^U_{i,S_j}}{\partial q_i} =& [a - (q_1 + q_2 + \cdots + q_N)] - \mathbb{E}(D_i \wedge q_i) \\ & - e_j(p_b - p_s)G_i(e_j q_i) - p_s e_j - c_j = 0.\end{aligned} \tag{A.34}$$

Adding Equation (A.34) from $i = 1$ to N, we can obtain

$$q_i^* = H(q_i)^{-1}[N(a - Q - p_s e_j - c_j)], \tag{A.35}$$

where $Q = q_1 + q_2 + \cdots + q_N$, and

$$H(q_i) = \sum_{i=1}^{N}[(a - Q)F_i(q_i) + \mathbb{E}(D_i \wedge q_i) + e_j(p_b - p_s)G_i(e_j q_i))]. \tag{A.36}$$

Taking the first order derivative of $H(q_i)$ with respect to q_i, then, we can get

$$\frac{H(q_i)}{q_i} = (a - Q)f_i(q_i) + [1 - F_i(q_i)] + e_j^2(p_b - p_s)G_i(e_j q_i) > 0. \tag{A.37}$$

Thus, $H(q_i)$ is increasing in q_i. The inverse function, $H(q_i)^{-1}$, is in existence and it is a decreasing function.

Q.E.D

Proposition 3.7 (i) shows that there is a unique equilibrium (N_t, N_g) in the sourcing game model when $p_s \leqslant p_b$. Following the equilibrium, the optimal order quantity of manufacturer i, q_i^*, has decreasing properties with the total number of competitors. That is, a few of the players may establish an alliance with/against the other players or to prevent the other potential players from entering the current competition market.

3.3.2 Decisions under the Carbon Emission Tax Scheme

In this section, we aim to study how the carbon tax scheme affects the equilibrium outcome of the sourcing game. For the model setting, let $\hat{c}$ denote the unit carbon tax imposed on one product. The cost, which is incurred by the carbon tax, is an increasing function of the amount of carbon emissions during production.

Proposition 3.8. *Facing different carbon tax structures, we can observe*
(i) the carbon tax is a linear structure, i.e., $\hat{c}e_j q_i$, *the unique equilibrium is* (S_g, S_g) *if* $\varepsilon < \hat{c}$, *the unique equilibrium is* (S_t, S_t) *when* $\varepsilon \geqslant \hat{c}$;
(ii) the carbon tax is a quadratic structure, i.e., $\hat{c}(e_j q_i)^2$, *the unique equilibrium is* (S_g, S_g) *if* $\varepsilon < \hat{c}(e_t + e_g)$; *the unique equilibrium is* (S_t, S_t) *if* $\varepsilon \geqslant \hat{c}(e_t + e_g)$.

Proof of Proposition 3.8.
(i) Facing a linear carbon tax, the payoff function of manufacturer i can be defined as

$$\Pi_{i,jk} = \mathbb{E}p(D_i \wedge q_i) - c_j q_i - \hat{c}e_j q_i \tag{A.38}$$

We need to examine the equilibrium strategy by checking the different values of the profit function when manufacturer $-i$ fixes its strategy S_t and manufacturer i adopts strategies S_t and S_g, respectively.

$$\Pi_{i,S_tS_t} - \Pi_{i,S_gS_t} = (c_g - c_t)q_i + \hat{c}q_i(e_g - e_t) \tag{A.39}$$

When $\varepsilon < \hat{c}$, we get $\Pi_{i,S_tS_t} < \Pi_{i,S_gS_t}$, that is strategy S_g is optimal for manufacturer i. Under the same condition, when manufacturer i fixes strategy S_g, we can get $\Pi_{i,S_gS_t} < \Pi_{i,S_gS_g}$, therefore, the unique equilibrium of the game is (S_g, S_g).
When $\varepsilon \geqslant \hat{c}$, using the similar procedure, we can find that the unique equilibrium of the game is (S_t, S_t).

(ii) Facing a quadratic carbon tax, the payoff function of manufacturer i can be defined as

$$\Pi_{i,jk} = \mathbb{E}p(D_i \wedge q_i) - c_jq_i - \hat{c}(e_jq_i)^2 \tag{A.40}$$

The difference of the profit function when manufacturer $-i$ fixes its strategy S_t and manufacturer i adopts strategies S_t and S_g, respectively, are

$$\Pi_{i,S_tS_t} - \Pi_{i,S_gS_t} = (c_g - c_t)q_i + \hat{c}q_i^2(e_g^2 - e_t^2) \tag{A.39}$$

If $\varepsilon < \hat{c}(e_t + e_g)$, we can get $\Pi_{i,S_tS_t} < \Pi_{i,S_gS_t}$, that is, strategy S_g is optimal for manufacturer i. Under the same condition, when manufacturer i fixes strategy S_g, we can get $\Pi_{i,S_gS_t} < \Pi_{i,S_gS_g}$, therefore, the unique equilibrium of the game is (S_g, S_g).
If $\varepsilon \geqslant \hat{c}(e_t+e_g)$, using the similar procedure, we can get that the unique equilibrium of the game is (S_t, S_t).
Q.E.D

Proposition 3.8 presents the equilibrium outcome of the sourcing game with the two types of tax schemes. As the carbon tax increases, manufacturers must adjust their strategies to respond to it. For the linear carbon tax scheme, the critical condition to adopt the strategy profile (S_g, S_g) is $\varepsilon < \hat{c}$; otherwise, (S_t, S_t) will be the unique equilibrium of the game model. With respect to the quadratic carbon tax scheme, the equilibrium strategies are similar to those for the linear one; however, the threshold has increased to $\hat{c}(e_t + e_g)$, and the growth rate of the quadratic scheme is much greater than the linear one.

3.3.3 Emissions Trading Mechanism vs. Carbon Tax Scheme

Both the emissions trading mechanism and the carbon tax scheme have been implemented in Europe, North America, Australia, and British Columbia among other regions. To save the emissions-related cost, an enterprise should set up factories in different regions or purchase foreign factories with better technologies when facing global differences in carbon emission regulations. On the basis of previous analyses, in this section, we analyze relatively how the two carbon emission regulations affect location decisions for a manufacturer or an enterprise.

Proposition 3.9. *Regardless of the strategies adopted by a manufacturer,*

(i) if $p_s \geqslant \hat{c}$, the carbon tax is superior to the emissions trading mechanism;

(ii) if $\hat{c} > p_s + (p_b - p_s)[G_i(e_j q_i) + e_j^2 g_i(e_j q_i)]$, the emissions trading mechanism is easily accepted.

Proof of Proposition 3.9.

Let $\Delta(q_i, e_j)$ denote the difference of the payoff functions between two manufacturers adopt emissions trading mechanism and the carbon tax scheme. It is sufficient to analyze the modularity of $\Delta(q_i, e_j)$, where

$$\begin{aligned}\Delta(q_i, e_j) &= \Pi_{i,jk} - \Pi^U_{i,jk} \\ &= p_b(e_jq_i - C_i)^+ - p_s(C_i - e_jq_i)^+ - \hat{c}e_jq_i\end{aligned} \tag{A.40}$$

Taking the cross partial derivative of $\Delta(q_i, e_j)$ with respect to q_i and e_j, respectively, we get

$$\frac{\partial^2\Delta(q_i, e_j)}{\partial q_i \partial e_i} = (p_b - p_s)[G_i(e_jq_i) + e_j^2 g_i(e_jq_i)] + (p_s - \hat{c}) \tag{A.41}$$

(i) If $p_s \geqslant \hat{c}$, then $\frac{\partial^2\Delta(q_i,e_j)}{\partial q_i \partial e_i} \geqslant 0$, $\Delta(q_i, e_j)$ is a supermodular function in (q_i, e_j). That is, $\Delta(q_i, e_j)$ is an increasing difference in (q_i, e_j). Therefore, a manufacturer who has higher emission factors and is willing to increasing the production quantity, prefers to accept the carbon tax scheme.

(ii) If $\hat{c} > p_s + (p_b - p_s)[G_i(e_jq_i + e_j^2 g_i(e_jq_i))]$, then $\frac{\partial^2\Delta(q_i,e_j)}{\partial q_i \partial e_i} \leqslant 0$, $\Delta(q_i, e_j)$ is a submodular function in (q_i, e_j). That is, $\Delta(q_i, e_j)$ is a decreasing difference in (q_i, e_j). Under this scenario, the manufacturer is willing to choose the emissions trading mechanism.

Q.E.D

Proposition 3.9 illustrates a sensitivity analysis for the cost of reducing carbon emissions under the two different mechanisms. For carbon-intensive industries, the volume of emissions is more sensitive, that is, these sorts of companies, such as power and cement companies, need to be sure about the total emission amounts, and are more willing to obey the emissions trading mechanism. For the companies who invest in technologies to reduce emissions, accepting the carbon tax scheme is a better choice. Therefore, the boundary conditions in Proposition 3.9 can assist a company in making better decisions about their location setting.

3.4 Managerial Implications

The results in this chapter provide meaningful managerial implications for making appropriate procurement decisions for manufacturers. Manufacturers can also benefit from the findings based on the outcomes of adopting flexible strategies when they comply with different carbon emissions regulations.

For a manufacturer, a greener supplier's materials can incur lower carbon emissions during production processes. The partial carbon emissions cost incurred by the supplier will be transferred to the manufacturer. Therefore, under an emissions trading mechanism, a manufacturer who adopts an environment-friendly strategy can share the benefits of emissions reductions with greener suppliers. Moreover, the findings in this chapter imply that once a manufacturer adopts an environment-friendly strategy, its competitor will adopt the same strategy if the additional production cost per allowance saved is less than the trading price (or the selling price). Therefore, this behavior can enhance cooperative relationships with suppliers, which further contribute to reducing the total GHG emissions of the upstream supply chain. In addition, regarding the scenario of manufacturers with sufficient emission allowances, both manufacturers apply a cost-effective strategy to offset the sufficient emission allowances. However, if the trading price (or the buying price) is greater than the additional production cost per allowance saved, the manufacturer would prefer to cooperate with traditional suppliers, because such trading can achieve more profits than saving emission allowances. Our findings also indicate that the market clearing price will increase if manufacturers adopt a cost-effective strategy rather than an environment-friendly strategy.

Regarding the carbon tax scheme, the equilibrium outcome of a sourcing game with two types of tax schemes, including a linear and a quadratic scheme, is studied. However, different types of manufacturers might not benefit from carbon emissions regulations. Thus, to maximize profit and minimize GHG emissions simultaneously, manufacturers also face a relocation issue. On the basis of the aforementioned analysis, the location decision issue for manufacturers facing global differences in carbon emission regulations is analyzed. Our findings focus on the sensitivity analysis for the cost of reducing carbon emissions under the emissions trading mechanism and the carbon tax scheme. The superiority of these regulations can be summarized as follows. Our findings imply that carbon-intensive industries, such as power and cement companies, can benefit more from the emissions trading mechanism, while for electronic industries, particularly for the 3C industries (Computers, Communication, and Consumer Electronics), which aim to reduce GHG emissions by technology investments, the carbon tax scheme is a better choice.

In general, the findings in this chapter provide effective decision supports for managers in three ways: First, the analysis outcomes identify the sustainable procurement pattern by which to achieve the goals of profit maximization and GHG emissions minimization. Second, by comparing the impacts of environmental regulations, this chapter demonstrates that different types of manufacturers might not benefit from the emissions trading mechanism or the carbon tax scheme. Managers should choose an appropriate plant location and reasonable sourcing decisions to improve their operational performance. Third, this chapter identifies the boundary conditions that can easily assist a manager in making a flexible sourcing decision.

3.5 Summary

Motivated by the sustainable operations mode in practice, such as the carbon emission regulations that implemented in the European Union and Australia, among other regions, this chapter proposed a game theory model to study the sourcing problem under the carbon emission regulations, where the manufacturers can cooperate with a greener supplier or a traditional supplier with lower cost.

First, the existence and the uniqueness of the sourcing game under the emissions trading mechanism were examined and derived. Two trading price scenarios were analyzed to examine the boundary conditions for the variance in the equilibrium outcome. The analysis results demonstrated that these boundary conditions are dependent on the trading prices and the additional production cost per allowance saved ε. The main finding can be summarized as follows. If ε is smaller than p_s and p_b, then, manufacturers will adopt strategy profile (S_g, S_g); that is, the trading cost incurred by buying or selling is higher than the cost of emission allowances saved. If both p_s and p_b are smaller than ε, the unique equilibrium is (S_t, S_t), and trading can produce more profit than saving emission allowances. If ε is in the interval (p_s, p_b), then the decision will be determined by the emission allowances of manufacturer i. That is, (S_t, S_t) or (S_g, S_g) can be the equilibrium when emission allowances are sufficient and inadequate, respectively.

Second, this study performed comparative statics analysis to characterize how the variance in the parameters affects the equilibrium outcome. These results indicate that a manufacturer can increase the order quantity in cooperation with a greener supplier. Interestingly, the market clearing price will increase if manufacturers cooperate with traditional suppliers rather than with greener suppliers.

Third, three possible directions were studied. The basic sourcing game model was extended to multiple competitors. The results show that the optimal order quantity of manufacturer i, has a decreasing property with the total number of competitors. That is, a few players may establish an alliance with or against the other players or prevent the other potential players from entering the current competition market. We also studied how the carbon tax scheme affects the equilibrium outcome of the sourcing game. Finally, the differences between the emissions trading mechanism and the carbon tax scheme were characterized. The results indicate how these two carbon emission regulations affect location decisions by international enterprises.

In summary, this chapter focuses on the sourcing strategies under two types of carbon emission regulations. The equilibrium outcomes were derived with respect to the uncertainty environment to provide guidance to the profit-maximization manufacturers in making reasonable procurement decisions.

Chapter 4

Contract Design with Information Asymmetry under an Emissions Trading Mechanism

4.1 Introduction

In confronting the challenges created by GHG emissions, an increasing number of firms have begun to realize the importance of environmental protection costs. Green engineering (GE), as an effective approach, has been proposed based on theoretical and practical considerations. GE mainly focuses on two goals, reducing the generation of pollution at the source and minimizing the risk to human health and the environment [Uni14]. As an example, Siemens AG has established its own sustainable goals. As a result, Siemens has built green factories to implement a green production cycle, i.e., one in which green materials are used in products to help preserve the environment [Roh13]. Genasci [Gen12] noted that non-governmental organizations (NGOs) in China investigated the supply chains of 49 brands, including Armani, Calvin Klein, Marks & Spencer, Disney, Zara, and Polo Ralph Lauren, by requesting information about pollution management issues regarding the materials provided by their suppliers. These firms were identified as having contributed to environmental pollution because their suppliers concealed the green information (i.e., the release of emissions) regarding their products; eventually, the reputations and brand values of these firms were seriously affected by this cheating. In practice, suppliers do not typically disclose complete details about their products, especially their core products, and may even conceal the information about the environmental friendliness of the materials used. For example, Shenzhen Sunshine Circuit Technology Co., Ltd., a national high-tech enterprise that produces printed circuit boards (PCBs), received a verification statement for the carbon footprint of their product in November 2014 [Pro14]. Because the evaluation processes concern the core production flows, this type of certification only discloses partial information about the carbon footprint of a product based on a lifecycle assessment rather than complete information about the green degree of the product. Therefore, the difficult issues for firms are how to quantify environmental costs and choose environmental materials from upstream suppliers to reduce GHG emissions when the green information of the materials is confidential and known only to the suppliers. This important issue is studied in this chapter using contract design under emissions constraints to establish a mutually beneficial and efficient business model.

For a manufacturer (or buyer), a greener supplier's materials can incur lower carbon emissions during the production processes. The green degree of a supplier primarily depends on its production technology; however, environmentally friendly production technology is expensive. Therefore, a conflict exists between the manufacturer and the supplier: the partial carbon emissions cost that is incurred by the supplier will be transferred to the manufacturer. In practice, the manufacturer cannot precisely know the green degree of the supplier. Thus, the manufacturer must estimate the value of the green degree of a supplier to control its carbon emission amounts and corresponding cost. However, this information is confidential and known only to the supplier. Different types of regulations have been designed and implemented to curb GHG emissions. An emissions trading scheme, which is a market-based mechanism, has been successfully implemented in the European Union, especially for companies in the carbon-incentive industry. When constrained by carbon emission regulations, a firm needs to consider cooperating with suppliers who can provide lower prices and environmentally friendly materials.

The interactions between carbon emissions and climate change have been addressed and documented in the academic literature [Dav10; Har12]. Researchers have also studied the problem of carbon emission regulations from the perspective of sustainable operations management [Hua11; Cho13; Jab13; Che13; Kon14]. Most of these studies focused on emissions control with classical operations research models, such as the economic order quantity (EOQ) and newsvendor models. Researchers have paid less attention to the interaction between suppliers and buyers (or manufacturers). This chapter fills this gap by addressing the manner in which a manufacturer designs an appropriate procurement contract to maximize profits through an effective mechanism, which is constrained by the emissions trading scheme. In addition, this chapter studies a realistic contract design under asymmetric information conditions. The research questions addressed in this chapter are detailed below.

First, how is an appropriate procurement contract designed for a manufacturer that is constrained by the emissions trading scheme? To balance the environmental costs, which are further determined by the carbon emission volumes, the manufacturer must design appropriate contractual mechanisms to elicit suppliers' confidential information, i.e., the unit emissions rate. In reality, decision makers have various preferences; that is, different evaluation criteria exist (e.g., the bidding price and the green degree), and different weights are associated with these criteria. Therefore, this chapter focuses on the issue of contract design for a manufacturer with a single supplier by adopting different strategies, including the use of green degree auctions, price auctions with carbon emission targets, and performance-based auctions.

Second, how is a contract for a competitive bidding scenario designed? Many researchers, including [Muk09], [Gan10], and [Bab12], have primarily focused on the cooperative relationship between a retailer (or a manufacturer) and a supplier. Although a manufacturer often has to cooperate with multiple suppliers to satisfy its demand when facing economic globalization, the supplier with the lower green degree has the lower selling price, and the manufacturer then can save money. In addition, the manufacturer also needs to manage its emissions allowances through cooperation with different types of suppliers. Therefore, it is worth to evaluating how an appropriate contract for a competitive bidding scenario with asymmetric information can be designed.

Third, how is the optimal order quantity under an emissions trading scheme determined? Emissions trading schemes, a market-based mechanism, have been implemented in many regions, such as the United States of America and the European Union. Emissions trading schemes not only have an effect on the characteristics of the payoff function of the manufacturer but also influence its contract structure;

the latter effect occurs because adoption of raw materials with various green degrees can incur different volumes of carbon emissions for the manufacturer. Trading with insufficient or redundant emission volumes may impact the total profit of the manufacturer. Thus, the manufacturer needs to balance the procurement quantity and control its emission allowances.

With respect to the contract design with asymmetric information, Ha [Haa01] analyzed a single supplier-single buyer relationship contracting problem with asymmetric cost information for a short-life-cycle product. A cutoff level policy was employed by the supplier to determine whether the buyer should sign the contract. Cachon [Cac03] provided a general review that focuses on supply chain contract design issues under asymmetric information conditions. Corbett et al. [Cor04] explored the optimal design of quantity-based contracts with incomplete information. Mukhopadhyay et al. [Muk09] studied the issue of optimal contract design for a single manufacturer that does not have information regarding the agents cost type and wishes to induce a downstream sales agent to invest in the marketing effort. Chaturvedi and Martínez-de-Albéniz [Cha11] considered the supply risk for a buyer with respect to the suppliers' cost of production and reliability, which is confidential information for the buyer. Özer and Raz [Oze11] studied two types of suppliers (large and small) competing to supply components to a manufacturer. Various information scenarios were discussed to examine the impact of the supplier type on the manufacturer's production costs. Çakanyldrm et al. [Cak12] analyzed the issues of contracting and coordination under asymmetric production cost information conditions between a retailer and a supplier. The types of suppliers are characterized by their unit production costs, which remain confidential. Their results suggested that confidential information leads to a significant loss of profit for the retailer. However, when facing highly volatile demand, confidential information has less impact on the retailer's profit. Kalkanci and Erhun [Kal12] analyzed decentralized assembly systems with a single manufacturer and two suppliers under asymmetric demand information and sequential contracting conditions. They demonstrated that a downstream supplier prefers information asymmetry to complete information, especially if the demand variability is moderate. Li et al. [Liz15] investigated the issue of procurement in an assortment-planning scenario. A screening model was built to integrate assortment planning into supply-chain contracting between a retailer and a manufacturer. Two independent types of manufacturers were analyzed in the model. Their results indicate that the asymmetry issue can be resolved in a multi-dimensional model. The limitation of the aforementioned papers is that they all assume that the suppliers belong to two specific types. In addition, there are a few studies that consider the issue of procurement with single or multiple suppliers under asymmetric information conditions, including [Che07], [Lee13], [Fan14], [Hee15], and [Wag15]. The study that is most similar to ours is [Fan14], in which the author studied the supply-side competition with a newsvendor model. The key difference from this chapter is that [Fan14] assumes suppliers belong to two specific types. In this chapter, the manufacturer can process the asymmetric information regarding the green degree of multiple suppliers and design attractive contract for suppliers.

This chapter is at the intersection of green procurement, applications of the emissions trading mechanism, and contract design. The contributions of this chapter can be summarized as follows. First, this chapter aims to study constrained procurement issues for a manufacturer with asymmetric information under stochastic demand. Different types of auctions, including price auctions with an emissions target and performance-based auctions, are designed to achieve a win-win result for both the supplier and the manufacturer. Second, this study focuses on analyzing the impact of an emissions trading scheme on contract design in the presence of asymmetric information for the manufacturer. The assumption about confidential information is extended as a continuous type. In addition, for an auction with an emissions trading policy, the optimal trading policy is derived based on the contract structure.

The remainder of this chapter is organized as follows. Section 4.2 introduces the basic context of the model. Section 4.3 describes and discusses the optimal contract structure and analyzes the characteristics of the optimal contract, the payoffs of both players, and the green degree of a supplier. Section 4.4 analyzes a general extension of the basic model with multiple independent suppliers. Section 4.5 studies the optimal emissions trading policy, the price auction with a carbon emissions target, and a performance-based auction. Section 4.6 illustrates the managerial implications of this research work. Section 4.7 concludes the chapter and discusses future extensions.

4.2 Model Setup

This section considers a procurement issue in a supply chain with a manufacturer and n ($n \geqslant 1$) potential suppliers to satisfy the random demand. To control the emissions volumes from the source, the manufacturer needs to use and purchase environmentally focused materials from potential suppliers. Assume that the demand of the manufacturer (D) is a random variable. Its cumulative distribution function (cdf) is denoted by $\Phi(\cdot)$ and its probability density function (pdf) is denoted by $\phi(\cdot)$. Here, let θ_i denote the green degree of the raw materials from supplier i. The green degree is also characterized by its type (θ_i), which is known only by the supplier. Specifically, the cooperation with a supplier of type $\theta_i,\ i \in [1, n]$ directly impacts the emissions volumes of the manufacturer.

However, the manufacturer only observes the type of a supplier with cdf, $F(\theta)$, and pdf, $f(\theta)$, $\theta \in [\underline{\theta}, \overline{\theta}]$, where $\underline{\theta} < \overline{\theta}$, $F(\underline{\theta}) = 0$, and $F(\overline{\theta}) = 1$. Both the manufacturer and suppliers are risk-neutral. The manufacturer aims at maximizing its expected profit by seeking an optimal procurement strategy. Two scenarios are studied here: procurement from a single supplier ($n = 1$); and competitive procurement among multiple suppliers ($n \geqslant 2$).

The scenario that focuses on procurement from a single potential supplier is studied. Regarding the cost structure of the manufacturer, the leftover product can be offered in the following period, and this generates salvage value. To reduce emissions volumes, the manufacturer needs to design an appropriate menu of contracts, $(Q(\theta),\ M(Q(\theta)))$, for different types of suppliers. That is, if the supplier supplies a quantity $Q(\theta)$, then the supplier obtains revenue $M(Q(\theta))$ from the manufacturer. Under the emissions trading mechanism, manufacturers first receive the initial emissions allowances, that is, manufacturers can emit a specified volume of emissions during the production process. Then, the manufacturer needs to make a decision to buy additional allowances from or sell redundant allowances to the trading market. Based on the above brief analysis, the objective functions of the manufacturer, Π_m, and the supplier, Π_s, can be developed as follows.

$$\Pi_m = R(Q(\theta)) + T(Q(\theta), C) - M(Q(\theta)), \tag{4.1}$$

$$\Pi_s = M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \tag{4.2}$$

where,

$$R(Q(\theta)) = p\mathbb{E}(D, Q(\theta))^{-} + r_v\mathbb{E}(Q(\theta) - D)^{+} - c_pQ(\theta), \tag{4.3}$$

$$T(Q(\theta), C) = w_1\mathbb{E}(C - \beta Q(\theta))^{+} - w_2\mathbb{E}(\beta Q(\theta) - C)^{+}, \tag{4.4}$$

$(x)^+ := \max\{0, x\}$, $(x, y)^- := \min\{x, y\}$, and $\mathbb{E}(\cdot)$ is the expectation operator. Equation (4.1) describes the payoff function of the manufacturer. The first item in Equation (4.1), $R(Q(\theta))$ consists of the sales revenue, the salvage value of the leftover product, and the production cost. The details of $R(Q(\theta))$ are presented in Equation (4.3). The sales revenue equals the unit price times the expected quantity of sales. The salvage value is determined by the expected inventory level and the unit salvage revenue r_v. The production cost equals the unit production cost (c_p) multiplied by the order quantity, $Q(\theta)$. The second item in Equation (4.1) illustrates the expected revenue from emissions trading activity. During the production processes, the unit emissions factor of the manufacturer is denoted by the coefficient β. Thus, the total emissions amount of the manufacturer equals β and $Q(\theta)$ of the product, which is determined by the production technology of the manufacturer. For a certain period, if the emissions allowances (C) of the manufacturer are greater than the total emissions amount, then the manufacturer could benefit from selling extra emissions allowances; otherwise, the manufacturer should purchase the insufficient allowances from the carbon market. In Equation (4.4), w_2 and w_1 are the buying and selling prices of carbon emissions, respectively. Assume that w_1 is smaller than w_2, which is an incentive to encourage the manufacturer to accept and implement the emissions trading mechanism during the initial period [Gon13]. Regarding the uncertainty of emissions allowances of the manufacturer, we denote $H(\cdot)$ and $h(\cdot)$ as the cdf and pdf, respectively, of the allowance prices. The last item in Equation (4.1) is the cash transfer from the manufacturer to the supplier. Equation (4.2) illustrates the payoff function of the supplier. The first item is the cash transfer from the manufacturer. The second item describes the environmental benefits of the supplier, which equals the coefficient α and the green degree θ of the product, and the environmental quality function of the supplier. The environmental benefits of the supplier can be explained as that of adopting a new technique or technology to produce raw materials. For instance, Apple implemented an innovative stage in producing iPhone models that may help its suppliers, especially those in China, cut carbon emissions [Xin15]. The most common practices of green supply chain management include assessing the environmental performance of suppliers to ensure the environmental quality of their products and evaluating the cost of waste in their operating systems [Han02]. Thus, in this chapter, we denote the environmental quality function by $W(Q(\theta))$, which is the impact on suppliers type, θ, without loss of generality, $W(Q(\theta))$ is assumed to be an increasing concave function. The last term is the production cost, which is the product of the unit production cost, c_s, and $Q(\theta)$.

For supplier participation, Π_s should not be less than Π_0; this constraint is referred to as the *Individual Rationality (IR)* constraint. Π_0 is the tolerance of the supplier in accepting the contract. Without loss of generality, assume that Π_0 is zero. In addition, for the supplier to choose the contract that is designed for them, the *Incentive Compatibility (IC)* constraint must be satisfied:

$$M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_sQ(\theta) \geqslant M(Q(\theta')) + \alpha\theta W(Q(\theta')) - c_sQ(\theta'). \quad (4.5)$$

Therefore, the manufacturer's decision problem can be formulated as follows.

$$\begin{aligned}&\max \Pi_m(\theta, Q(\theta)) = \max \mathbb{E}(R(\theta, Q(\theta)) + T(Q(\theta), C) - M(Q(\theta)))\\&= \int_{\underline{\theta}}^{\overline{\theta}} (R(\theta, Q(\theta)) + T(Q(\theta), C) - M(Q(\theta)))f(\theta)d\theta\end{aligned} \tag{4.6}$$

$$\begin{aligned}s.t.\ & M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \geqslant \Pi_0 = 0\\& M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \geqslant M(Q(\theta')) + \alpha\theta W(Q(\theta')) - c_s Q(\theta'),\\& for\ all\ \theta\ and\ \theta'.\end{aligned}$$

In the following section, the properties of the manufacturer's decision issue in Equation (4.6) will be analyzed. The optimal contract will be derived. In addition, the relationship between the green degree of the supplier and the order quantity will be further discussed in the following sections.

4.3 Contract Analysis and Implications

This section examines the properties of the manufacturer's decision problem specified by Equation (4.6). The technical approach applied here is a lattice and modularity analysis. The analysis presents propositions that illustrate the important properties of the manufacturer's payoff function, the optimal contact, and the supplier's profit.

The decision problem specified by Equation (4.6) assumes that the manufacturer does not have information regarding the supplier type. That is, the supplier does not offer its confidential information to the manufacturer. A supplier that does not disclose its confidential information can obtain a higher profit than the reservation profit, but this type of behavior may lead to increases in the emission volumes of the manufacturer. However, information rent can be used appropriately to illustrate this phenomenon. The information rent is denoted as follows:

$$r(\theta) = M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \tag{4.7}$$

Based on Equation (4.5), the first order derivative of the information rent $r'(\theta)$ is $\alpha W(Q(\theta))$, which is greater than or equal to zero. Therefore, the information rent $r(\theta)$ must be an increasing function with respect to θ, and $r(\underline{\theta})$ should equal to zero; then, the *IR* condition is automatically satisfied. On the basis of the above analysis, the objective function of the manufacturer can be re-written as follows:

$$\begin{aligned} \Pi_m &= \int_{\underline{\theta}}^{\overline{\theta}} (R(Q(\theta)) + T(Q(\theta)) - M(Q(\theta)))d\theta \\ &= \int_{\underline{\theta}}^{\overline{\theta}} (R(Q(\theta)) + T(Q(\theta)) - r(\theta) + \alpha\theta W(Q(\theta)) - c_s Q(\theta))f(\theta)d\theta \end{aligned} \tag{4.8}$$

Because the objective function of the manufacturer is decreasing in $r(\theta)$, and $r(\theta)$ is an increasing function, the information rent $r(\theta)$ and Equation (4.8) can be re-written as follows:

$$r(\theta) = \int_{\underline{\theta}}^{\theta} \alpha W(Q(\theta))d\theta \tag{4.9}$$

$$\Pi_m = \int_{\underline{\theta}}^{\overline{\theta}} (R(Q(\theta)) + T(Q(\theta)) - \alpha W(Q(\theta))\frac{1 - F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta) f(\theta) d\theta \tag{4.10}$$

Maximization of Π_m corresponds to maximization of the integral function in Equation (4.10). Thus, denote

$$\begin{aligned}G(Q(\theta)) &= R(Q(\theta)) + T(Q(\theta)) - \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta)\\ &= p\mathbb{E}\min(Q(\theta), D) + r_v\mathbb{E}(Q(\theta)-D)^+ - c_p Q(\theta) + \mathbb{E}w_1(C-\beta Q(\theta))^+\\ &- \mathbb{E}w_2(\beta Q(\theta)-C)^+ - \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta)\end{aligned} \tag{4.11}$$

Proposition 4.1. *The characteristics of $Q(\theta)$ and $G(Q(\theta))$ are:*

(i) $Q(\theta)$ is an increasing function in θ;

(ii) if $\theta \geqslant \frac{1-F(\theta)}{f(\theta)}$, $G(Q(\theta))$ is a concave function in $Q(\theta)$.

Proof of Proposition 4.1.

(i) Based on the *IC* condition in Equation (4.5), the payoff function of the supplier Π_s can be maximized when θ' equals to θ, that is, the result of the first order derivative of the right hand-side of Equation (4.5) for θ' equals to zero when $\theta' = \theta$, i.e.,

$$[M'(Q(\theta)) + \alpha\theta W'(Q(\theta)) - c_s)]Q'(\theta) = 0. \tag{B.1}$$

For a further analysis of the characteristics of $Q(\theta)$, the second order derivative for θ is as follows:

$$\begin{aligned}&M''(Q(\theta))[Q'(\theta)]^2 + M'(Q(\theta))Q''(\theta) + \alpha W'(Q(\theta))Q'(\theta) + \alpha\theta W''(Q(\theta))[Q'(\theta)]^2\\ &+ \alpha\theta W'(Q(\theta))Q''(\theta) - c_s Q''(\theta) = 0.\end{aligned} \tag{B.2}$$

The second order derivative for $\theta' = \theta$ to be maximized should satisfy:

$$\begin{aligned}&M''(Q(\theta))[Q'(\theta)]^2 + M'(Q(\theta))Q''(\theta) + \alpha\theta W''(Q(\theta))[Q'(\theta)]^2\\ &+ \alpha\theta W'(Q(\theta))Q''(\theta) - c_s Q''(\theta) \leqslant 0.\end{aligned} \tag{B.3}$$

The above analysis implies that the necessary condition is $\alpha W'(Q(\theta))Q'(\theta) \geqslant 0$. This is because $W(Q(\theta))$ is assumed to be an increasing function, that is, $W'(Q(\theta))$ is greater than or equal to zero. Therefore, the necessary condition requires that $Q'(\theta)$ is greater than or equal to zero. That is, $Q(\theta)$ is an increasing function in θ.

(ii) The second order derivative of the function in Equation (4.11) for $Q(\theta)$ is shown as:

$$\frac{\partial^2 G(Q(\theta))}{\partial Q^2(\theta)} = (r_v - p)\phi(Q(\theta)) + \beta^2(w_1 - w_2)h(\beta Q(\theta)) + \alpha W''(Q(\theta))(\theta - \frac{1 - F(\theta)}{f(\theta)}). \tag{B.4}$$

This is because the pdf function is greater than zero and the coefficients of the first two items in Equation (B.4) are negative values, thus, the first two terms of Equation (B.4) are non-positive. In addition, $W(Q(\theta))$ is an increasing concave function, thus, $W''(Q(\theta)$ is smaller than or equal to zero. Based on the above analysis, the result of the second order condition for $G(Q(\theta))$ is non-positive when $\theta \geqslant \frac{1-F(\theta)}{f(\theta)}$. That is, $G(Q(\theta))$ is a concave function in $Q(\theta)$ if $\theta \geqslant \frac{1-F(\theta)}{f(\theta)}$.
Q.E.D

In Proposition 4.1, the first property describes the relationship between the order quantity and the green degree of the supplier. The increasing property demonstrates that the value of the order quantity designed by the manufacturer is positively correlated with the green degree of the supplier. The first result is intuitive and consistent with real-world situations because the production emissions of the manufacturer are stable if there is no change to its production technology. The production quantity primarily determines the emissions amount of the manufacturer for a certain period, which is also the main reason that the properties of the model focus on the interaction between the order quantity and the green degree.

With respect to Equation (4.11), the second property in Proposition 4.1 illustrates the existence of the optimal order quantity, $Q(\theta)$, which can be assumed to be adopted. The results also indicate that the manufacturer can maximize its total profit by following the order quantity. Finally, the concavity of $G(Q(\theta))$ in $Q(\theta)$ indicates that the marginal value of the order quantity decreases if the order quantity increases.

Proposition 4.2. *Given the condition of an increasing failure rate, $G(Q(\theta))$ is supermodular in $(\theta, Q(\theta))$.*

Proof of Proposition 4.2.

Taking the mixed partial differential for $Q(\theta)$ and θ, respectively, we can obtain

$$\frac{\partial^2 G(Q(\theta))}{\partial Q(\theta)\partial\theta} = \alpha W'(Q(\theta))\frac{f(\theta)(1-F(\theta))+f^2(\theta)}{f^2(\theta)} + \alpha W'(Q(\theta)) \tag{B.5}$$

Therefore, under the condition of an increasing failure rate, Equation (B.5) is greater than or equal to zero. This is because $W(Q(\theta))$ is an increasing function and other parts in Equation (B.5) are greater than zero. Based on lattice and modularity theory [Top98], $G(Q(\theta))$ is supermodular in $(Q(\theta),\ \theta)$ under the condition of an increasing failure rate.

Q.E.D

Based on the results described in Proposition 4.1, the monotonicity of $G(Q(\theta))$ is further discussed. The supermodularity of $G(Q(\theta))$ in $((\theta, Q(\theta))$ indicates that under the condition of an increasing failure rate, an increasing optimal match between the supplier type (the green degree of the supplier) and the optimal order quantity exists. For the manufacturer, the expected profit can be maximized by cooperating with the greener supplier; for the supplier, becoming greener results in increased competitive power because the supplier can claim a greater market share. Following the aforementioned prosperities of $G(Q(\theta))$, the optimal menu of the contract for the supplier can be derived. The following proposition provides a detailed explanation.

Proposition 4.3. *The characteristics of the optimal contract and the payoff function of the supplier are:*

(i) suppose that $(Q^*(\theta), M(Q^*(\theta)))$ *is the optimal menu of the contract, which is designed by the manufacturer. Then, the optimal payment for the supplier,* $M(Q^*(\theta))$*, is*

$$M(Q^*(\theta)) = \int_{\underline{\theta}}^{\theta} \alpha W(Q^*(\xi))d\xi + c_s Q^*(\theta) - \alpha\theta W(Q^*(\theta)), \tag{4.12}$$

where $Q^*(\theta) = \arg\max\ G(Q(\theta))$.

(ii) Π_s *is a supermodular function in* θ *and* $Q(\theta)$*.*

Proof of Proposition 4.3.

(i) Taking the first order derivative of $G(Q(\theta))$ with respect to $Q(\theta)$, we obtain

$$\begin{aligned} \frac{\partial G(Q(\theta))}{\partial Q(\theta)} =& p - \beta w_1 - c_p - c_s + (r_v - p)\Phi(Q(\theta)) + \beta(w_1 - w_2)H(\beta Q(\theta)) \\ &+ \alpha W'(Q(\theta))(\theta - \frac{1-F(\theta)}{f(\theta)}). \end{aligned} \tag{B.6}$$

Let

$$\frac{\partial G(Q(\theta))}{\partial Q(\theta)} = 0. \tag{B.7}$$

Then, the optimal $Q^*(\theta)$ can be derived from Equations (B.6) and (B.7). In addition, the optimal cash transfer can be obtained.

Because

$$\int_{\underline{\theta}}^{\theta} \alpha W(Q^*(\xi))d\xi = r(\theta) = M(Q^*(\theta)) + \alpha\theta W(Q^*(\theta)) - c_s Q^*(\theta). \tag{B.8}$$

thus,

$$M(Q^*(\theta)) = \int_{\underline{\theta}}^{\theta} \alpha W(Q^*(\xi))d\xi + c_s Q^*(\theta) - \alpha\theta W(Q^*(\theta)). \tag{B.9}$$

The optimal contract for the supplier is $(Q^*(\theta),\ M(Q^*(\theta)))$.

(ii) Substituting Equation (B.9) into the payoff function of the supplier, we can obtain $\Pi_s = r(\theta)$. The result of the mixed partial differential in terms of θ and $Q(\theta)$ is $\alpha W(Q(\theta))Q'(\theta)$, which is greater than or equal to zero, because both $W(Q(\theta))$ and $Q(\theta)$ are increasing functions. Thus, Π_s is supermodular in $(\theta, Q(\theta))$.

Q.E.D.

The first property described in Proposition 4.3 describes the optimal contract, which depends on the green degree of the supplier. Following the optimal contract $(Q^*(\theta), M(Q^*(\theta)))$, both the manufacturer and the supplier can maximize their payoff functions simultaneously. Regarding the manufacturer, this optimal contract not only can assist it in controlling the emissions amount from the source, but also can develop a relatively stable relationship with the supplier under asymmetric information conditions. The supermodular nature of Π_s in $((\theta, Q(\theta))$ indicates that the incremental revenue of the supplier in choosing a higher $Q(\theta)$ is greater when θ is higher. That is, a supplier can rapidly enlarge its business volume share by increasing its green degree.

Finally, contract design in the presence of multiple suppliers is worth studying. Facing multiple potential suppliers, the manufacturer should decide on the amount to purchase and which supplier(s) to cooperate with to maximize the expected payoff. These issues are further discussed in the following section.

4.4 Decision on Multiple Suppliers

This section extends the basic model presented in Section 4.3 to the case of multiple suppliers. The first purpose is to check the robustness of the results presented in the previous section. Second, additional characteristics are analyzed in a general setting. Assume a manufacturer has $n(n \geqslant 2)$ potential suppliers and each supplier is characterized by their type, θ_i, $\theta_i \in [\underline{\theta}, \overline{\theta}]$, which is confidential information known only by each individual supplier. The manufacturer and other suppliers have prior knowledge to characterize supplier i with cdf $F_i(\theta_i)$ and pdf $f_i(\theta_i)$. The payoff functions of the manufacturer ($\tilde{\Pi}_m$) and suppliers ($\tilde{\Pi}_{s_i}$) can be formulated as follows.

$$\tilde{\Pi}_m = \mathbb{E}(R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1, \ldots, \theta_n))), \tag{4.13}$$

$$\tilde{\Pi}_{s_i} = m_i(q_i(\theta_i)) + \alpha_i \theta_i W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i) \tag{4.14}$$

where

$$\begin{aligned} R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n) =& p\mathbb{E}\min(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n), D) \\ &+ c_h \mathbb{E}(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n) - D)^+ - c_p \sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n), \end{aligned} \tag{4.15}$$

$$T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) = w_1 \mathbb{E}(C - \sum_{i=1}^{n} \beta Q_i(\theta_1, \ldots, \theta_n))^+ - w_2 \mathbb{E}(\beta \sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n) - C)^+. \tag{4.16}$$

In the multiple-supplier scenario, Equation (4.14) consists of three items, the sales revenue, the salvage value of leftover products, and the production cost. The parameters in Equation (4.14) have the same meaning as the parameters in Equation (4.3). Equation (4.15) describes the revenue or expenditure obtained by selling or purchasing the carbon emission allowances of the manufacturer. The emissions volume of the manufacturer is determined by the total order quantity and the unit emissions rate, β. The supplier i payoff function in Equation (4.14) has the same meaning as Equation (4.2). For an individual supplier i, the manufacturer only knows its type because θ_i is confidential information for the manufacturer. Thus, let $q_i(\theta_i)$ denote the manufacturer's preferred order quantity, which equals to $\mathbb{E}_{\theta_{-i}} Q_i(\theta_i, \theta_{-i})$; then, the payment is $\mathbb{E} M_i(Q_i(\theta_i, \theta_{-i}))$.

Let $(Q_i(\theta_i, \theta_{-i}), M_i(Q_i(\theta_i, \theta_{-i})))$ denote the contract structure, which is designed for individual suppliers, $i = 1, \ldots, n$, where θ_{-i} represents the bids of all suppliers except for supplier i. $Q_i(\theta_i, \theta_{-i})$ is the appropriate order quantity of supplier i and $M_i(Q_i(\theta_i, \theta_{-i}))$ is the payment transfer from the manufacturer to supplier i. Therefore, the manufacturer would announce a mechanism based on each supplier's bidding on the green degree. Each supplier can then make an individual decision as to whether to accept the contract. Each supplier aims to maximize its expected profit; thus, we assume that a supplier will accept the contract if and only if the expected profit is not less than zero. In addition, for supplier i to choose the contract that is designed for it, the following *IC* condition must hold.

$$m_i(q_i(\theta_i)) + \alpha_i \theta_i W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i) \geqslant m_i(q_i(\theta_i)) + \alpha_i \delta W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i) \quad (4.17)$$

Therefore, the manufacturer's decision problem with multiple suppliers can be described as follows:

$$\tilde{\Pi}_m = \mathbb{E}(R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1, \ldots, \theta_n)))$$

$$\begin{aligned} s.t. \quad & m_i(q_i(\theta_i)) + \alpha_i \theta_i W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i) \geqslant 0, \\ & m_i(q_i(\theta_i)) + \alpha_i \theta_i W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i) \geqslant m_i(q_i(\theta_i)) + \alpha_i \delta W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i), \\ & for\ all\ \delta\ and\ \theta_i. \end{aligned} \tag{4.18}$$

We denote the information rent as $r_i(\theta_i) = m_i(q_i(\theta_i)) + \alpha_i \theta_i W_i(q_i(\theta_i)) - c_{s_i} q_i(\theta_i)$. The first order derivative for the information rent $r'_i(\theta_i)$ is then $\alpha_i W_i(q_i(\theta_i))$, which is greater than or equal to zero. Thus, the information rent $r_i(\theta_i)$ must be increasing, and $r_i(\underline{\theta})$ should equal to zero; consequently, the *IR* condition is automatically satisfied. The expected payment from the manufacturer is given by Equation (4.19):

$$\begin{aligned} & \mathbb{E}[\sum_{i=1}^{n} M_i(q_i(\theta_1, \ldots, \theta_n))] = \mathbb{E}[\sum_{i=1}^{n} m_i(q_i(\theta_i))] \\ & = \sum_{i=1}^{n} \int_{\underline{\theta}}^{\overline{\theta}} [r_i(\theta_i) - \alpha_i \theta_i W_i(q_i(\theta_i)) + c_{s_i} q_i(\theta_i)] dF(\theta_i) \\ & = \int_{\underline{\theta}}^{\overline{\theta}} \cdots \int_{\underline{\theta}}^{\overline{\theta}} \sum_{i=1}^{n} [c_{s_i} Q_i(\theta_i, \theta_{-i}) - \alpha_i W_i(Q_i(\theta_i, \theta_{-i}))(\theta_i - \frac{1 - F_i(\theta_i)}{f_i(\theta_i)})] dF(\theta_i), \end{aligned} \tag{4.19}$$

where $dF(\theta_i) = \prod_{i=1}^{n} dF_i(\theta_i)$.

Based on the above analysis, the objective function of the manufacturer can be re-written as follows:

$$
\begin{aligned}
\tilde{\Pi}_m = & \int_{\underline{\theta}}^{\overline{\theta}} [R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) \\
& - \sum_{i=1}^{n} M_i(Q_i(\theta_1, \ldots, \theta_n))] dF(\theta_i) \\
& = \int_{\underline{\theta}}^{\overline{\theta}} [R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) - r_i(\theta_i) + \alpha_i \theta_i W_i(q_i(\theta_i)) \\
& - c_{s_i} q_i(\theta_i)] dF(\theta_i) \\
& = \int_{\underline{\theta}}^{\overline{\theta}} \cdots \int_{\underline{\theta}}^{\overline{\theta}} [R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) - c_{s_i} Q_i(\theta_i, \theta_{-i}) \\
& + \alpha_i W_i(Q_i(\theta_i, \theta_{-i}))(\theta_i - \frac{1 - F_i(\theta_i)}{f_i(\theta_i)})] dF(\theta_i)
\end{aligned}
\tag{4.20}
$$

Maximization of the manufacturer's payoff corresponds to maximize of the integral function in Equation (4.20), which implies

$$
\begin{aligned}
& K(Q_i(\theta_1, \ldots, \theta_n)) \\
& = R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1, \ldots, \theta_n)) \\
& = p\mathbb{E}(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n), D)^- + r_v \mathbb{E}(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n) - D)^+ - c_p \sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n) \\
& + w_1 \mathbb{E}(C - \beta \sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n))^+ - w_2 \mathbb{E}(\beta \sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n) - C)^+ - c_{s_i} Q_i(\theta_i, \theta_{-i}) \\
& + \alpha_i W_i(Q_i(\theta_i, \theta_{-i}))(\theta_i - \frac{1 - F_i(\theta_i)}{f_i(\theta_i)})
\end{aligned}
\tag{4.21}
$$

Proposition 4.4. For the scenario of multiple suppliers,

(i) $q_i(\theta_i)$ is an increasing function in θ_i;

(ii) if $\theta_i > \frac{1-F_i(\theta_i)}{f_i(\theta_i)}$, $K(Q(\theta_1, \ldots, \theta_n))$ is a concave function in $Q_i(\theta_1, \ldots, \theta_n)$.

Proof of Proposition 4.4.

(i) In order to guarantee the IC condition in Equation (4.17), we take the first order derivative for θ_i, which aims at maximizing the payoff of the supplier i. Then,

$$[m_i'(q_i(\theta_i)) + \alpha_i\theta_i W_i'(q_i(\theta_i)) - c_{s_i}]q_i'(\theta_i) = 0. \tag{B.10}$$

Thus, the second order derivative for θ_i is:

$$\begin{aligned} & m_i''(q_i(\theta_i))(q_i'(\theta_i))^2 + m_i'(q_i(\theta_i))q_i''(\theta_i) + \alpha_i W_i'(q_i(\theta_i))q_i'(\theta_i) + \alpha_i\theta_i W_i''(q_i(\theta_i))(q_i'(\theta_i))^2 \\ & + \alpha_i\theta_i W_i'(q_i(\theta_i))q_i''(\theta_i) - c_{s_i}q_i''(\theta_i) = 0. \end{aligned} \tag{B.11}$$

The first order derivative for θ_i should be maximized by:

$$\begin{aligned} & m_i''(q_i(\theta_i))(q_i'(\theta_i))^2 + m_i'(q_i(\theta_i))q_i''(\theta_i) + \alpha_i\theta_i W_i''(q_i(\theta_i))(q_i'(\theta_i))^2 \\ & + \alpha_i\theta_i W_i'(q_i(\theta_i))q_i''(\theta_i) - c_{s_i}q_i''(\theta_i) \leqslant 0 \end{aligned} \tag{B.12}$$

This implies that the necessary condition is that $\alpha_i W_i'(q_i(\theta_i))q_i'(\theta_i)$ is greater than zero. Because $W_i(q_i(\theta_i))$ is assumed to be an increasing function, so, the necessary condition is that $q_i(\theta_i)$ is greater than or equal to zero. Thus, $q_i(\theta_i)$ is increasing in θ_i.

(ii) Taking the second order derivative for the integrand function in Equation (4.20) with respect to $Q_i(\theta_1, \ldots, \theta_n)$, we can obtain the following result, as shown in Equation (B.13):

$$\begin{aligned} \frac{\partial^2 K(Q_i(\theta_1, \ldots, \theta_n))}{\partial Q_i^2(\theta_1, \ldots, \theta_n)} &= (r_v - p)\phi(Q_i(\theta_1, \ldots, \theta_n)) + \beta^2(w_1 - w_2)h(\beta Q_i(\theta_1, \ldots, \theta_n)) \\ & + \alpha_i W_i''(Q_i(\theta_1, \ldots, \theta_n))(\theta_i - \frac{1 - F_i(\theta_i)}{f_i(\theta_i)}) \end{aligned} \tag{B.13}$$

Because the pdf function is greater than zero, the coefficient of the first two items in Equation (B.13) are negative, and $W(Q_i(\theta_1,\ldots,\theta_n))$ is an increasing concave function, the result of the second order condition of $K(Q_i(\theta_1,\ldots,\theta_n))$ is negative if $\theta_i \geqslant \frac{1-F_i(\theta_i)}{f_i(\theta_i)}$. That is, $K(Q_i(\theta_1,\ldots,\theta_n))$ is a concave function in $Q_i(\theta_1,\ldots,\theta_n)$ if $\theta_i \geqslant \frac{1-F_i(\theta_i)}{f_i(\theta_i)}$.

Q.E.D.

Proposition 4.4 (i) presents the relationship between each individual type of supplier i and each corresponding order quantity. The increasing characteristic indicates that suppliers can own a larger business volume share if they can supply raw materials with a higher green degree to the manufacturer. The emissions amount for the manufacturer is determined by the type of supplier i. The second property of Proposition 4.4 illustrates the aspect of the integrated function, $K(Q_i(\theta_1,\ldots,\theta_n))$, which directly determines the payoff function of the manufacturer. It implies that the marginal value from each supplier decreases if the value of the order quantity increases. Therefore, the manufacturer should follow this rule to design the appropriate contracts.

Proposition 4.5. *Under the condition of an increasing failure rate,* $K(Q_i(\theta_1,\ldots,\theta_n))$ *is a supermodular function in* θ_i *and* $Q_i(\theta_1,\ldots,\theta_n)$*.*

Proof of Proposition 4.5.

Taking the mixed partial differential in terms of $Q(\theta)$ and θ for Equation (4.21), we can obtain the following result, as shown in Equation (B.14):

$$\frac{\partial^2 K(Q_i(\theta_1,\ldots,\theta_n))}{\partial Q_i(\theta_1,\ldots,\theta_n)\partial\theta_i} = \alpha_i W_i'(Q_i(\theta_1,\ldots,\theta_n))(\frac{f_i^2(\theta_i) - f_i'(\theta_i)(1-F_i(\theta_i))}{f_i^2(\theta_i)} + 1) \tag{B.14}$$

Thus, under the condition of an increasing failure rate, Equation (B.14) is not less than zero, because $W(Q_i(\theta_1,\ldots,\theta_n))$ is an increasing function. This result indicates that $K(Q_i(\theta_1, \ldots, \theta_n))$ is supermodular in $(Q(\theta), \theta)$ under the condition of an increasing failure rate.

Q.E.D.

Regarding monotonicity, Proposition 4.5 presents a characteristic of $K(Q_i(\theta_1, \ldots, \theta_n))$. The results indicate that the function $K(Q_i(\theta_1, \ldots, \theta_n))$ has increasing differences in $(\theta_i, Q_i(\theta_1, \ldots, \theta_n))$. That is, the incremental gain in choosing a higher $Q_i(\theta_1, \ldots, \theta_n)$ is greater if θ_i is greater. In a loose supplier market, a supplier with higher value of θ_i would build more market share. In addition, a higher order quantity brings more profit to the manufacturer. Therefore, the optimal results of the function $K(Q_i(\theta_1, \ldots, \theta_n))$ will be used to design the contract by the manufacturer. The details of the contract are provided in the following proposition.

Proposition 4.6. *In a scenario with multiple suppliers,*

(i) if $\theta_1 \leqslant \theta_2 \leqslant \ldots \theta_n$*, supplier* n *is selected.* $(Q^*(\theta_n), M_n(Q^*(\theta_n))$ *is the optimal menu of the contract that is designed by the manufacturer, and the optimal payment for the supplier is*

$$M_n(q_n^*(\theta_n)) = \int_{\underline{\theta}}^{\theta} \alpha_n W_n(q_n^*(\xi))d\xi + c_{s_n} q_n^*(\theta_n) - \alpha_n \theta_n W_n(q_n^*(\theta_n)), \tag{4.22}$$

where, $Q^*(\theta_n) = \arg\max \ K(Q_i(\theta_1, \ldots, \theta_n))$*;*

(ii) The payoff function of the selected supplier is supermodular in $(\theta_n, Q^*(\theta_n))$.

Proof of Proposition 4.6.

(i) Following the results in Proposition 4.4, $K(Q(\theta_1, \ldots, \theta_n))$ is a concave function in $Q(\theta_1, \ldots, \theta_n)$. If $\theta_1 \leqslant \theta_2 \leqslant \ldots \theta_n$, then the optimal mechanism is $Q^*(\theta_1, \ldots, \theta_n) = Q^*(\theta_n)$ and $Q^*(\theta_j) = 0,\ j = 1, \ldots, n-1$. $Q^*(\theta_n)$ is the maximizer of the concave function $K(Q(\theta_1, \ldots, \theta_n))$. Therefore, the optimal payment can be characterized as follows:

$$M_i(Q^*(\theta_n)) = \alpha_i W_i(Q^*(\theta n))(\frac{1 - F_i(\theta_n)}{f(\theta_n)} - \theta_n) + c_s Q^*(\theta n) \tag{B.15}$$

Because

$$\int_{\underline{\theta}}^{\theta} \alpha_n W_n(q_n^*(\xi))d\xi = r_n(\theta_n) = m_n(q_n^*(\theta_n)) + \alpha_n\theta_n W_n(q_n^*(\theta_n)) - c_{s_n} q_n^*(\theta_n). \tag{B.16}$$

thus,

$$M_n(q_n^*(\theta_n)) = \int_{\underline{\theta}}^{\theta} \alpha_n W_n(q_n^*(\xi))d\xi + c_{s_n} q_n^*(\theta_n) - \alpha_n\theta_n W_n(q_n^*(\theta_n)). \tag{B.17}$$

The optimal contract for the supplier is $(q_n^*(\theta_n),\ M_n(q_n^*(\theta_n)))$.

(ii) Substituting Equation (B.17) into the payoff function of the supplier, the profit of the supplier equals to $r(\theta)$. The result of the mixed partial differential in terms of θ_n and $Q^*(\theta_n)$ is greater than or equal to zero, because $W(Q(\theta_1, \ldots, \theta_n))$ is an increasing function.

Q.E.D.

In Proposition 4.6, the first result indicates that the optimal structure of a contract with a partially ordered set consists of the suppliers' types. With respect to the characteristics among $\theta_i, Q_i(\theta_1, \ldots, \theta_n)$, and $K(Q_i(\theta_1, \ldots, \theta_n))$, the optimal purchasing contract is $Q^*(\theta_1, \ldots, \theta_n) = Q^*(\theta_n)$ and $Q^*(\theta_j) = 0, j = 1, 2, \ldots, n-1$. $Q^*(_n)$ is the maximizer of the concave function $K(Q_i(\theta_1, \ldots, \theta_n))$. The second property of Proposition 4.6 implies that the suppliers' payoff is the consistent with the manufacturer's payoff. This type of contract is a win-win situation in the pursuit of both parties' own interests. In addition, Propositions 4.4, 4.5, and 4.6 indicate that incentive schemes can also be applied to a scenario with n independent potential suppliers.

This section discussed the extension of the basic model formulated in Section 4.2. Under the scenario with multiple independent suppliers, the robustness of the results were studied, and the results indicate that the scenario with multiple independent suppliers yields similar results as the optimal contract for a single supplier. In the next section, three extensions, including the emissions trading policy, price auction with a carbon emissions target, and a performance-based auction, are further analyzed.

4.5 Model Extensions

4.5.1 Emissions Trading Policy

Based on the structure analysis of the payoff functions of suppliers and the manufacturer, this section focuses on studying the optimal emissions trading policy for the manufacturer. The details of the policy are as follows:

Proposition 4.7. *Given an order quantity $Q(\theta)$, the optimal emissions trading policy is a piecewise function that is designed to maximize the payoff of the manufacturer. In addition, both the lower and the upper bounds increase in $Q(\theta)$.*

$$C^* = \begin{cases} L(Q(\theta)), & if\ C \leqslant L(Q(\theta)) \\ C, & if\ L(Q(\theta)) \leqslant C \leqslant U(Q(\theta)) \\ U(Q(\theta)), & if C \geqslant U(Q(\theta)) \end{cases}, \tag{4.23}$$

where

$$U(Q(\theta)) = arg\max_C\{R(Q(\theta)) - M(Q(\theta)) + w_1\mathbb{E}(C - \beta Q(\theta))^+\} \tag{4.24}$$

$$L(Q(\theta)) = arg\max_C\{R(Q(\theta)) - M(Q(\theta)) - w_2\mathbb{E}(\beta Q(\theta) - C)^+\} \tag{4.25}$$

Proof of Proposition 4.7.

Based on the integrated function of the manufacturer,

$$\begin{aligned} G(Q(\theta)) &= R(Q(\theta)) + T(Q(\theta)) - \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \\ &= p\mathbb{E}min(Q(\theta), D) + c_h\mathbb{E}(Q(\theta) - D)^+ - c_p Q(\theta) + w_1\mathbb{E}(C - \beta Q(\theta))^+ \\ &- w_2\mathbb{E}(\beta Q(\theta) - C)^+ - \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \end{aligned} \tag{B.18}$$

The above equation can be rewritten as

$$\begin{aligned} G(Q(\theta)) = &\max\{R(Q(\theta)) - M(Q(\theta)) + w_1\mathbb{E}(C - \beta Q(\theta))^+, \\ &R(Q(\theta)) - M(Q(\theta)) - w_2(\beta Q(\theta) - C)^+\}, \end{aligned} \tag{B.19}$$

where $M(Q(\theta)) = \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} - \alpha\theta W(Q(\theta)) + c_s Q(\theta)$.

Define

$$U(Q(\theta)) = \arg\max_C\{T_1(Q(\theta), C)\} = \arg\max_C\{R(Q(\theta)) - M(Q(\theta)) + w_1\mathbb{E}(C - \beta Q(\theta))^+\} \tag{B.20}$$

$$L(Q(\theta)) = \arg\max_C\{T_2(Q(\theta), C)\} = \arg\max_C\{R(Q(\theta)) - M(Q(\theta)) - w_2\mathbb{E}(\beta Q(\theta) - C)^+\} \tag{B.21}$$

$$\frac{\partial^2 w_1\mathbb{E}(C - \beta Q(\theta))^+}{\partial Q(\theta)\partial\theta} = w_1\beta^2 h(\beta Q(\theta))Q'(\theta) \tag{B.22}$$

$$\frac{\partial^2 w_2\mathbb{E}(\beta Q(\theta) - C)^+}{\partial Q(\theta)\partial\theta} = w_2\beta^2 h(\beta Q(\theta))Q'(\theta) \tag{B.23}$$

Both Equations (B.20) and (B.21) are greater than zero, thus, $w_1\mathbb{E}(C-\beta Q(\theta))^+$ and $w_2\mathbb{E}(\beta Q(\theta)-C)^+$ are supermodular in $(\theta, Q(\theta))$.

In addition,

$$\frac{\partial(R(Q(\theta))-M(Q(\theta)))}{\partial Q(\theta)\partial\theta} = \alpha W'(Q(\theta))\frac{f(\theta)(1-F(\theta))+f^2(\theta)}{f^2(\theta)} + \alpha W'(Q(\theta)) \tag{B.24}$$

is greater than zero, thus, $R(Q(\theta))-M(Q(\theta))$ is supermodular in $(\theta, Q(\theta))$.

Following the above analysis and Theorem 2.6.4 [Top98], both $T_1(Q(\theta), C)$ and $T_2(Q(\theta), C)$ are supermodular in $(\theta, Q(\theta))$. Therefore, following the above analysis and Theorem 2.7.6 and Theorem 2.8.2 [Top98], both $L(Q(\theta))$ and $U(Q(\theta))$ are increasing in $Q(\theta)$.

Q.E.D.

Proposition 4.7 specifies the optimal emissions trading policy, which consists of lower $(L(Q(\theta)))$ and upper $(U(Q(\theta)))$ bounds on the emissions level of the manufacturer. In a certain period, if the current emissions allowances are greater than $U(Q(\theta))$, the manufacturer should sell the redundant emission volumes to the trading market; if the current emissions allowances are less than $L(Q(\theta))$, the manufacturer should purchase additional allowances to cover the gap. That is, the manufacturer should increase its emissions allowances to be at least $L(Q(\theta))$. Note that both the lower and upper bounds are non-decreasing in $Q(\theta)$. With the guidance of the emissions trading policy, the manufacturer can adjust the emissions trading policy in a timely manner to maximize its profit by holding appropriate emission allowances.

4.5.2 Price Auction with a Carbon Emission Target

Facing a carbon emissions target, a manufacturer can calculate the required order quantity. That is, the manufacturer would select the target supplier with a fixed green degree and a reasonable price. We focus on the symmetric case, in which the confidential values of all suppliers are drawn from a common cdf F, which is a continuous function.

For the first price bid, suppose that all suppliers except supplier i bid following function $\delta(\cdot)$; let p denote the bidding price for supplier i. Assume that $\delta(\cdot)$ is an increasing function. The bidder wins if and only if $p < \delta^{-1}(p_j)$, or equivalently, $\delta^{-1}(p) < p_j$, for all $j \neq i$, which occurs with probability $\Pr(p_j > \delta^{-1}(p))$. Here, we define that a function of the emissions cost and the production cost for supplier i is $\mu(\theta_i)$ times p. Therefore, the expected profit of supplier i can be formulated as follows:

$$\Pi_i = (x - \mu(\theta_i)p)\Pr(p_j > \delta^{-1}(p)). \tag{4.26}$$

Proposition 4.8. *Consider a price auction with an emissions target. With n independent suppliers, the symmetric Bayesian-Nash equilibrium bidding strategy on the first price bid is* $\frac{\mathbb{E}(P|P\leqslant p)}{\mu(\theta_i)}$, *where* P *is the highest price among the remaining* $n-1$ *bidders,* $P = \max\{p_j\},\ j \neq i$. *The second price bid for the weakly dominant strategy is* $\frac{x}{\mu(\theta_i)}$.

Proof of Proposition 4.8.

We focus on the first price auction only, because the second price auction is straightforward. Assume player j will bid lower than p if and only if the value of the order is less than $\delta^{-1}(p)$. Then, the probability for all players to bid less than p is $(1 - F(\delta^{-1}(p)))^{n-1}$. Thus, supplier i's expected profit is $\Pi_i =$

$(x - \mu(\theta_i)p)\mathrm{Pr}(p_j > \delta^{-1}(p))$, and $\delta(\cdot)$ is a Bayesian-Nash equilibrium only if Π_i is maximized by $p = \delta(x)$. The first order condition for the optimal p should satisfy:

$$-\delta'(x)(F(x))^{n-1} + (x - \mu(\theta_i)\delta(x))(F(x)^{n-1})' = 0. \tag{B.25}$$

The above equation can be written as:

$$(\mu(\theta_i)\delta(x)F(x)^{n-1})' = x(F(x)^{n-1})' \tag{B.26}$$

Let $\underline{x}$ be the smallest x under which the bidder does not bid, then $\delta(x) = 0$. Therefore,

$$\delta(x) = \frac{1}{F(x)^{n-1}} \int_{\underline{x}}^{x} zdF(z)^{n-1} = \frac{1}{\mu(\theta_i)}\mathbb{E}(P|P \leqslant p), \tag{B.27}$$

where $P = \max\{p_j\},\ j \neq i.$

Q.E.D.

In a price auction with a carbon emissions target, the required order quantity is first determined by the emissions capacity of the manufacturer. That is, the manufacturer establishes the target objectives for the cooperation with a certain type of suppliers. Thus, independent suppliers only aim at bidding on their profits. The advantages of this type of auction can further narrow the option pool for the manufacturer.

4.5.3 A Performance-Based Auction

In a performance-based auction, a supplier submits all of the bidding information simultaneously, including the green degree and the price. The manufacturer then evaluates the bidding information following the evaluation procedure. The evaluation results reflect the performance of suppliers from different dimensions. Without loss of generality, assume that a supplier submits (θ, M), which denotes the green degree and the cash transfer of the supplier, respectively. Let $V(\theta, M)$ denote the performance of a supplier, which is determined by the manufacturer. By adopting this auction type, the manufacturer cooperates with the supplier with the highest performance. The evaluation function for the determination of the suppliers performance is as follows:

$$V(\theta, p) = M(Q(\theta)) + c_m Q(\theta) \tag{4.27}$$

Proposition 4.9. *For a performance-based auction,*

(i) following the evaluation function, $V(\theta, M)$, the dominant strategy for a supplier is to bid the optimal green degree θ^* and M^*;

(ii) with n independent suppliers, the symmetric equilibrium bidding strategy on the first bidding strategy is $(\theta^*(c_s), M^*)$, where $M^* = \delta(\theta^*) - c_m Q^*(\theta)$, $\delta(\theta^*) = \mathbb{E}[Z(\theta^*)|Y < v]$, $Y = max\{v_1, v_2, \ldots, v_{n-1}\}$, $Z(\theta^*) = (c_s + c_m)Q(\theta^*) - \alpha\theta^* W(Q(\theta^*))$.

Proof of Proposition 4.9.

For a supplier with bidding information (θ, M), the supplier with a certain performance v, wins the contract, the following mathematical programming model should be satisfied:

$$\begin{aligned} &\max_{\theta,p} \Pi_s = M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \\ &s.t.\ M(Q(\theta)) + c_m Q(\theta) = v \end{aligned} \tag{B.28}$$

It is equivalent to maximizing $v-(c_s+c_m)Q(\theta)+\alpha\theta W(Q(\theta))$ with respect to the decision variable θ, so the optimal value of θ can be expressed as

$$\theta^* = \arg\max_{\theta}\{v-(c_s+c_m)Q(\theta)+\alpha\theta W(Q(\theta))\}. \tag{B.29}$$

Assume supplier i wins if and only if $v > \delta(v_j)$, or equivalently $\delta^{-1}(v) > v_j$ for all $j = 1, ..., n, j \neq i$, which occurs with probability $\Pr(\delta^{-1}(v) > v_j)$. Therefore, the expected profit of supplier i is:

$$\begin{aligned}\Pi_i &= [v-(c_s+c_m)Q(\theta)+\alpha\theta W(Q(\theta))]\Pr(\delta^{-1}(v) > v_j)\\ &= [v-(c_s+c_m)Q(\theta)+\alpha\theta W(Q(\theta))][F(\delta^{-1}(v))]^{n-1}\end{aligned} \tag{B.30}$$

The first order derivative for the optimal v should satisfy:

$$F(\delta^{-1}(v))^{n-1} + [v-(c_s+c_m)Q(\theta)+\alpha\theta W(Q(\theta))][F(\delta^{-1}(v))^{n-1}]' = 0. \tag{B.31}$$

Because $\theta = \delta^{-1}(v)$, then, $v = \delta(\theta)$, and rearranging the above equation yields,

$$[\delta(\theta)]' = [(c_s+c_m)Q(\theta)-\alpha\theta W(Q(\theta))][F(\delta^{-1}(v))^{n-1}]', \tag{B.32}$$

which implies:

$$\delta(\theta)F(\delta^{-1}(v))^{n-1} = \int_{\underline{\theta}}^{\theta}\{[(c_s+c_m)Q(\xi)-\alpha\theta W(Q(\xi))][F(\xi^{-1}(v))^{n-1}]'\}d\xi. \tag{B.33}$$

Let $H(v) = \Pr\{\max\{v_1, v_2, \ldots, v_{n-1}\} \leqslant v\} = F(v)^{n-1}$, and $Y = \max\{v_1, v_2, \ldots, v_{n-1}\}$. Then, Y has its cdf $H(\cdot)$ and pdf $h(\cdot)$.

$$\delta^*(\theta)\frac{1}{H(\theta)}\int_{\underline{\theta}}^{\theta}[(c_s+c_m)Q(\xi)-\alpha\theta W(Q(\xi))]h(\xi)d\xi = \mathbb{E}[Z(\theta^*)|Y < v], \tag{B.34}$$

where $Z(\theta^*) = (c_s + c_m)Q(\theta^*) - \alpha\theta W(Q(\theta^*))$, therefore, $M^*(Q(\theta)) = \delta^*(\theta) - c_m Q^*(\theta)$.

Q.E.D.

The intuition of Proposition 4.9 is straightforward: the optimal strategy for independent suppliers is to bid according to their green degree, which is essentially determined by the suppliers' production cost. Another parameter, the bidding price, is determined by the optimal value of the green degree θ^*. This type of auction is an alternative method of selecting appropriate suppliers for the manufacturer. The difference between a price auction with an emissions target and a performance-based auction is that the former only focuses on the price of the raw material from suppliers, whereas the latter provides a more comprehensive viewpoint for the manufacturer to design reasonable contracts. In addition, the evaluation function can also be modified to fit different decision preferences; that is, the performance function can be developed with other evaluation criteria.

4.6 Managerial Implications

Starting from the viewpoint of sustainable operations management, we present a game model to illustrate the intersection of supplier evaluation, emissions trading mechanisms, and asymmetric contract design. The research results provide meaningful managerial implications for contract design for both the manufacturer and suppliers. The manufacturer can understand how to design attractive contracts to jointly maximize profit and emissions trading benefits. The suppliers should have a better understanding of methods for maintaining or increasing their market shares and the mutual effects of the strategies on the manufacturer and suppliers. The suppliers can benefit from the findings by understanding the outcomes of adopting flexible strategies in different auction types.

For manufacturers, balancing the environmental cost and revenue is a key goal. In practice, the total emissions volume of a manufacturer is predominantly determined by the green degree, θ, of the raw materials from the suppliers. However, this factor is confidential information known only to the supplier. The results of the comparative statics analysis indicate that θ brings a different concern to the manufacturer's decision and the payoffs of the manufacturer. Under an emissions trading scheme, the manufacturer prefers to cooperate with a greener supplier with sufficient emission allowances because the manufacturer can benefit from emissions trading. As an example of a typical case in China, Beijing Eastern Petrochemical Co. Ltd. earned 0.5 million RMB in profit in 2015 [Bei15]. Otherwise, the manufacturer has to select the supplier with the lower green degree. This reduces the amount of funds that can be used to purchase emission allowances from the carbon market. The effective emissions trading policy was established to guide the manufacturer in making reasonable trading decisions. Regarding the payoffs for the members of the supply chain, the research results indicate that the incremental revenue for the manufacturer to choose a higher ordering quantity $Q(\theta)$ is greater when θ is greater.

Regarding the suppliers, we first identified the optimal contract design between a single supplier and the manufacturer. The optimal contract not only can provide an effective control for the manufacturer but also can assist the manufacturer in developing a stable cooperative relationship in consideration of asymmetric information from suppliers. The results indicate that there are increasing differences in the payoffs of the suppliers with respect to their green degrees and supply quantities. That is, a supplier can rapidly enlarge its market share by providing greener raw materials or updating its production technology, which would be a strong competitive advantage for the supplier. To observe additional outcomes in a general setting, we further tested the robustness of the aforementioned results. In addition, two other types of auctions are analyzed for the supplier. For a price auction with a carbon emissions target, the ordering quantity of the manufacturer is predominately determined by its emissions target, that is, a certain type of supplier is screened out. In this scenario, the supplier only aims at bidding by providing the most attractive price. In a performance-based auction, the bidding information not only includes the green degree but also involves the price because these two factors operate simultaneously. The performance of the supplier is a key factor for the manufacturer in making procurement decisions.

In general, to achieve the goal of mutual benefit of profit-maximization and carbon emissions control, the aforementioned three types of mechanisms provide an effective method to promote sustainable operations for the upstream of a supply chain.

4.7 Summary

The issue of contract design in the presence of asymmetric information in a supply chain with a manufacturer and multiple suppliers facing uncertain demand and subject to an emissions trading scheme was studied in this chapter. Regarding the confidential information for the green degree of the raw materials from suppliers, the manufacturer needs to adopt reasonable procurement strategies to earn profit and control its emissions volumes under the emissions trading policy. Therefore, selecting the appropriate suppliers and setting attractive payment rates are the two key issues for profit-maximization for the manufacturer. This chapter revealed the concerns and analyzed a general contract design for this problem setting.

First, a basic model was developed. This model focuses on contract design with a single supplier. Following the emissions trading policy, the manufacturer seeks to maximize its expected profit by trading its emission allowances. The optimal procurement strategy in this situation was derived. Moreover, the relationship between the green degree of a supplier and the optimal structure of the contract were further analyzed. The results demonstrate that this mechanism is effective for both the manufacturer and the supplier.

The impact of multiple independent suppliers on the manufacturers decision is also worth studying. Therefore, a second model for the general setting of multiple suppliers based on the basic model was formulated, and the robustness characteristics of a single supplier was analyzed.

Third, on the basis of a structured analysis of an auction with a single manufacturer and multiple suppliers, an effective emissions trading policy for the manufacturer to control its carbon emission allowances was determined. The lower and upper bounds of the emissions capacity for the manufacturer were derived to guide the manufacturer to balance its environmental costs effectively. In addition, two extensions to alternative auctions, including a price auction with an emissions target and a green performance-based auction, were studied. These two auction types are flexible methods for a manufacturer to control its emissions.

In summary, this chapter analyzed a significant procurement issue for a manufacturer subject to information asymmetry regarding its suppliers' green degrees. The findings in this chapter provide insight into this procurement issue. Future research may investigate how the key factors, such as emissions trading prices and a carbon tax, affect the pricing issue for the manufacturer. In addition, it is worthwhile to study methods of selecting the appropriate factory locations for the manufacturers under different types of carbon emission regulations.

Chapter 5

Coordinated Pricing Analysis under the Carbon Tax Scheme

5.1 Introduction

Human activities have brought huge challenges, particularly the phenomenon of global warming, to the sustainable development of Earth. Curbing greenhouse gas (GHG) emissions is considered a significant way to develop sustainability worldwide. According to McKinsey survey, 43% of the interviewed companies in 2014 seek to align sustainability with their overall business goals, mission, or values up from 30% in 2012 [Mck14]. In practice, several actions have been implemented in different countries to develop sustainability. For example, the United States Environmental Protection Agency (EPA) has carried out a clean power plan with the aim to improve the environment, health, and the economy [Uni15a]. Besides, as an effective financial instrument, the carbon tax scheme has been implemented in several countries to incentivize firms to improve sustainability by adopting cleaner production technologies or using environmentally friendly raw materials [Max16]. For instance, British Columbia (B.C.) implemented the carbon tax on July 1, 2008, at a rate of C$10 per ton of CO_2. In 2015, the B.C. carbon tax was increased to C$30 per ton of CO_2 [Mur15]. In Australia, the initial price of the carbon tax was set as a fixed number. However, it was replaced by a flexible price, which is determined by the market, on July 1, 2015 [Ora15].

Constrained by the carbon tax scheme, firms are under strong pressure to respond to business pricing. Based on a survey from Ai Australian Industry Group, there is a large gap between the proportion of manufacturing businesses experiencing immediate input price rises (61%) and the proportion of manufacturing businesses planning to increase their selling prices (40%) as a result of a carbon tax [Aia13]. In particular, food manufacturers prefer to immediate input price rises and pass on environmental-related costs through the supply chain to the end consumers of products [Aia13]. In addition, to produce sustainable products, manufacturers must source sustainably materials from suppliers, however, in practice, it is challenging to source sustainable inputs [Agr16]. Therefore, it is crucial for firms to identify effective methods of determining appropriate pricing and choosing environmentally friendly materials from upstream suppliers to reduce GHG emissions simultaneously.

This chapter takes the viewpoint of how to coordinate pricing in a supply chain with multiple suppliers and a manufacturer. That is, we focus on the interaction of different pricing strategies for profit-maximization suppliers and the manufacturer under the carbon tax scheme. In such a situation, suppliers have a fixed initial inventory setting, and they compete with each other by adjusting their sales price to enlarge their business volume share. With respect to the manufacturer, reasonable procurement decisions should be made with flexible ordering probabilities to satisfy demand in consideration of the carbon emissions cost. To curb emissions amount, the ordering probability of the manufacturer depends on the unit procurement price of raw materials, the emission rates of suppliers, the procurement schedule, and the total emissions volumes of the manufacturer.

This research work also aims to identify reasonable strategies for the dynamically coordinated pricing issue. Two-stage differential game models are formulated to describe the aforementioned coordination issues for the manufacturer and suppliers. The effects of the variances of state conditions on pricing strategies are analyzed. To perform this analysis, the open-loop equilibrium and the Markovian Nash equilibrium for two sub-games of the two-stage game are derived. These solutions can be used to establish appropriate operations strategies for both suppliers and the manufacturer under different scenarios. The trade-off of the game models also indicates a supplier selection issue for the manufacturer. Should a manufacturer purchase more from a greener supplier with environmentally friendly raw materials or a traditional supplier with a lower procurement price? How can this decision affect the pricing strategy of the manufacturer?

The main purpose of this chapter is to seek a better understanding for this topic. A comparative statics analysis is conducted based on the equilibrium prices of both suppliers and the manufacturer, and whether the parameters (e.g., the market size, the production cost, and the carbon tax) can affect the pricing issue.

Several scholars have studied the pricing issue from the viewpoints involving discrete and continuous time. Debo et al. [Deb05] studied the joint pricing and production technology selected for remanufacturable products in a market consisting of heterogeneous consumers. Using the Arrow-Karlin model, Dobos [Dob05] studied the production and inventory strategy of a firm under the emissions trading scheme. The linear emissions procurement or selling cost was integrated into the model. Perakis and Sood [Per06] analyzed a discrete-time stochastic game for the pricing issue. The purpose of their study was to address the competitive aspect of the problem along with demand uncertainty using robust optimization and variational inequalities. Mookherjee and Friesz [Moo08] also focused on a discrete-time dynamic game model to study the integrated problems including pricing, resource allocation, and overbooking under random demand. Martnez-de-Albniz and Talluri [Mar11] studied price competition for an oligopoly in a dynamic setting. A unique subgame-perfect equilibrium for a duopoly was presented. This game model can extend the marginal-value concept of bid-price control to a competitive model. In addition, Liu and Zhang [Liu13] considered dynamic pricing competition between two firms which offer vertically differentiated products to strategic customers. The results show that high-end businesses charging constant prices are frequently a desirable market outcome for sellers.

This chapter focuses on the topic, which is an intersection of green procurement from multiple suppliers, the efficacy of the carbon tax scheme in operations management, and coordination of pricing. This research work is the initial work on the coordinated pricing issue for both suppliers and the manufacturer in the presence of inventory and carbon emissions constraints. The open-loop equilibrium and the Markovian Nash equilibrium for both suppliers and the manufacturer over an infinite time horizon are analyzed. Secondly, in the scenario of multiple suppliers, a more general model is developed to derive more general equilibrium strategies of the manufacturer. Thirdly, the effect of the carbon tax on the price setting and emissions control for the manufacturer is investigated. In addition, the monotonicity characteristics for equilibrium of the game models are analyzed.

The remainder of this chapter is organized as follows. Section 2 describes the basic setting of dynamic pricing game models for both suppliers and the manufacturer. Section 3 identifies the open-loop equilibrium and the Markovian Nash equilibrium for two sub-games. In addition, a comparative statics analysis is conducted for these equilibria of the sub-games. To observe a more general outcome, Section 4 extends the basic sub-game model of the manufacturer and a single supplier to an n-suppliers oligopoly. Section 5 summaries this chapter.

5.2 Model Setup

In the model setting, both suppliers and the manufacturer independently set the sales prices in a decentralized supply chain. With suppliers being the Stackelberg leader, we consider two separate games to analyze the strategic price interactions over time. Each individual supplier determines its sales price and production rate with respect to the variance of its inventory level.

This section aims to analyze a pricing issue in a supply chain with a manufacturer and n ($n \geqslant 1$) suppliers, which is constrained the carbon tax scheme, over an infinite time horizon. Firstly, suppliers determine their sales prices of different types of raw materials, i.e., environmentally friendly raw materials and traditional raw materials, to the manufacturer who adopts an assemble to order (ATO) strategy. Secondly, under the constraint of the carbon tax scheme, the manufacturer can choose a supplier who provides substitutable raw materials with reasonable prices. The sales prices of the supplier can be set or adjusted in each period to enlarge its business volume share. In the basic model setting, two types of suppliers: traditional and environmental are considered. A traditional supplier provides raw materials with a lower sales price, but the emissions rate of the raw materials is high; an environmental supplier has a lower emissions rate but a higher sales price. Based on the price setting of suppliers, the manufacturer determines its ordering probability. Then, under the carbon tax scheme, the manufacturer makes dynamic adjustment regarding its sales price and emissions amount. This chapter focuses on complicated operations issues, including production and inventory management, pricing, procurement planning, and emissions control between suppliers and the manufacturer. The manufacturer can cooperate with traditional suppliers, environmental suppliers or both types of suppliers. In particular, the manufacturer's profit is predominantly determined by the procurement cost and the carbon tax. With respect to the demand function, assume that $D(p,\omega) := \varepsilon d(p) + \mu$, where $\omega = (\varepsilon, \mu)$ is an independent variable over the time horizon. The additive and multiplicative scenarios are two special cases where $\varepsilon = 1$ and $\mu = 0$, respectively [Che04], of the this demand function.

5.2.1 The Supplier's Decision Issue

For each individual supplier, the emissions rate of its product (raw material) is directly determined by its production technology. Therefore, the value of the emissions rate can be taken as a fixed constant. In such a scenario, a supplier predominately focuses on production planning, inventory control, and price setting to maximize its profit. With respect to the demand function of the supplier, $D_s(t) = \alpha_s - \beta_s p_s(t)$, the additive case is adopted, where α_s is the vertical intercept and β_s is the slope of the demand curve; both α_s and β_s are nonnegative constants. The sales price of the raw material of a supplier, $p_s(t)$, directly determines the demand of a supplier. Due to the mutual influence between production and inventory control, the inventory dynamics of the individual supplier can be modeled with the following kinematic equation.

$$\dot{x}_s(t) = q_s(t) + x_s(t) - D_s(t), \tag{5.1}$$

where $x_s(t)$ denotes the inventory level of the supplier, and $q_s(t)$ is the production rate of the supplier. The available inventory level is the summation of the production quantity and the leftover inventory. As shown in Equation (5.1), for a certain period t, the dynamics of the inventory level is the difference between the available inventory level and the demand. Assume the initial inventory level of the supplier is zero, i.e., $x(0) = 0$.

Each individual supplier tries to maximize its cumulative profits over an infinite time horizon. Let r denote the discount rate, which is an exogenous variable. On the basis of the dynamic processes of demand and inventory in Equation (5.1), the net discounted profit, Π_s, of the supplier over an infinite horizon can be established as follows.

$$\Pi_s = \int_0^\infty e^{-rt}[p_s(t)D_s(t) - \frac{1}{2}h_s x_s^2(t) - \frac{1}{2}c_s q_s^2(t)]dt \tag{5.2}$$

In Equation (5.2), the supplier's sales revenue is given by $p_s(t)(\alpha_s - \beta_s p_s(t))$. Backlogging is allowed in this model; that is, the holding cost is incurred by the leftover raw materials at the end of each period. The holding cost is modeled as $\frac{1}{2}h_s x_s^2(t)$, where h_s is the unit holding cost for each raw material, as the level of inventory increases, so does the labor force or time spent in inventory, which in turn increases the risk of obsolescence [Cho13]. The production cost is given by $\frac{1}{2}c_s q_s^2(t)$, where c_s is the unit production cost, that is, production cost is a convex increasing in production rate. In addition, the holding cost and the production cost are modeled using the quadratic concave functions to fit practical situations [Jor86; Eri11].

5.2.2 The Manufacturer's Decision Issue

Under the carbon emission regulation, i.e., the carbon tax scheme, the emissions-related cost is the vital component of the manufacturer's total cost. Let $E(t)$ denote the emissions amount of the manufacturer in period t, which is predominantly determined by the emission rates of raw materials and the demand of the manufacturer. In the basic mode, we assume that the manufacturer purchases raw materials from two suppliers, i.e., supplier 1 (the traditional supplier) and supplier 2 (the environmental supplier), with ordering probabilities ξ and $1-\xi$, respectively. Here, we use multinomial logit to describe the ordering probability [Lin09].

$$\xi = \frac{e^{\tau_1 - \rho p_1}}{\sum_{i=1}^{2} e^{\tau_i - \rho p_i}}, \tag{5.3}$$

where τ_i is the manufacturer's expected utility for the raw materials from supplier i, and ρ is the price sensitivity parameter.

Analogously, the additive demand function is applied to describe the demand of the manufacturer, $D_m(t) = \alpha_m - \beta_m p_m(t)$, where $p_m(t)$ is the unit sales price of the manufacturer; both α_m and β_m are nonnegative constants. Let ε_i and p_i denote the unit emissions rate and the sales price of supplier i, where $i = 1, 2$. Assume $\varepsilon_1 > \varepsilon_2 > 0$ and $0 < p_1 < p_2$. This assumption means that supplier i cannot strictly dominate the other with respect to ε_i and p_i. Therefore, $E(t)$ can be established as the following kinematic equation.

$$\dot{E}(t) = \varepsilon_1 \xi(\alpha_m - \beta_m p_m(t)) + \varepsilon_2(1-\xi)(\alpha_m - \beta_m p_m(t)) + zE(t) \tag{5.4}$$

The first two parts of Equation (5.4) represent the emissions amount incurred using raw materials from suppliers 1 and 2, respectively. The third part is the amount of environmental absorption, where z ($z < 0$) is the absorption rate. In particular, the model can also be applied to study the scenario of procurement management from multiple suppliers, which will be discussed in the following section. At the initial period, assume the emissions amount of the manufacturer is zero, i.e., $E(0) = 0$.

The objective of the manufacturer is to maximize its profits over an infinite time horizon. The profit discounting is accomplished through discount factor e^{rt}, where r is the discount rate (an exogenous variable). It is particularly important to discount returns if the time horizon is infinite, so the integrand as shown in Equation (5.5) can be finite [Eri11]. Following the emissions dynamics in Equation (5.4), the payoff function of the manufacturer can be formulated as follows.

$$\Pi_m = \int_0^{\infty} e^{-rt}[\xi(p_m(t) - p_1(t))D_m(t) + (1-\xi)(p_m(t) - p_2(t))D_m(t) - \frac{1}{2}\omega E^2(t)]dt \tag{5.5}$$

With respect to the integrand as shown in Equation (5.5), the first two parts represent the revenue using the raw materials from suppliers 1 and 2, respectively. The purchasing quantity is determined by ordering probability ξ. The third term is the emissions-related cost incurred by the carbon tax scheme. In this chapter, the emissions cost is established using a quadratic concave function [Sub07; Cho13; Ber14; lis14], and the unit carbon tax, ω, is determined by the government. The difference value in the total revenue and the emissions cost is the profit of the manufacturer. In this model, in consideration of dynamic pricing with the constraint of the carbon tax scheme, since a manufacturer adopts an ATO strategy; thus, the inventory cost is ignored.

5.3 Equilibrium Analysis

This section focuses on the equilibrium analysis of two sub-games, including the supplier sub-game and the manufacturer sub-game, under the carbon tax scheme. Both the two suppliers and the manufacturer seek to maximize their payoff functions (the present value of the profit functions) by adopting appropriate pricing strategies over an infinite time horizon. Assume suppliers and the manufacturer make their decisions simultaneously. Then, equilibria, including open-loop equilibrium and Markovian Nash equilibrium, for the individual supplier and the manufacturer, respectively, are derived. Both open-loop and the Markovian Nash of equilibria can be regarded as the solutions of two different models under specific situations, where the former one depends only on time and the later one is made based on the state variable at that particular time [Chi12]. There is no reason to believe that one type of equilibrium is generally better than another [Doc00].

5.3.1 Supplier's Sub-game Division

This subsection aims to address issues of optimal production and inventory management for an individual supplier. The decision issues are the optimization of the inventory level, which is a state variable, and the sales price and the production rate, which are control variables.

On the basis of the standard procedure from differential game theory [Doc00], the Hamiltonian function of the supplier sub-game can be established as follows:

$$H_s = p_s(t)(\alpha_s - \beta_s p_s(t)) - \frac{1}{2} h_s x_s^2(t) - \frac{1}{2} c_s q_s^2(t) + \lambda[q_s(t) + x_s(t) - (\alpha_s - \beta_s p_s(t))] \quad (5.6)$$

where λ is a co-state variable (or the shadow price).

The supplier's necessary conditions for optimality are

$$\frac{\partial H_s}{\partial p_s} = \alpha_s - 2\beta_s p_s(t) + \lambda\beta_s = 0 \tag{5.7}$$

$$\frac{\partial H_s}{\partial q_s} = -c_s q_s + \lambda = 0 \tag{5.8}$$

Now, $p_s = (1/2)(\alpha_s/\beta_s + \lambda)$ and $q_s = \lambda/c_s$ can be got.

Proposition 5.1. *There exists the Nash equilibrium for the supplier's sub-game.*

Proof of Proposition 5.1.

Based on the Hamiltonian function of the supplier,that is, Equation (5.6), the Hession matrix for both p_s and q_s can be formulated as follows.

$$HM_s = \begin{bmatrix} \frac{\partial^2 H_s}{\partial^2 q_s} & \frac{\partial^2 H_s}{\partial q_s \partial p_s} \\ \frac{\partial^2 H_s}{\partial p_s \partial q_s} & \frac{\partial^2 H_s}{\partial^2 p_s} \end{bmatrix} = \begin{bmatrix} -c_s & 0 \\ 0 & -2\beta_s \end{bmatrix}, \tag{C.1}$$

where c_s and β_s are nonnegative variables.

The Hamiltonian function of the supplier is concave in (p_s, q_s), because the Hessian matrix is negative definite and the Legendre-Clebsch condition [Gra08] can be satisfied.

Q.E.D.

Proposition 5.1 indicates the existence of the Nash equilibrium for the supplier's sub-game model. In addition, the maximized Hamiltonian function of the suppliers sub-game is a concave function with respect to $x_s(t)$, $p_s(t)$, and $q_s(t)$. Therefore, we need to further analyze how these three variables influence the decisions of the supplier. The equilibria analysis for the three variables over time are summarized in the following propositions.

Proposition 5.2. **(Open-Loop Equilibrium)** *The open-loop inventory level, the production rate, and the sales price, respectively, are given by*

$$x_s(t) = \frac{(1-r)\alpha_s}{2(bh_s - r + 1)}(1 - e^{a_1 t}), \tag{5.9}$$

$$q_s(t) = \frac{1}{c_s}\left(\frac{\alpha_s h_s}{2(bh_s - r + 1)} - \frac{(1-r)\alpha_s w_1}{2(bh_s - r + 1)} e^{a_1 t}\right), \tag{5.10}$$

$$p_s(t) = \frac{1}{2}\left(\frac{\alpha_s}{\beta_s} + \frac{\alpha_s h_s}{2(bh_s - r + 1)} - \frac{(1-r)\alpha_s w_1}{2(bh_s - r + 1)} e^{a_1 t}\right), \tag{5.11}$$

where $b = \frac{1}{c_s} + \frac{\beta_s}{2}$,$w_1 = \frac{rb - \sqrt{r^2 - 4r + 4bh_s + 4} - 2}{2b}$ *,and* $a_1 = \frac{1}{2}(r - \sqrt{r^2 - 4r + 4bh_s + 4})$.

Proof of Proposition 5.2.

Substituting p_s and q_s into Equation (5.1), then, the inventory dynamics can be obtained as

$$\dot{x}_s(t) = \left(\frac{1}{c_s} + \frac{\beta_s}{2}\right)\lambda(t) + x_s(t) - \frac{\alpha_s}{2}. \tag{C.2}$$

A non-homogeneous linear system with constant coefficients can be developed as follows, by combining the co-state equation

$$\dot{\lambda}(t) = (r-1)\lambda(t) + h_s x_s(t). \tag{C.3}$$

Note that

$$\begin{bmatrix} \dot{\lambda} \\ \dot{x} \end{bmatrix} = A \begin{bmatrix} \lambda \\ x \end{bmatrix} + B, \tag{C.4}$$

where $A = \begin{bmatrix} r-1 & h_s \\ b & 1 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ -.5\alpha_s \end{bmatrix}$, and $b = \frac{1}{c_s} + \frac{\beta_s}{2}$.

Two eigenvalues of A are denoted by a_1, a_2, and the eigenvector of A is denoted by H as follows.

$$a_1 = .5(r - \sqrt{r^2 - 4r + 4bh_s + 4}), \tag{C.5}$$

$$a_2 = .5(r + \sqrt{r^2 - 4r + 4bh_s + 4}), \tag{C.6}$$

$$H = \begin{bmatrix} \frac{rb-\sqrt{r^2-4r+4bh_s+4}-2}{2b} & \frac{rb+\sqrt{r^2-4r+4bh_s+4}-2}{2b} \\ 1 & 1 \end{bmatrix}. \tag{C.7}$$

Therefore, λ and x can be specified as

$$\begin{aligned} \begin{bmatrix} \lambda \\ x \end{bmatrix} &= H \begin{bmatrix} e^{a_1 t} & 0 \\ 0 & e^{a_2 t} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} - A^{-1}B \\ &= \begin{bmatrix} e^{a_1 t} w_1 & e^{a_2 t} w_2 \\ e^{a_1 t} & e^{a_2 t} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} - \frac{\alpha_s}{2(bh_s - r + 1)} \begin{bmatrix} -h_s \\ r - 1 \end{bmatrix}, \end{aligned} \tag{C.8}$$

where $w_1 = \frac{rb-\sqrt{r^2-4r+4bh_s+4}-2}{2b}$, $w_2 = \frac{rb+\sqrt{r^2-4r+4bh_s+4}-2}{2b}$.

The two boundary conditions $x_s(0) = 0$ and $\lim_{t\to\infty} e^{-rt}\lambda(t)x_s(t) = 0$ imply $k_1 = \frac{\alpha_s(r-1)}{2(bh_s-r+1)}$, and $k_2 = 0$. Thus, the optimal inventory level path, the production path, and the price path can be obtained as follows:

$$x_s(t) = \frac{(1-r)\alpha_s}{2(bh_s - r + 1)}(1 - e^{a_1 t}), \tag{C.9}$$

$$q_s(t) = \frac{1}{c_s}(\frac{\alpha_s h_s}{2(bh_s - r + 1)} - \frac{(1-r)\alpha_s w_1}{2(bh_s - r + 1)} e^{a_1 t}), \tag{C.10}$$

$$p_s(t) = \frac{1}{2}(\frac{\alpha_s}{\beta_s} + \frac{\alpha_s h_s}{2(bh_s - r + 1)} - \frac{(1-r)\alpha_s w_1}{2(bh_s - r + 1)} e^{a_1 t}). \tag{C.11}$$

Q.E.D.

Proposition 5.2 illustrates the optimal operation trajectories, including the sales price, the production rate, and the inventory level of the supplier. When the supplier makes its individual decision at the initial state, both the price trajectory and the trajectory of the production rate demonstrate the decreasing trends. It is because the first order conditions of $p(t)$ and $q(t)$ with respect to t are smaller than zero. The decreasing phenomenon of the inventory level is particularly apparent at the starting phase. Then, with the increasing in the production rate, this phenomenon will increase the inventory level. In addition, the way other parameters involved in control and state variables influence the supplier's decision is worth discussion. Based on Proposition 5.2, closed-forms of the stable states ($t \to \infty$) and their monotonicity can be obtained.

Proposition 5.3. *The stable states of sales price, production rate, and inventory level are given as follows:*

(i) the stable state of the inventory level is

$$\tilde{x} = \frac{(1-r)\alpha_s}{2(bh_s - r + 1)}, \tag{5.12}$$

which is a submodular function in $(h_s,\ \alpha_s)$*;*

(ii) the stable state of the production rate is

$$\tilde{q} = \frac{\alpha_s h_s}{2c_s(bh_s - r + 1)}, \tag{5.13}$$

which is a submodular function in $(\alpha_s,\ c_s)$*;*

(iii) the stable state of the sales price is

$$\tilde{p} = \frac{\alpha_s}{2}\left(\frac{1}{\beta_s} + \frac{h_s}{2(bh_s - r + 1)}\right), \tag{5.14}$$

which is a supermodular function in $(h_s,\ c_s)$*.*

Proof of Proposition 5.3.

Limiting the price path, the path of production rate, and the path of inventory level with respect to time t, enable the stable states of price, production rate, and inventory level, respectively, to be obtained. In view of Topkis [Top98], it is equivalent to verifying that the cross-partials of $\frac{\partial^2 \tilde{x}}{\partial \alpha_s \partial h_s}$, $\frac{\partial^2 \tilde{q}}{\partial \alpha_s \partial c_s} \leqslant 0$, and $\frac{\partial^2 \tilde{p}}{\partial h_s \partial c_s} \geqslant 0$, respectively.

(i) The cross partial derivative of $\tilde{x}$ with respect to h_s and α_s is

$$\frac{\partial^2 \tilde{x}}{\partial \alpha_s \partial h_s} = -\frac{2(1-r)b}{[2(bh_s - r + 1)]^2} < 0s. \tag{C.12}$$

Thus, $\tilde{x}$ is submodular in (α_s, h_s).

(ii) The cross partial derivative of $\tilde{q}$ with respect to α_s and c_s is

$$\frac{\partial^2 \tilde{q}}{\partial \alpha_s \partial c_s} = -\frac{h_s/\beta_s + 2(1-r)}{[2c_s(bh_s - r + 1)]^2} < 0. \tag{C.13}$$

Thus, $\tilde{q}$ is submodular in (α_s, c_s).

(iii) The cross partial derivative of $\tilde{p}$ with respect to h_s and c_s is

$$\frac{\partial^2 \tilde{p}}{\partial h_s \partial c_s} = \frac{(1-r)h_s}{c_s^2(bh_s - r + 1)^3} > 0. \tag{C.14}$$

Thus, $\tilde{p}(t)$ is supermodular in (h_s, c_s).

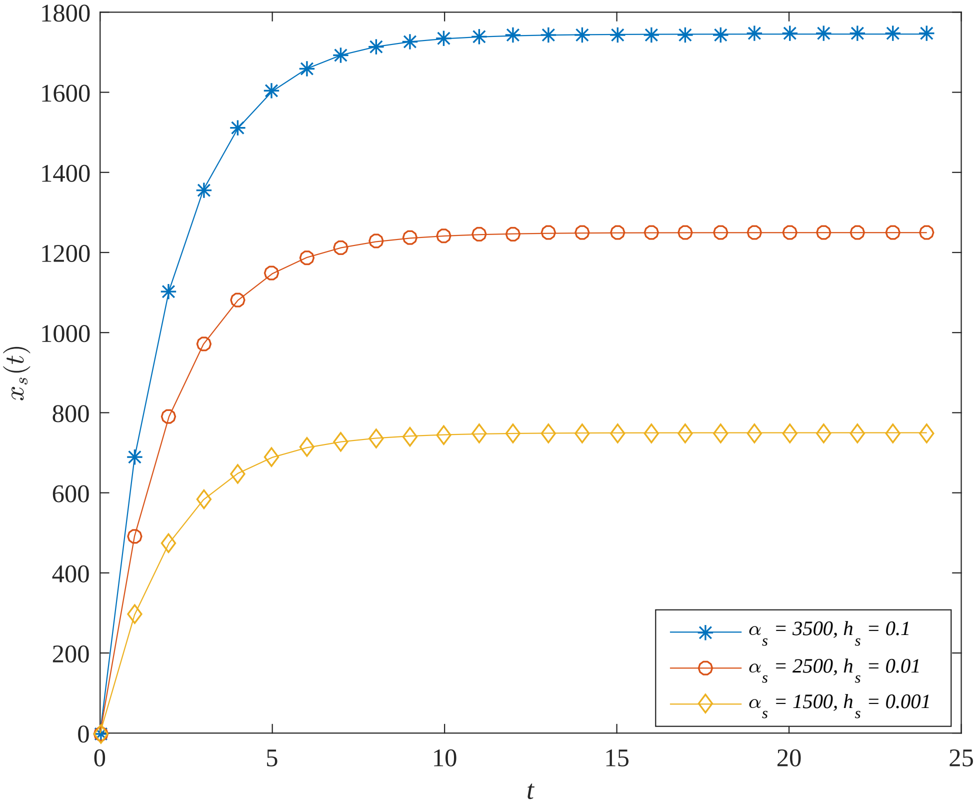
Q.E.D.

As discussed above, the increasing phenomenon is particularly apparent at the starting phase. Therefore, controlling and adjusting these factors for maximization of supplier profit is critical. The results of Proposition 5.3 present stable states of the inventory level, the production rate, and the sales price. In the long-run, their trajectories tend to constant values, which can assist suppliers in coordinating their operational behavior in the initial period. The results in Propositions 5.2 and 5.3 are presented in the following three numerical examples.

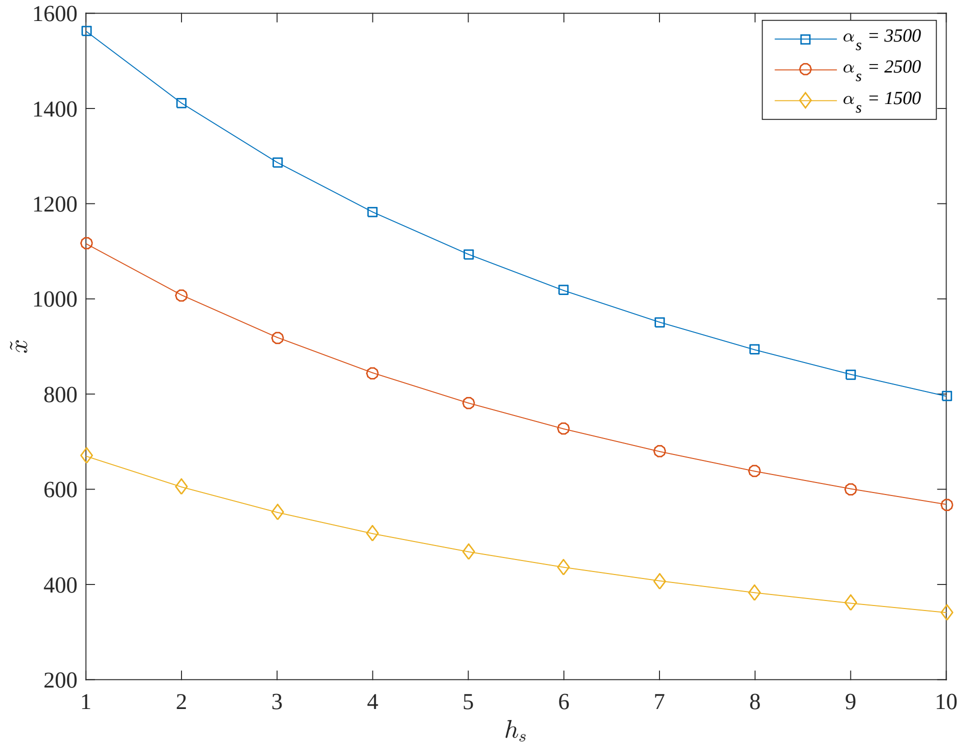
EXAMPLE 1. Suppose $c_s = 100$, $\beta_s = 0.1$, and $r = 0.5$. The inventory trajectory with the variance of h_s and α_s is shown in Figure 5.1 (a), and the submodularity of $\tilde{x}$ is shown in Figure 5.1 (b). As shown in Figure 5.1 (a), $x(t)$ will converge to a constant value, which can be described in a closed-form, as shown in Equation (5.12). With the same initial setting, the supplier is willing to increase the inventory level to meet the large-scale market demand, even facing a higher inventory holding cost. In addition, the submodularity of $\tilde{x}$ implies that the individual supplier needs to adjust its stock level if the holding cost is continuously increasing, even with a larger market size; this is because the supplier has to spend more sales revenue to cover the inventory holding cost.

EXAMPLE 2. Suppose $h_s = 0.8$, $\beta_s = 0.1$, and $r = 0.5$. The trajectory of the production rate with the variance of α_s and c_s is shown in Figure 5.2 (a), and the submodularity of $\tilde{q}$ is shown in Figure 5.2 (b). The production rate converges to a constant value illustrated in Equation (5.13). With respect to $\tilde{q}$, it shows an intuitive result; that is, $\tilde{q}$ is decreasing when both h_s and c_s are increasing. The submodularity of $\tilde{q}$ shows that a supplier will reduce its production rate when facing a smaller market size and a higher unit production cost. In practice, this result can occur when a supplier is preparing for adjustment production technology.

EXAMPLE 3. Suppose $\alpha_s = 10$, $\beta_s = 0.1$, and $r = 0.5$. The price trajectory with the variance of c_s and h_s is shown in Figure 5.3 (a), and the supermodularity of $\tilde{p}(t)$ is shown in Figure 5.3 (b). Considering an increase in c_s and h_s, a supplier will increase the sales price to cover production and inventory costs. In this scenario, the supplier has to increase the sales price; that is, part of the cost will be shifted to the manufacturer. However, with respect to the suppliers, the increase in sales prices could induce a loss of market share. Therefore, there exists a trade-off between the manufacturer and suppliers. Based on sales prices of suppliers, the manufacturer should jointly focus on suppliers sales prices and emissions rates to determine its order profile maximization profit and minimization emissions amount. That is, adopting a new technology to reduce the production cost is a way out for suppliers, particularly for the oligopoly market. Once a supplier takes over the market share from its competitors, it will generate a high barrier for new entrants.



(a)



(b)

FIGURE 5.1: Inventory trajectory with the variance of h_s and α_s and its submodularity

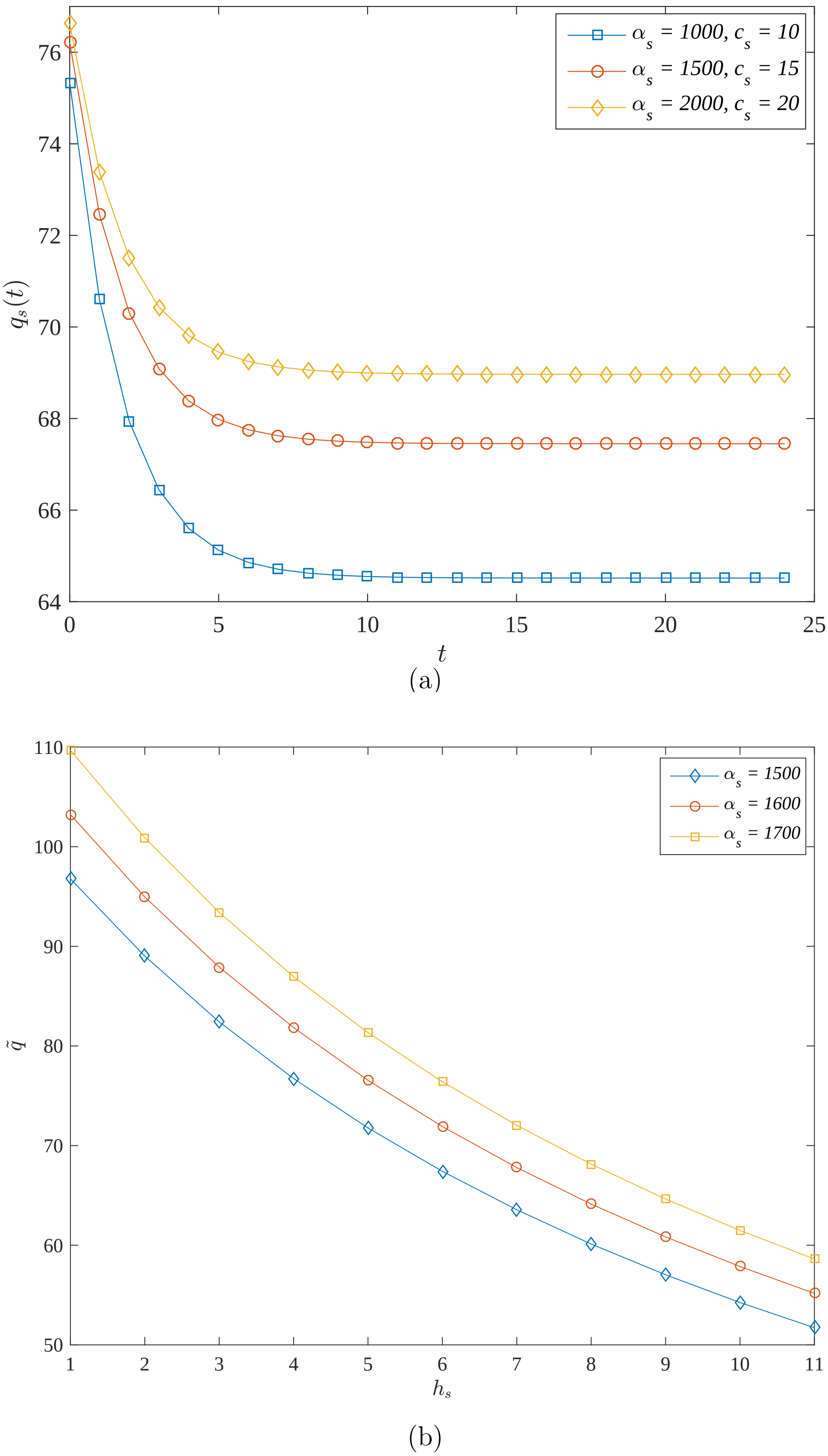
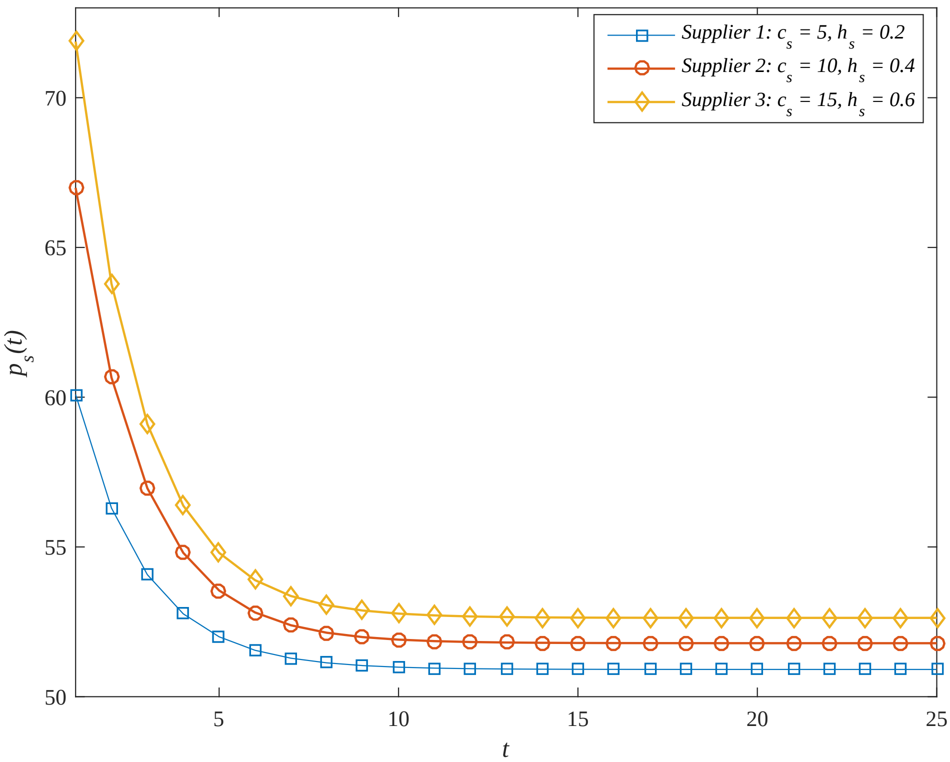
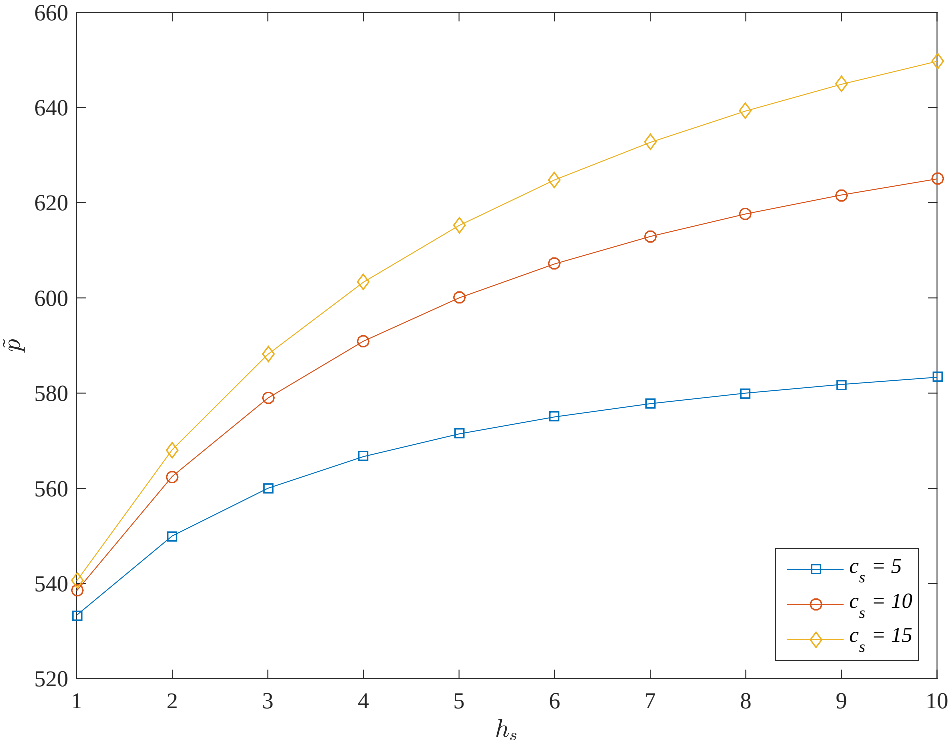


FIGURE 5.2: Production rate trajectory with the variance of c_s and α_s and its submodularity



(a)



(b)

Figure 5.3: The price trajectory with the variance of c_s and h_s and its supermodularity

Note that the open-loop equilibrium presents the original best decisions in which is easier to derive tractable strategies. However, the open-loop equilibrium is time-inconsistent. If a supplier adopts an open-loop strategy, it cannot observe the change in the state variable [Doc00]. That is, the supplier can make an irreversible precommitment decision only at the beginning of the game using the open-loop strategy [Gal14]. Therefore, it is worth examining another strategy, the Markov Nash Equilibrium, to analyze the game model. Based on the state equation of a supplier, the inventory level is influenced by the interaction between the sales price and the production rate. In this scenario, the supplier needs to design appropriate pricing and production strategies that depend on the state of the inventory level. That is, the supplier can make timely adjustments based on the changing states in order to pursuit the maximized total profit.

Proposition 5.4. **(Markovian Nash Equilibrium)** *The Markovian Nash equilibria of the sales price and the production rate are characterized by*

$$\hat{p}_s(t) = \frac{1}{2}(\frac{\alpha_s}{\beta_s} + B + 2Dx(t)), and \tag{5.15}$$

$$\hat{q}_s(t) = \frac{1}{c_s}(B + 2Dx(t)), \tag{5.16}$$

and the corresponding inventory level over time is given by

$$\hat{x}(t) = \frac{c_s(\alpha_s - \beta_s B) - 2B}{4D + 2c_s(1 + \beta_s D)}[1 - e^{(\frac{2D}{c_s} + \beta_s D + 1)t}], \tag{5.17}$$

where $B = \frac{\alpha_s D}{1+\beta_s D - r + 2D/c_s}$, $D = \frac{(r-2)-\sqrt{(2-r)^2+2h_s(\beta_s+2/c_s)}}{2(\beta_s+2/c_s)}$.

Proof of Proposition 5.4.

The Markov perfect equilibrium is derived by use of the Hamilton-Jacobi-Bellman equations.

$$
\begin{aligned}
rV_s = \max_{p_s,q_s}\{ & p_s(t)(\alpha_s - \beta_s p_s(t)) - \frac{1}{2}h_s(x_x(t))^2 - \frac{1}{2}c_s(q_s(t))^2 \\
& + \frac{\partial V_s}{\partial x}[q_s(t) + x_s(t) - (\alpha_s - \beta_s p_s(t))]\}
\end{aligned}
\tag{C.15}
$$

Taking the first order derivative of Equation C.15 with respect to p_s and q_s, respectively, for maximization of C.15, we get

$$
\frac{\partial V_s}{\partial p_s} = \alpha_s - 2\beta_s p_s + \frac{\partial V_s}{\partial x}\beta_s = 0, \tag{C.16}
$$

$$
\frac{\partial V_s}{\partial q_s} = -c_s q_s + \frac{\partial V_s}{\partial x} = 0. \tag{C.17}
$$

Then, we can obtain $p_s = \frac{1}{2}(\frac{\alpha_s}{\beta_s} + \frac{\partial V_s}{\partial x})$ and $q_s = \frac{1}{c_s}\frac{\partial V_s}{\partial x}$. Substituting p_s and q_s into Equation C.13 gives

$$
rV_s = \frac{\alpha_s^2}{4\beta_s} - \frac{1}{2}h_s x^2 + (x - \frac{\alpha_s}{2})\frac{\partial V_s}{\partial x} + (\frac{\beta_s}{4} + \frac{1}{2c_s})(\frac{\partial V_s}{\partial x})^2. \tag{C.18}
$$

Conjecture the functional form for the value function: $V_s = A + Bx + Dx^2$, where A, B, and D are determined by C.18. Substituting $\frac{\partial V_s}{\partial x} = B + 2Dx$ into C.18, gives

$$
\begin{aligned}
rV_s &= r(A + Bx + Dx^2) \\
&= \frac{\alpha_s^2}{4\beta_s} - \frac{1}{2}h_s x^2 + (x - \frac{\alpha_s}{2})(B + 2Dx) + (\frac{\beta_s}{4} + \frac{1}{2c_s})(B + 2Dx)x^2 \\
&= [(\beta_s + \frac{2}{c_s})D^2 + 2D - \frac{h_s}{2}]x^2 + [B(1 - \beta_s D + \frac{2D}{c_s}) - \alpha_s D]x \\
&+ \frac{\alpha_s^2}{4\beta_s} - \frac{\alpha_s B}{2} + \frac{\beta_s B^2}{4} + \frac{B^2}{2c_s},
\end{aligned}
\tag{C.19}
$$

which implies

$$
\begin{aligned}
& (\beta_s + \frac{2}{c_s})D^2 + 2D - \frac{h_s}{2} = 0, \\
& B(1 - \beta_s D + \frac{2D}{c_s}) - \alpha_s D = 0, \\
& \frac{\alpha_s^2}{4\beta_s} - \frac{\alpha_s B}{2} + \frac{\beta_s B^2}{4} + \frac{B^2}{2c_s} - rA = 0.
\end{aligned}
\tag{C.20}
$$

Giving

$$\begin{aligned} D &= \frac{(r-2) \pm \sqrt{(2-r)^2 + 2h_s(\beta_s + 2/c_s)}}{2(\beta_s + 2/c_s)}, \\ B &= \frac{\alpha_s D}{1 + \beta_s D - r + 2D/c_s}, \\ A &= \frac{1}{r}(\frac{\alpha_s^2}{4\beta_s} - \frac{\alpha_s B}{2} + \frac{\beta_s B^2}{4} + \frac{B^2}{2c_s}). \end{aligned} \tag{C.21}$$

Substituting p_s and q_s into $x(t)$, the inventory dynamics equation can be specified as

$$\dot{x}(t) = (\frac{2D}{c_s} + \beta_s D + 1)x + \frac{B}{c_s} + \frac{\beta_s B - \alpha_s}{2}, \tag{C.22}$$

since $x(t)$ has to converge in t, the solution of D must satisfy $D < 0$ [Eri11]. Only one of the two roots of D is eligible.

The solution of $x(t)$ is

$$x(t) = \frac{c_s(\alpha_s - \beta_s B) - 2B}{4D + 2c_s(1 + \beta_s D)}[1 - e^{(\frac{2D}{c_s} + \beta_s D + 1)t}]. \tag{C.23}$$

Therefore, the Markov perfect equilibria can be obtained as follows.

$$p_s(t) = \frac{1}{2}[\frac{\alpha_s}{\beta_s} + B + 2Dx(t)], \tag{C.24}$$

$$q_s(x(t)) = \frac{1}{c_s}(B + 2Dx(t)). \tag{C.25}$$

Q.E.D.

The Markovian Nash equilibria of the supplier are presented in Proposition 5.4, which indicate the more general results. Because each Markovian Nash equilibrium of a differential game is time consistent [Doc00], these solutions allow suppliers to control/adjust their production and pricing rates contingent on the state of the game, which are more realistic and tractable results than those of models in (5.1) and (5.2). In addition, the Markovian Nash equilibria of both price and production are dependent on and non-decreasing in the state variables. The characteristics of the monopolist for price and production rate are similar to the results in Proposition 5.2 because the Markovian Nash equilibrium takes into full consideration of the strategic interactions through the evolution of cumulative demand, which is sub-game perfect [Chi12]. Compared with the results in Propositions 5.2 and 5.4, the differences between two types of equilibria can be observed. That is, these results provide the two types of decision modes for suppliers. However, unlike the open-loop equilibrium, the Markovian Nash equilibrium takes time and inventory into consideration jointly.

5.3.2 Manufacturer's Sub-game Division

This subsection focuses on the decision issue for the manufacturer. With respect to the effect of the carbon tax, the manufacturer needs to determine the optimal price to maximize its total profit. In this sub-game model, the emissions amount is a state variable, and the sales price is a control variable. First, the decision issue is analyzed in consideration of the time factor. Then, the optimal sales price strategy with the state of the emissions amount is discussed.

The Hamiltonian function of the manufacturer can be developed as follows.

$$\begin{aligned} H_m = &\xi(p_m - p_1)(\alpha_m - \beta_m p_m) + (1-\xi)(p_m - p_2)(\alpha_m - \beta_m p_m) \\ &- \frac{1}{2} w E^2 + \mu[\varepsilon_1 \xi(\alpha_m - \beta_m p_m) + \varepsilon_2(1-\xi)(\alpha_m - \beta_m p_m) + zE], \end{aligned} \tag{5.18}$$

where μ is the co-state variable. The manufacturer's necessary condition for optimality should satisfy the following equation.

$$\frac{\partial H_m}{\partial p_m} = \alpha_m - 2\beta_m p_m + p_2\beta_m + \xi\beta_m(p_1 - p_2) - u\beta_m[\xi(\varepsilon_1 - \varepsilon_2) + \varepsilon_2] = 0. \quad (5.19)$$

Proposition 5.5. *There exists the Nash Equilibrium for the manufacturer's subgame.*

Proof of Proposition 5.5.

The second order derivative of the manufacturer's Hamiltonian function is $-2\beta_m$, where β_m is a nonnegative variable, because the manufacturer's Hamiltonian function is strictly concave in p_m. Thus, the existence of the Nash equilibrium is proven. Q.E.D.

This proposition indicates the existence of the equilibrium of the manufacturer's sub-game. Based on Equation (5.19), we can obtain $p_m = [\alpha_m + p_2\beta_m + \beta_m\xi(p_1 - p_2)]/2\beta_m - \mu\beta_m[\xi(\varepsilon_1 - \varepsilon_2) + \varepsilon_2]/2$. In addition, the maximized Hamiltonian function of the manufacturer is a concave function with respect to $E(t)$. The optimal pricing strategy of the manufacturer can be summarized in the following propositions.

Proposition 5.6. **(Open-Loop Equilibrium)** *The open-loop sales price and emissions amount of the manufacturer are given by*

$$p_m = A + B^2(\alpha_m - \beta_m A)[\frac{r - 2z + \sqrt{K}}{2\sqrt{K}}e^{m_1 t} + \frac{[\sqrt{K} - (r - 2z)]^2}{2(\beta_m B)^2\sqrt{K}}], \quad (5.20)$$

$$E(t) = B(\alpha_m - \beta_m A)\frac{r - 2z - \sqrt{K}}{2\sqrt{K}}(1 - e^{m_1 t}), \quad (5.21)$$

where $A = [\alpha_m + p_2\beta_m + \beta_m\xi(p_1 - p_2)]/2\beta_m$, $B = \xi(\varepsilon_1 - \varepsilon_2) + \varepsilon_2$, $K = (r - 2z)^2 + 2w(\beta_m B)^2$, *and* $m_1 = (r - \sqrt{K})/2$.

Proof of Proposition 5.6.

The manufacturer's Hamiltonia function can be developed as

$$\begin{aligned} H_m =& \xi(p_m - p_1)(\alpha_m - \beta_m p_m) + (1-\xi)(p_m - p_2)(\alpha_m - \beta_m p_m) \\ & - wE^2/2 + \mu[e_1\xi(\alpha_m - \beta_m p_m) + e_2(1-\xi)(\alpha_m - \beta_m p_m) + zE] \end{aligned} \tag{C.26}$$

and the necessary condition for the optimality is

$$\frac{\partial H_m}{\partial p_m} = \alpha_m - 2\beta_m p_m + p_2\beta_m + \xi\beta_m(p_1 - p_2) - \mu[\xi\beta_m(e_1 - e_2) + e_2] = 0, \tag{C.27}$$

Leading to

$$p_m = [\alpha_m + p_2\beta_m + \beta_m\xi(p_1 - p_2)]/2\beta_m - \mu\beta_m[\xi(e_1 - e_2) + e_2]/2 = A - \mu\beta_m B/2, \tag{C.28}$$

where $A = [\alpha_m + p_2\beta_m + \beta_m\xi(p_1 - p_2)]/2\beta_m$, $B = \xi(e_1 - e_2) + e_2$. Substituting p_m into Equation (5.4), the dynamics of the emissions amount can be obtained as

$$\dot{E}(t) = B(\alpha_m - \beta_m A) + u\beta_m B^2/2 + zE, \tag{C.29}$$

A non-homogeneous linear system with constant coefficients can be developed as follows by combining the co-state equations.

$$\dot{u}(t) = ru - \frac{\partial H_m}{\partial E} = (r - z)u + wE. \tag{C.30}$$

Note that

$$\begin{bmatrix} \dot{u} \\ \dot{E} \end{bmatrix} = M \begin{bmatrix} u \\ E \end{bmatrix} + N, \tag{C.31}$$

where $M = \begin{bmatrix} r-z & w \\ (\beta_m B)^2/2 & z \end{bmatrix}, N = \begin{bmatrix} 0 \\ B(\alpha_m - \beta_m A). \end{bmatrix}$ The two eigenvalues of M (m_1 and m_2) and the eigenvector of M (L) are as follows.

$$m_1 = \frac{r - \sqrt{(r-2z)^2 + 2w(\beta_m B)^2}}{2} \tag{C.32}$$

$$m_2 = \frac{r + \sqrt{(r-2z)^2 + 2w(\beta_m B)^2}}{2} \tag{C.33}$$

$$L = \begin{bmatrix} \frac{r-2z-\sqrt{(r-2z)^2+2w(\beta_m B)^2}}{2\beta_m B^2} & \frac{r+2z+\sqrt{(r-2z)^2+2w\beta_m B^2}}{2\beta_m B^2} \\ 1 & 1 \end{bmatrix} = \begin{bmatrix} x_1 & x_2 \\ 1 & 1 \end{bmatrix} \tag{C.34}$$

Therefore, u and E can be expressed as

$$\begin{aligned} \begin{bmatrix} u \\ E \end{bmatrix} &= L \begin{bmatrix} e^{m_1 t} & 0 \\ 0 & e^{m_2 t} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} - L^{-1} N \\ &= \begin{bmatrix} x_1 e^{m_1 t} & x_2 e^{m_2 t} \\ e^{m_1 t} & e^{m_2 t} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} - B(\alpha_m - \beta_m A) \begin{bmatrix} \frac{r-2z+\sqrt{(r-2z)^2+2w(\beta_m B)^2}}{2\sqrt{(r-2z)^2+2w(\beta_m B)^2}} \\ \frac{\sqrt{(r-2z)^2+2w(\beta_m B)^2}-(r-2z)}{2\sqrt{(r-2z)^2+2w(\beta_m B)^2}} \end{bmatrix} \end{aligned} \tag{C.35}$$

Two boundary conditions $E(0) = 0$ and $\lim_{t\to\infty} e^{-rt} u(t)E(t) = 0$ imply that $k_1 = B(\alpha_m - \beta_m A)\frac{2z-r+\sqrt{(r-2z)^2+2w(\beta_m B)^2}}{2\sqrt{(r-2z)^2+2w(\beta_m B)^2}}$ and $k_2 = 0$. Therefore, the open-loop sales price and the emissions amount of the manufacturer can be derived as follows.

$$\begin{aligned} p_m =& A + B^2(\alpha_m - \beta_m A)[\frac{r-2z+\sqrt{(r-2z)^2+2w(\beta_m B)^2}}{2\sqrt{(r-2z)^2+2w(\beta_m B)^2}} e^{m_1 t} \\ &+ \frac{[\sqrt{(r-2z)^2+2w(\beta_m B)^2} - (r-2z)]^2}{2(\beta_m B)^2\sqrt{(r-2z)^2+2w(\beta_m B)^2}}], \end{aligned} \tag{C.36}$$

$$E(t) = B(\alpha_m - \beta_m A)\frac{r-2z-\sqrt{(r-2z)^2+2w(\beta_m B)^2}}{2\sqrt{(r-2z)^2+2w(\beta_m B)^2}}(1-e^{m_1 t}), \tag{C.37}$$

Q.E.D.

Proposition 5.6 presents the equilibrium of the sales price and emissions amount of a manufacturer purchasing from two independent suppliers. The sales price of the manufacturer is jointly determined by the carbon tax and its procurement cost (the sales prices of suppliers). Facing a specific carbon tax ω, when the manufacturer orders more from the greener supplier 2 (is decreasing), its sales price presents the decreasing trend. The emissions volume of the manufacturer shows the decreasing trend with the increasing of the carbon tax. Further analysis is conducted when t moves towards infinity, the stable states of $p_m(t)$ and $E(t)$ $(t \to \infty)$ and their monotonicity are summarized in the following proposition.

Proposition 5.7. *The stable states of the sales price and emissions amount of the manufacturer are given as follows:*

(i) the stable state of the sales price of the manufacturer is

$$\tilde{p}_m = A + B^2(\alpha_m - \beta_m A)\frac{[\sqrt{K} - (r - 2z)]^2}{2(\beta_m B)^2\sqrt{K}}, \tag{5.22}$$

which is a supermodular function in both (ω, p_1) *and* (ω, p_2)*;*

(ii) the stable state of the emissions amount of the manufacturer is

$$\tilde{E} = B(\alpha_m - \beta_m A)\frac{r - 2z - \sqrt{K}}{2\sqrt{K}}, \tag{5.23}$$

which is a submodular function in both (ω, p_1) *and* (ω, p_2)*.*

Proof of Proposition 5.7.

With limitation of the sales price path, and the path of the emissions amount with respect to time t, we can find the stable states for the sales price and the emissions amount, respectively.

(i) The cross partial derivatives of $\tilde{p}_m$ with respect to ω, p_1 and p_2, respectively, are

$$\frac{\partial^2 \tilde{p}_m}{\partial\omega\partial p_1} = \frac{\beta_m^5 B^4 \xi(r-2z)}{4[(r-2z)^2+2\omega(\beta_m B)^2]^{\frac{3}{2}}} \geqslant 0, \tag{C.38}$$

$$\frac{\partial^2 \tilde{p}_m}{\partial\omega\partial p_2} = \frac{\beta_m^5 B^4 (1-\xi)(r-2z)}{4[(r-2z)^2+2\omega(\beta_m B)^2]^{\frac{3}{2}}} \geqslant 0, \tag{C.39}$$

because $0 \leqslant \xi \leqslant 1$ and $z \ll r$.

Thus, $\tilde{p}_m$ is a supermodular function in both (ω, p_1) and (ω, p_2).

(ii) The cross partial derivatives of $\tilde{E}$ with respect to ω, p_1 and p_2 are

$$\frac{\partial^2 \tilde{E}}{\partial\omega\partial p_1} = -\frac{\beta_m^3 B^2 \xi(r-2z)}{2\sqrt{(r-2z)^2+2\omega(\beta_m B)^2}} \leqslant 0, \tag{C.40}$$

$$\frac{\partial^2 \tilde{E}}{\partial\omega\partial p_2} = -\frac{\beta_m^3 B^2 (1-\xi)(r-2z)}{2\sqrt{(r-2z)^2+2\omega(\beta_m B)^2}} \leqslant 0, \tag{C.41}$$

Thus, $\tilde{E}$ is a submodular function in both (ω, p_1) and (ω, p_2).

Q.E.D.

This proposition describes the main results for the manufacturer's pricing issue. The characteristic of the stable price value has a monotonic trend with respect to the carbon tax and procurement prices. The increase in p_m reduces the demand of the manufacturer. That is, the total cost is transfered to customers. However, the amounts of carbon emissions of the manufacturer presents a decreasing trend with respect to the carbon tax and procurement prices. In addition, the above pricing strategy focuses only on the one-shot decision based on the initial setting. The submodularity of $\tilde{E}$ indicates that the manufacturer would select a greener supplier to reduce the emissions amount even when facing a higher procurement price and the carbon tax. The manufacturer also can adjust its pricing strategy based on the real-time emissions level and the value of the carbon tax in order to make a dynamic decision. In the following, the time-consistent equilibrium is analyzed. The Markovian Nash Equilibrium for models (5.3) and (5.4) is shown as follows.

Proposition 5.8. **(Markovian Nash Equilibrium)** *The Markovian Nash equilibrium strategies of the sales price and the emissions amount of a manufacturer are given as*

$$\hat{p}_m(t) = A - \frac{1}{2}BM + BQE(t), \tag{5.24}$$

$$E(t) = \frac{B(\alpha_m - \beta_m M)}{z - 2\beta_m QB}[e^{(z-2\beta_m QB)t} - 1], \tag{5.25}$$

where $B = \xi(\varepsilon_1 - \varepsilon_2) + \varepsilon_2$, $Q = \frac{r-2z-\sqrt{(r-2z)^2+2w\beta_m B^2}}{2\beta_m B^2}$, $M = \frac{\alpha_m BQ}{r-z-\beta_m QB^2}$, *and* $A = [\alpha_m/ + \beta_m p_2 + \beta_m \xi(p_1 - p_2)]/2\beta_m$.

Proof of Proposition 5.8.

The Markov perfect equilibrium is derived by use of the Hamilton-Jacobi-Bellman (HJB) equations.

$$\begin{aligned} rV_m = \max_{p_m}\{&\xi(p_m - p_1)(\alpha_m - \beta_m p_m) + (1-\xi)(p_m - p_2)(\alpha_m - \beta_m p_m) \\ &- wE^2/2 + \frac{\partial V_m}{\partial E}[B(\alpha_m - \beta_m p_m) + zE]\}, \end{aligned} \tag{C.42}$$

where $B = \xi(\varepsilon_1 - \varepsilon_2) + \varepsilon_2$. Taking the first order derivative of Equation C.42 with respect to p_m for maximization of C.42, we can obtain

$$p_m = A - \frac{B}{2}\frac{\partial V_m}{\partial E}, \tag{C.43}$$

where $A = [\alpha_m/ + \beta_m p_2 + \beta_m \xi(p_1 - p_2)]/2\beta_m$. Substituting C.43 into Equation C.42, rV_m can be rewritten as

$$\begin{aligned}rV_m =&\frac{1}{4}\beta_m B^2(\frac{\partial V_m}{\partial E})^2 + (\frac{1}{2}\alpha_m B + zE)\frac{\partial V_m}{\partial E}\\&+ \alpha_m A + \alpha_m[\xi(p_2 - p_1) - p_2] - \beta_m A^2 - \frac{1}{2}wE^2\end{aligned} \tag{C.44}$$

Conjecture the functional form for the value function $V_m = N + ME + QE^2$, where M, N, and Q are determined by Equations C.43 and C.44. Substituting $\frac{\partial V_m}{\partial E} = M + 2QE$ into Equation C.44, then

$$\begin{aligned}rV_m =&(\beta_m B^2 Q^2 + 2Qz - \frac{1}{2}w)E^2 + [\beta_m MQB^2 + zM + 2\alpha_m BQ]E\\&+ \frac{1}{4}\beta_m B^2 M^2 + \frac{1}{2}\alpha_m BM + \alpha_m A + \alpha_m[\xi(p_2 - p_1) - p_2] - \beta_m A^2\end{aligned} \tag{C.45}$$

Then, Q, N, and G can be derived by the following equations.

$$\beta_m B^2 Q^2 + (2z - r)Q - \frac{1}{2}w = 0, \tag{C.46}$$

$$\beta_m MQB^2 + zM + 2\alpha_m BQ - rM = 0, \tag{C.47}$$

$$G - rM = 0, \tag{C.48}$$

where $G = \frac{1}{4}\beta_m B^2 M^2 + \frac{1}{2}\alpha_m BM + \alpha_m A + \alpha_m[\xi(p_2 - p_1) - p_2] - \beta_m A^2$. Then, we can observe

$$Q = \frac{r - 2z \pm \sqrt{(r - 2z)^2 + 2\omega\beta_m B^2}}{2\beta_m B^2}, \tag{C.49}$$

$$M = \frac{\alpha_m BQ}{r - z - \beta_m QB^2}, \tag{C.50}$$

$$M = G/r, \tag{C.51}$$

This is because $E(t)$ has to converge in t and is larger than zero, so the solution of Q must satisfy $Q < 0$. Only one of the two roots of Q is eligible [Eri11]. That is, $Q = \frac{r-2z-\sqrt{(r-2z)^2+2\omega\beta_m B^2}}{2\beta_m B^2}$. Therefore, the Markov perfect equilibrium can be obtained as follows.

$$\hat{p}_m(t) = A - \frac{1}{2}BM + BQE(t), \tag{C.52}$$

$$E(t) = \frac{B(\alpha_m - \beta_m M)}{z - 2\beta_m QB}[e^{(z-2\beta_m QB)t} - 1], \tag{C.53}$$

where $B = \xi(\varepsilon_1 - \varepsilon_2) + \varepsilon_2$, and $A = [\alpha_m/ + \beta_m p_2 + \beta_m \xi(p_1 - p_2)]/2\beta_m$.

Q.E.D.

In contrast to the static outcomes in the open-loop equilibrium, Proposition 5.8 characterizes the trajectory path of the price with respect to the changing of emissions amount. That is, the manufacturer can timely adjust the pricing strategy based on the observation of the current emissions level. The emissions level of the manufacturer shows a decreasing trend with respect to the carbon tax. In addition, in the Markovian Nash equilibrium strategy, seals price of the manufacturer is decreasing regarding the reducing of its emissions amount. Further, examination of Equation (5.25) reveals the effect of emissions on the long-run values of the manufacturers sales price. The carbon tax scheme is an effective way to curb the emissions amount of the manufacturer by flexible sourcing from multiple suppliers.

5.4 Sourcing from Multiple Suppliers

This section extends the sub-game model of the manufacturer in the previous sections to n ($n \geqslant 2$) independent suppliers, where n is a constant. The objective is to analyze the robustness of the strategies and to further study more general observations for the pricing strategies of the manufacturer. Let ξ_i denote the ordering probability for supplier i,

$$\xi_i = \frac{e^{\tau_i - \rho p_i}}{\sum_{j=1}^{n} e^{\tau_j - \rho p_j}}, \tag{5.26}$$

where the summation of ξ_i equals one; that is, $(\xi_1, \xi_2, \ldots, \xi_n)$ is the sourcing profile of the manufacturer. Similarly, the emissions rate can be denoted by $e_i, 1 \leqslant i \leqslant n$. Therefore, the sub-game model of the manufacturer can be established as follows.

$$\Pi_m^n = \int_0^\infty e^{-rt}[(\alpha_m - \beta_m p_m(t)) \sum_{i=1}^n \xi_i(p_m(t) - p_i) - \frac{1}{2}\omega E^2(t)]dt \tag{5.27}$$

$$\dot{E}_n(t) = \sum_{i=1}^n e_i \xi_i(\alpha_m - \beta_m p_m(t)) + zE(t) \tag{5.28}$$

The existence of the equilibrium of models (5.26) and (5.27) is straightforward to prove. It is because the second order condition of the Hamiltonian function with respect to p_m is smaller than zero; that is, it is strictly concave in p_m. Therefore, the maximized Hamiltonian function can be achieved. The optimal pricing strategy of the scenario with multiple independent suppliers ($n \geqslant 2$) are illustrated in the following propositions.

Proposition 5.9. **(Open-Loop Equilibrium**) *For $n \geqslant 2$, the open-loop equilibria of the sales price and the emissions amount of the manufacturer are*

$$p_m^n = \frac{1}{2}V + \frac{(\alpha_m - \frac{1}{2}\beta_m\Lambda)J^2}{4\sqrt{K_1}}[(r-2z) + \sqrt{K_1} - [(r-2z) - \sqrt{K_1}]y_1 e^{w_1 t}], \tag{5.29}$$

$$E_n(t) = (\alpha_m - \frac{1}{2}\beta_m\Lambda)J\frac{\sqrt{K_1} - (r-2z)}{2\sqrt{K_1}}(1 - e^{w_1 t}), \tag{5.30}$$

where $V = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^n p_i\xi_i$, $\Lambda = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^n c_i\xi_i$, $J = \sum_{i=1}^n e_i\xi_i$, $w_1 = \frac{r - \sqrt{(r-2z)^2 + 2w\beta_m B}}{2}$, $K_1 = (r-2z)^2 + 2\beta_m wB^2$, *and* $y_1 = \frac{r\beta_m J^2 - 4z - 2\sqrt{(r-2z)^2 + 2\omega\beta_m J^2}}{2\beta_m J^2}$.

Proof of Proposition 5.9.

The manufacturer's Hamiltonian function can be developed as

$$H_m^n = (\alpha_m - \beta_m p_m)\sum_{i=1}^n \xi_i(p_m - p_i) - \frac{1}{2}\omega E^2 + u[\sum_{i=1}^n \varepsilon_i\xi_i(\alpha_m - \beta_m p_m) + zE], \tag{C.54}$$

The manufacturer's necessary condition for the optimality is

$$\frac{\partial H_m^n}{\partial p_m} = \alpha_m - 2\beta_m p_m + \beta_m \sum_{i=1}^{n} p_i \xi_i - u\beta_m \sum_{i=1}^{n} \varepsilon_i \xi_i = 0, \tag{C.55}$$

then

$$p_m = \frac{1}{2}(V - uJ), \tag{C.56}$$

where $V = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^{n} p_i \xi_i$, and $J = \sum_{i=1}^{n} \varepsilon_i \xi_i$. Substituting p_m into Equation (5.28), the dynamics of the emission volumes can be obtained as

$$\dot{E}_n(t) = \frac{1}{2}\beta_m u J^2 + zE(t) + (\alpha_m - \frac{1}{2}\beta_m V)J \tag{C.57}$$

A non-homogeneous linear system with constant coefficients can be developed as follows by combining the co-state equations

$$\dot{u}(t) = ru - \frac{\partial H_m^n}{\partial E} = (r - z)u + \omega E. \tag{C.58}$$

Note that

$$\begin{bmatrix} \dot{u} \\ \dot{E} \end{bmatrix} = W \begin{bmatrix} u \\ E \end{bmatrix} + R, \tag{C.59}$$

where $W = \begin{bmatrix} r - z & \omega \\ \beta_m J^2/2 & z \end{bmatrix}$, $R = \begin{bmatrix} 0 \\ J(\alpha_m - \frac{1}{2}\beta_m V). \end{bmatrix}$, and $/j = \sum_{i=1}^{n} e_i \xi_i$. The two eigenvalues of W are w_1, w_2, and the eigenvector of R is I.

$$w_1 = \frac{r - \sqrt{(r - 2z)^2 + 2\omega\beta_m J^2}}{2} \tag{C.60}$$

$$w_2 = \frac{r + \sqrt{(r - 2z)^2 + 2\omega\beta_m J^2}}{2} \tag{C.61}$$

$$I = \begin{bmatrix} \frac{r\beta_m J^2 - 4z - 2\sqrt{(r-2z)^2 + 2\omega\beta_m J^2}}{2\beta_m J^2} & \frac{r\beta_m J^2 - 4z + 2\sqrt{(r-2z)^2 + 2\omega\beta_m J^2}}{2\beta_m J^2} \\ 1 & 1 \end{bmatrix} = \begin{bmatrix} y_1 & y_2 \\ 1 & 1 \end{bmatrix} \tag{C.62}$$

Therefore, u and E_n can be expressed as

$$\begin{aligned} \begin{bmatrix} u \\ E_n \end{bmatrix} &= I \begin{bmatrix} e^{w_1 t} & 0 \\ 0 & e^{w_2 t} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} - I^{-1} R \\ &= \begin{bmatrix} y_1 e^{w_1 t} & y_2 e^{w_2 t} \\ e^{w_1 t} & e^{w_2 t} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} - J(\alpha_m - \beta_m V) \begin{bmatrix} \frac{r-2z+\sqrt{(r-2z)^2+2\omega\beta_m J^2}}{2\sqrt{(r-2z)^2+2\omega\beta_m J^2}} \\ \frac{r-2z-\sqrt{(r-2z)^2+2\omega\beta_m J^2}}{2\sqrt{(r-2z)^2+2\omega\beta_m J^2}} \end{bmatrix} \end{aligned} \tag{C.63}$$

The two boundary conditions $E(0) = 0$ and $\lim_{t\to\infty} e^{-rt}u(t)E(t) = 0$ imply that $k_1 = J(\alpha_m - \beta_m V)\frac{r-2z-\sqrt{(r-2z)^2+2\omega\beta_m J^2}}{2\sqrt{(r-2z)^2+2\omega\beta_m J^2}}$ and $k_2 = 0$. Therefore, the open-loop equilibrium strategies of the sales price and the emissions amount of the manufacturer can be found as follows.

$$p_m^n = \frac{1}{2}V + \frac{(\alpha_m - \frac{1}{2}\beta_m\Lambda)J^2}{4\sqrt{K_1}}[(r-2z) + \sqrt{K_1} - [(r-2z) - \sqrt{K_1}]y_1 e^{w_1 t}], \tag{C.64}$$

$$E_n(t) = (\alpha_m - \frac{1}{2}\beta_m\Lambda)J\frac{\sqrt{K_1} - (r-2z)}{2\sqrt{K_1}}(1 - e^{w_1 t}), \tag{C.65}$$

where $V = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^{n} p_i\xi_i$, $\Lambda = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^{n} c_i\xi_i$, $J = \sum_{i=1}^{n} \varepsilon_i\xi_i$, $w_1 = \frac{r-\sqrt{(r-2z)^2+2\omega\beta_m J}}{2}$, $K_1 = (r-2z)^2 + 2\beta_m w J^2$, and $y_1 = \frac{r\beta_m J^2-4z-2\sqrt{(r-2z)^2+2\omega\beta_m J^2}}{2\beta_m J^2}$.

Q.E.D.

For the scenario of multiple sourcing, each individual independent supplier still follows the equilibrium strategy based on Propositions 5.4 or 5.5. However, the manufacturer has to face the conflict issue in sourcing from the supply pool with a large number of suppliers. Proposition 5.9 presents a more general result of the open-loop equilibrium strategies of the manufacturer. When $n = 2$, this proposition reduces to Proposition 5.6. With respect to the manufacturer, the price is predominately determined by the ordering probability and unit procurement cost from each individual supplier. This also indicates that the carbon tax has less effect on the pricing issue for the manufacturer. The shadow price shows a positive correlation with the carbon tax. Accordingly, the manufacturer can adjust the price based on the initial setting in order to maximize its profit.

Proposition 5.10. **(Markovian Nash Equilibrium)** *For $n \geqslant 2$, the Markov equilibria of the sales price and the emission volumes of the manufacturer are given as*

$$\hat{p}_m^n(t) = \frac{1}{2}[V - JN - 2JQE(t)], \tag{5.31}$$

$$\hat{E}_n(t) = \frac{\alpha_m - \frac{1}{2}\beta_m V + \frac{1}{2}\beta_m JN}{\beta_m QJ}(e^{\beta_m QJ^2 t} - 1), \tag{5.32}$$

where $V = \frac{\alpha_m}{\beta_m} + \sum\limits_{i=1}^{n} p_i\xi_i$, $J = \sum\limits_{i=1}^{n} e_i\xi_i$, $N = \frac{2QB_1}{r-4QA_1}$, $Q = \frac{r \pm \sqrt{r^2+8wA_1}}{8A_1}$, $A_1 = \frac{1}{4}\beta_m J^2$, *and* $B_1 = \frac{1}{2}J(\alpha_m - \beta_m \sum\limits_{i=1}^{n} \xi_i p_i) + z\hat{E}_n$.

Proof of Proposition 5.10.

For the case of multiple sourcing, the Hamiltion-Jacobo-Bellman equation can be established as follows.

$$rV_m^n = \max_{\hat{p}_m^n}\{(\alpha_m - \beta_m\hat{p}_m)\sum_{i=1}^{n}\xi_i(\hat{p} - p_i) - \frac{1}{2}w\hat{E}_n^2 + [\sum_{i=1}^{n} e_i\xi_i(\alpha_m - \beta_m\hat{p}_m) + zE]\frac{\partial V_m^n}{\partial \hat{E}_n}\} \tag{C.66}$$

Taking the first order derivative of Equation C.66 with respect to $\hat{p}_m$, we can obtain

$$\hat{p}_m = \frac{1}{2}(V - J\frac{\partial V_m^n}{\partial \hat{E}_n}), \tag{C.67}$$

where $V = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^{n} p_i \xi_i$ and $J = \sum_{i=1}^{n} e_i \xi_i$. Substituting $\hat{p}_m$ into Equation C.67, rV_m^n can be rewritten as

$$rV_m^n = A_1 (\frac{\partial V_m^n}{\partial \hat{E}_n})^2 + B_1 \frac{\partial V_m^n}{\partial \hat{E}_n} + C_1, \tag{C.68}$$

where $A_1 = \frac{1}{4}\beta_m J^2$, $B_1 = \frac{1}{2}J(\alpha_m - \beta_m \sum_{i=1}^{n} \xi_i p_i) + z\hat{E}_n$, and $C_1 = \frac{1}{4}V(2\alpha_m - \beta_m V) - (\alpha_m + \frac{1}{2}\beta_m V)\sum_{i=1}^{n} \xi_i p_i$. Conjecture the form of $V_m^n = M + NE + Q\hat{E}_n^2$, then, substituting $\frac{\partial V_m^n}{\partial \hat{E}_n} = N + 2Q\hat{E}_n$ into Equation C.68, we can obtain

$$rV_m^n = 4A_1 Q^2 E^2 + (4NQA_1 + 2QB_1)E + A_1 N^2 + B_1 N + C_1. \tag{C.69}$$

Then, M, N, and Q can be derived by the following equations.

$$4A_1 Q^2 - rQ - \frac{1}{2}w = 0, \tag{C.70}$$

$$4NQA_1 + 2QB_1 - rN = 0, \tag{C.71}$$

$$A_1 N^2 + B_1 N + C_1 - rM = 0, \tag{C.72}$$

That is,

$$Q = \frac{r \pm \sqrt{r^2 + 8wA_1}}{8A_1} \tag{C.73}$$

$$N = \frac{2QB_1}{r - 4QA_1}, \tag{C.74}$$

$$M = (A_1 N^2 + B_1 N + C_1)/r, \tag{C.75}$$

Because $\hat{E}_n$ has to converge in t and is larger than zero, thus, Q must satisfy $Q < 0$, i.e. $Q = \frac{r - \sqrt{r^2 + 8wA_1}}{8A_1}$. Therefore, the Markov perfect equilibrium can be derived.

$$\hat{p}_m^n(t) = \frac{1}{2}[V - JN - 2JQE(t)], \tag{C.76}$$

$$\hat{E}_n(t) = \frac{\alpha_m - \frac{1}{2}\beta_m V + \frac{1}{2}\beta_m JN}{\beta_m QJ}(e^{\beta_m QJ^2 t} - 1), \tag{C.77}$$

where $V = \frac{\alpha_m}{\beta_m} + \sum_{i=1}^{n} p_i\xi_i$, $J = \sum_{i=1}^{n} e_i\xi_i$, $N = \frac{2QB_1}{r-4QA_1}$, $Q = \frac{r-\sqrt{r^2+8wA_1}}{8A_1}$, and $A_1 = \frac{1}{4}\beta_m J^2$.

Q.E.D.

In contrast to the sales price in the open-loop equilibrium, Proposition 5.10 illustrates that the Markovian Nash equilibrium of the sales price decreases over time with a relatively higher initial setting, and it converges to a fixed constant. This convergent tendency is observable, because the Markovian Nash equilibrium takes full consideration of the interaction between the sales price and the emissions amount of the manufacturer over the time horizon. The result in Proposition 5.10 is also sub-game perfect and time consistent. Proposition 5.10 is a more general equilibrium outcome of Proposition 5.8 (where $n = 2$). In addition, the limit value of $E_n(t)$ is also a fixed constant that is negatively correlated with carbon tax w. This further shows that the carbon tax scheme shows a cost effective way to curb carbon emissions. The manufacturer can follow the variance of the unit carbon tax to control and adjust its emissions amount and pricing, respectively. The following example is presented to describe the pricing trajectory and the trajectory of the emission volumes with respect to the variance of ξ and w when $n = 2$.

EXAMPLE 4. Suppose $\alpha_m = 500, \beta_m = 2, \varepsilon_1 = 0.8, \varepsilon_2 = 0.5, \varepsilon_3 = 0.1, \omega = 12, r = 0.5$, and $z = 0.05$. The price trajectory of the manufacturer sourcing from three suppliers with the variance of ξ_i is shown in Figure 5.4. Adopting the same data setting, the trajectory of emission amounts and the profit of the manufacturer are shown in Figure 5.5 and Figure 5.6, respectively, with the variance of the carbon tax. The sales price of the manufacturer presents a concave trend with the variance of ξ_i. At the initial period, the sales price is lower if the manufacturer sources more from supplier 1 with the lowest sales price and the highest emissions rate. Meanwhile, the emissions amount of the manufacturer increases by using raw materials from supplier 1. The manufacturer must pay more emissions cost, which is incurred by the carbon tax, and to increase its sales price to gain profit, which can reduce the demand of the manufacturer. As the time change, the manufacturer should make adjustment regarding its order profile. Then, as we can see from Figure 5.4, the sales price of the manufacturer shows a decreasing trend by increasing its sourcing quantity from a greener supplier (supplier 3) to reduce its emissions cost. On the one hand, the manufacturer can source from a traditional supplier, such as supplier 1, with a lower procurement cost; on the other hand, the manufacturer can source from a greener supplier, such as supplier 3, to control its emissions amount. In the same situation, Figure 5.5 implies that the emissions volume of the manufacturer can also be controlled effectively under the carbon tax scheme. Figure 5.6 indicates that the profit of the manufacturer shows an increasing trend, that is, the manufacturer benefits from adopting mixed sourcing strategy from multiple suppliers. In addition, this flexible or mixed sourcing strategy can benefit the manufacturer even facing a higher value of the carbon tax.

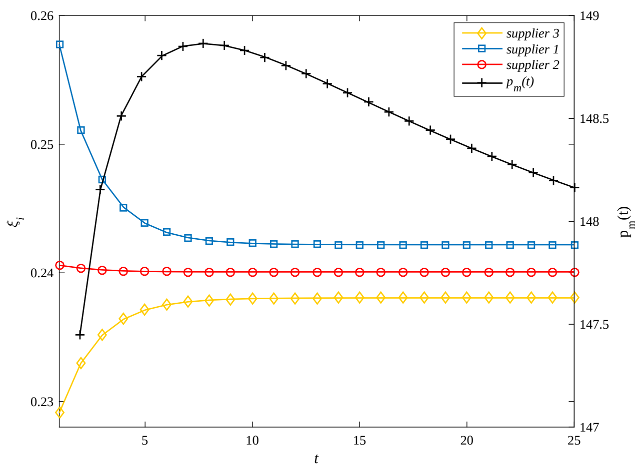


FIGURE 5.4: Pricing trajectory of the manufacturer sourcing from three suppliers with the variance of ξ_i and ω

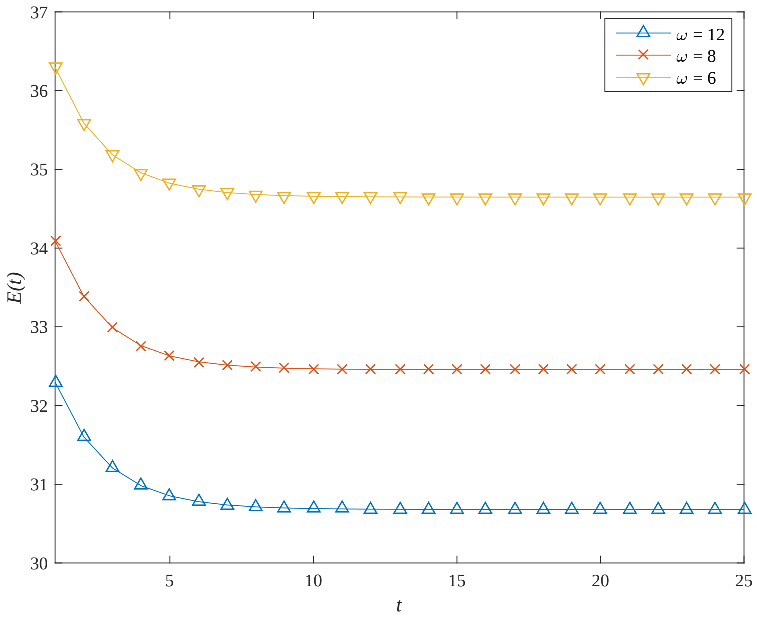


FIGURE 5.5: Emissions volume' trajectory of the manufacturer sourcing from three suppliers with the variance of ξ_i and ω

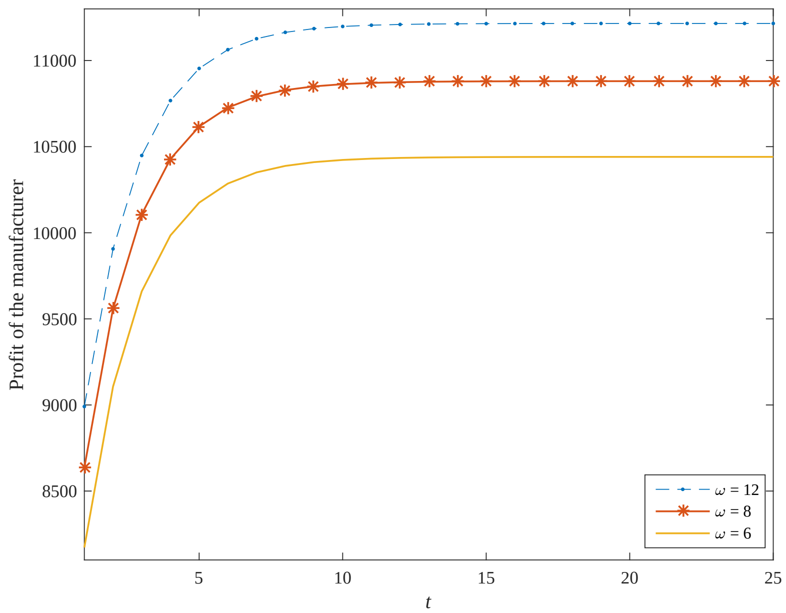


FIGURE 5.6: The profit of the manufacturer sourcing from three suppliers with the variances of ξ_i and ω

5.5 Managerial Implications

The research results provide meaningful managerial implications for both suppliers and the manufacturer. The suppliers can have a better understanding of setting appropriate prices in consideration of production planning and inventory control. The manufacturer can also understand how to determine a reasonable price to jointly maximize profit and minimize emissions-related cost.

For the manufacturer, the results of the comparative statics analysis for emission volumes indicate that the manufacturer would select a greener supplier to reduce the emissions amount even when facing a higher procurement price and a carbon tax. In addition, the characteristic of the sales price of the manufacturer presents a monotone trend with respect to the carbon tax and procurement cost (sourcing prices of raw materials). With the increasing sales price, the total cost will be transferred to customers. The manufacturer would cooperate with the traditional suppliers in the initial phase of implementing the carbon tax scheme. However, this phenomenon will change in the long run. The sales price shows a significant convergence trend. This implies that cooperating with a greener supplier incurs the lowest sales price, which in turn, contributes to expanding the market demand for the manufacturer. Therefore, to avoid losing business volumes, the manufacturer needs to adjust its pricing strategy and make a dynamic decision based on the real-time emissions level and the price of carbon tax.

For both traditional and greener suppliers, increasing the inventory level to meet the large-scale market demand is a good choice, even when facing a higher inventory holding cost. Nevertheless, each supplier needs to adjust its stock level dynamically if the holding cost is continuously increasing, even with a larger market size. This is because the increasing inventory holding cost can affect the suppliers sales revenue significantly. As mentioned above, the manufacturer would prefer cooperating with a greener supplier in the long run. If a supplier is preparing to transfer its current production technology from traditional to environmental, the supplier has to increase its sales price, and part of the cost will shift to the manufacturer. The increase in sales prices could induce the loss of market share. Nevertheless, the buyers are willing to pay higher for the environmentally friendly materials in the future [Agr16]. A greener supplier takes over the market share from its competitors and also sets up a high barrier for new entrants as the technology transition process is lengthy. Therefore, to achieve the goal of profit maximization, both types of suppliers should adopt inter-temporal strategies based on the original best decisions. In addition, to avoid time-inconsistent, the suppliers should make adjustments dynamically based on the changing inventory states which are influenced by the interaction between the production and pricing strategies.

To summarize, the pre-committed or contingent pricing strategies presented in this chapter can help achieve the goals of profit maximization and carbon emissions minimization for both suppliers and manufacturers simultaneously, and also can facilitate sustainable operations of the upstream supply chains.

5.6 Summary

Motivated by the influence of global climate change in recent years, and the research trends of sustainable supply chain management, this chapter describes a two-stage differential game model to study pricing issues between a manufacturer and suppliers under the carbon tax scheme. The outcomes and managerial insights in this chapter can be summarized as follows.

First, a sub-game model for each independent supplier was developed with the constraint of inventory capacity. The open-loop strategies for the price, the production, and the inventory level were derived. In addition, with respect to the interactions among price, production rate, and inventory level, the Markovian Nash equilibrium was identified to illustrate the time consistency for these strategies. The managerial insight of this sub-game is that each individual supplier can adjust its pricing and production strategies with respect to timely information on its inventory level. That is, each individual supplier can maximize its total profit by controlling the current inventory level and can update its price and production rate to enlarge its business volume share in a timely manner.

Second, starting from the viewpoint of the manufacturer that adopts an ATO strategy, a sub-game model was developed under the carbon tax scheme. In this model, the manufacturer has to consider the constraint of its emissions amount. This factor will affect the pricing issue for the manufacturer. The results indicate that the carbon tax and the unit procurement price are two predominant factors. The manufacturer might be inclined to allocate an order to the traditional suppliers when facing a lower carbon tax at the starting period. In the long-run, the manufacturer can benefit from the cooperation with greener suppliers. In addition, the Markovian Nash equilibrium further presents the interaction between the price setting of the manufacturer and its emissions level.

Third, the basic pricing model for the manufacturer was extended by the cooperation with multiple suppliers. Due to the selection preference of the manufacturer, enlarging the pool of potential suppliers could benefit the manufacturer and curb its emissions. The more general settings for both the open-loop equilibrium and the Markovian Nash equilibrium were derived. The latter aimed to overcome the time inconsistency of the open-loop equilibrium. The Markovian Nash equilibrium indicates that the manufacturer can follow the variance of the unit carbon tax to control and adjust its emissions amount and pricing, respectively.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

To improve business operations for reducing GHG emissions of firms, this research project focuses on the issue of procurement management from the perspective of sustainable supply chain management. On the basis of two types of carbon emissions regulations, i.e., the emissions trading mechanism and the carbon tax scheme, three specific sub-topics are analyzed, and the boundary conditions for the optimal green procurement strategy are identified. The main results of the study can be summarized as follows.

Perfect Competition. The dissertation not only focuses on the competition between a supplier and a manufacturer, but also aims at the peer-level competition i.e., the competition among manufacturers. We first focus on the symmetric duopoly competition between manufacturers. The green procurement strategies are analyzed for manufacturers to obtain insights into how to determine a reasonable sourcing strategy and optimal sourcing quantity under two types of carbon emissions regulations, i.e., the emissions trading mechanism and the carbon tax scheme. By analysis of the parameters, i.e., trading prices and the carbon tax, of competition among manufacturers, the boundary conditions are identified to assist the manufacturer in making an appropriate sourcing strategy. Then, with respect to suppliers, three types of auctions are analyzed for the individual supplier to achieve the mutually beneficial goal of profit-maximization and carbon emissions control, simultaneously. The results can provide a comprehensive understanding of how to keep or enlarge the business volume share under different conditions.

Asymmetric Information. With respect to raw materials from suppliers who hold private information about the green degree, i.e., the unit emission rates of raw materials, we first focus on the contract design issue for the manufacturer. Under this scenario, the manufacturer can deeply understand how to design attractive contracts to jointly maximize profit and emissions trading benefits. The contracts include a series of the payments and the order quantities; the suppliers are subsequently invited to bid for the contracts. With respect to the payoffs for the members of the supply chain, the incremental revenue for both a manufacturer and a supplier to choose a higher ordering quantity is greater when the green degree of a supplier is higher. In addition, an efficient emissions trading policy is established for the guide of the manufacturer on how to balance its emission allowances based on the optimal order quantity and asymmetric information. The general outcomes can provide effective decision support for both the manufacturer and suppliers.

Dynamic Coordination. The variance of the carbon tax could affect the coordinated behavior or strategies of the agents in a supply chain, so we take the viewpoint of how to coordinate pricing for both a manufacturer and a supplier.

The intersections of the pricing strategies for both the manufacturer and the supplier are analyzed dynamically. To achieve this objective, a two-stage game model is developed, and two types of equilibria are derived, i.e., the open-loop and the Markovian Nash equilibria, respectively. These equilibrium prices for the supplier and the manufacturer can be regarded as the solutions of two different models under specific situations. A comparative statics analysis is conducted based on the equilibrium prices for both the supplier and the manufacturer. We observe the following interesting results. The manufacturer prefers to cooperate with greener suppliers if facing a higher carbon tax, especially at the initial period, however, this strategy incurs a higher price. This implies that the manufacturer worries about lost profits when the carbon tax scheme is just launched. However, in the long-run, we observe that this strategy generates a lower price and it can result in a relatively higher demand for the manufacturer.

6.2 Contributions

The contributions of this research can be summarized as follows:

Firstly, the research work in Chapter 3, the procurement decision issue is studied for the peer-level competition between manufacturers with various constraints, in which market information, such as the demand, emission allowances, and emissions trading prices, is uncertain. Then, the structural properties and the boundary conditions for the equilibrium strategy and the optimal ordering quantity are identified. Manufacturers or managers can better understand how to make reasonable procurement decisions by adopting flexible strategies in an oligopoly market to simultaneously achieve profits maximization and GHG emissions minimization. In addition, to make a reasonable facility location decision, we have conducted a difference analysis for manufacturers who are constrained by the emissions trading mechanism and the carbon tax scheme. That is, by characterizing their own development patterns, manufacturers can make appropriate location decisions based on our analysis results in considering of the constraints of carbon emissions regulations.

Secondly, the research work in Chapter 4, the green procurement issue with asymmetric information under uncertain demand is studied. The assumption about confidential information in this chapter is extended as a continuous type. An effective contract is proposed to maximize the payoff functions of the manufacturer and the supplier and to minimize the emissions trading cost jointly. The robustness of the contract is characterized for the competitive bidding scenario with asymmetric information. In addition, two other types of auctions, involving the price auction with an emissions target and a performance-based auction are designed to achieve a win-win situation for both suppliers and the manufacturer. An effective emissions trading policy is established based on the asymmetric information and the optimal ordering quantity, which can assist the manufacturer in making appropriate emissions trading decisions.

Thirdly, the research work in Chapter 5, reasonable strategies for the dynamically coordinated pricing issue in a supply chain with multiple suppliers and one manufacturer are studied. The pricing strategies for both suppliers and the manufacturer are identified. In addition, by adding other constrained variables, involving production constraint, inventory constraint and the constraint on the emissions amount, for both sub-game models, the characteristics of monotonicity for an equilibrium outcome are analyzed. Two types of equilibria, including the open-loop and the Markovian Nash equilibrium, are derived for members of the supply chain, based on both irreversible actions and real-time actions. These pricing strategies can provide appropriate strategies for the manufacturer and suppliers to achieve the goal of profit-maximization under the constraint of the carbon tax scheme.

6.3 Future Research Work

Some possible future researches are pointed out as follows:

This research project predominantly studies decision making for the manufacturer and suppliers with a deterministic demand distribution in order to describe the uncertain environment. However, it is worthwhile to study the equilibrium if the demand information is incomplete. Here, assume the demands in each period are independent and identically distributed. Let $\varphi(\xi|\theta)$ denote the demand density, $\varphi(\xi|\theta) \sim \mathbb{E}(\zeta|\theta)$, where θ is an unknown parameter which can be used to classify the different types of raw materials. In addition, a manufacturer has a prior density function,g, with the unknown parameter θ, so assume $g(\theta) \sim \Gamma(\theta|a, S)$. Based on the Bayes rule, the predictive demand density function can be described by using the conjugate priors as follows. The demand of the conjugate priors distribution includes an exponential distribution (θ is unknown) and the prior on θ follows a gamma distribution (a and S are known).

$$\begin{aligned}\phi(\xi|a,S) &= \int_0^\infty \varphi(\xi|\theta)g(\theta|a,S)d\theta - \int_0^\infty \theta e^{-\theta\xi}\frac{S^a\theta^{a-1}e^{-\theta S}}{\Gamma(a)} \\ &= \frac{S^a}{\Gamma(a)}\int_0^\infty \theta^a e^{-(\xi+S)\theta}d\theta - \frac{-S^a}{(\xi+S)\Gamma(a)}\int_0^\infty \theta^a de^{-(\xi+S)\theta} \\ &= \frac{aS^a}{(\xi+S)^{a+1}}\end{aligned} \tag{6.1}$$

In consideration of the cost of carbon emissions, a manufacturer not only should improve the operations strategies, but also should encourage the suppliers to provide environmentally-friendly raw materials and cleaner production equipment. In order to achieve the goal of reducing carbon emissions, the manufacturer needs to cooperate with more professional suppliers. The raw material suppliers should be encouraged to adopt advanced production technology, which can reduce the carbon-intensity of the whole raw material market. On the other hand, suppliers of production equipment should improve their awareness of the technology with lower carbon emissions. Suppliers should establish the cooperative relationships with manufacturers. Although the investment on the implementation of new production equipment and technologies will incur additional cost to suppliers, these suppliers will have advantages and would benefit once these technologies become the necessity.

The second direction is to study the other alternative technologies, e.g. using carbon capture and storage (CCS) to reduce carbon emissions, especially for those carbon-intensive industries, such as in the cement sector, the iron and steel sector, and in oil refineries. The investment on CCS could weaken the influence of carbon emission factors. In the long-run, the application of CCS could cut the amount of emissions for a manufacturer or an industry. On the other hand, an appropriate technology also changes the total structure of a manufacturer. Once the manufacturer decides to apply CCS technology, its cost structure will be very complicated. This not only includes the carbon tax, but also should cover other series of sub-costs, such as the costs incurred from CO_2 capture technology, CO_2 transportation by pipeline, and CO_2 storage. So before investment, the manufacturer should balance the cost of financial instruments and technology investment in the long-run.

The solutions in this dissertation provide effective operational strategies for the manufacturers to gain profits and control emissions volumes. The methodologies adopted in the research work present a successful application of game theory models in green procurement management. Incorporating the aforementioned factors into decision making should lead to promising outcomes.

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