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Contract Design with Information Asymmetry in a Supply Chain under an Emissions Trading Mechanism

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Abstract

We aim 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 is 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 balance their emission allowances based on the optimal order quantities. Our approach provides an effective decision support system for both the manufacturer and suppliers.

Keywords

Green procurement; Contract design; Emissions trading; Asymmetric information

1. Introduction

In confronting the challenges created by greenhouse gas (GHG) emissions and the market demand for sustainable products, firms are under strong pressure to minimize their impacts on the environment. For the electronics industry, manufacturers have to adjust their traditional operations. For example, green engineering has been proposed with two goals of reducing the generation of pollution at the source and minimizing the risk to human health and the environment (EPA 2014). 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 (Rohrmus et al., 2013). In order to provide sustainable products, a manufacturer has to purchase eco-friendly materials from suppliers. However, it is challenging for a manufacturer sourcing sustainable materials as inputs (Agrawal and Lee, 2016), mainly because of the asymmetric green information of raw materials provided by suppliers.

In many cases, suppliers do not disclose complete details about their products, especially their core products, and may even conceal information about the environmental friendliness of materials used. The reason is straightforward, that is, suppliers will take a tremendous amount of time and capital to evaluate their carbon footprint (Pyper, 2013). The privately green information can lead to the benefit loss of a manufacturer. Genasci (2012) reported 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 scandal. Therefore, to improve the sustainability performance and to reduce climate risks of entire supply chains, the managers have to adopt reasonable methods to control GHG emissions of their entire supply chain

To improve the sustainability performance and to reduce climate risks of entire supply chains, Hewlett-Packard (HP) Company has collaborated closely with their suppliers. A primary environmental focus in the HP's supply chain is tacking greenhouse gas emissions due to raw materials use, which is a key contributor to GHG emissions in a supplier base (HP, 2014). However, there exists a conflict between the manufacturer and the supplier. The manufacturer prefers to adopt sustainable raw materials, which can incur lower carbon emissions during the production processes. For example, Apple Inc. is switching to greener materials to create safer products and manufacturing processes. Using recycling materials can generate fewer carbon emissions such as aluminum than by mining and smelting new materials (Apple, 2016). For suppliers, the decision to offer environmental products to meet sustainability targets is costly, especially improving its production technologies. For example, as a textile and garment supplier, the Yeh Group has spent $3.5m on each of its DyeCoo machines, and $10m for equipment, research and development to produce sustainable DryDye clothing for Adidas, Peak Performance, Kjus and Mizuno (Hepburn, 2015). Due to the enormous cost pressure, suppliers would not be willing to take risks to offer sustainable products. As a consequence, the GHG emissions which are incurred by a supplier to produce raw materials will be transferred to the manufacturer during manufacturing processes. Here, we focus on the embodied carbon from transforming the raw materials into final products, known as the "cradle-to-gate". The embodied carbon not only involves carbon emissions to produce raw materials, but also includes other carbon emissions from the manufacturing processes to make final products (Circular Ecology, 2015).

In practice, different types of environmental regulations have been designed and implemented to curb global GHG emissions. An emissions trading scheme, as a market-based mechanism, has been successfully implemented in the United States of America and the European Union, especially for companies in carbon-incentive industries. Constrained by carbon emission regulations, a manufacturer needs to consider cooperating with suppliers who can provide lower prices and eco-friendly materials. According to the aforementioned cases, we see that the manufacturer cannot precisely know the carbon information of raw materials as this information is privately known to the supplier. Thus, the manufacturer must estimate the value of the embodied carbon information of raw materials to control its carbon emission volumes and corresponding cost. It is challenging for a manufacturer to quantify the environmental costs and to choose environmental materials from upstream suppliers to reduce GHG emissions of their supply chain when facing asymmetric green information of raw materials. This motivates us to use contract design under emissions constraints with asymmetric green information to establish a mutually beneficial and efficient business model.

Researchers have studied the problem of carbon emission regulations from the perspective of sustainable operations management (Hua et al. 2011; Choi, 2013; Jaber et al. 2013; Chen et al. 2013; Konur et al. 2014). Most of these studies focused on emissions control with classical operations research models, such as the economic order quantity (EOQ) and newsvendor models. However, researchers have paid less attention to the interaction between suppliers and manufacturers. This paper 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 paper studies a realistic contract design issue with asymmetric information.

Research questions addressed in this paper are as follows. 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 emission rates. 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 paper 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 have primarily focused on the cooperative relationship between a retailer (or a manufacturer) and a supplier (Mukhopadhyay et al., 2009; Gan et al., 2010; Babich et al., 2012). 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, which can mean cost savings for the manufacturer. In addition, the manufacturer also needs to manage its emission allowances through cooperation with different types of suppliers. Therefore, it is worth evaluating how an appropriate contract for a competitive bidding scenario with asymmetric information can be designed.

Third, how is the optimal order quantity under the emissions trading scheme determined? 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. For example, for magnesium production, using dolomite and magnesite can generate 5.13 and 2.83 tonnes carbon emissions per tonne primary Mg produced, respectively (IPCC, 2006). Trading with insufficient or redundant emission volumes can impact the profit of the manufacturer. Thus, the manufacturer needs to balance the procurement quantity and control its emission allowances.

The remainder of this paper is organized as follows. Section 2 presents the related literature. Section 3 introduces the basic context of the model. Section 4 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 5 analyzes a general extension of the basic model with multiple independent suppliers. Section 6 studies the optimal emissions trading policy, the price auction with a carbon emission target, and a performance-based auction. Section 7 illustrates the managerial implications of our research work. Section 8 concludes the paper and discusses future extensions. The Appendix provides all proofs.

2. Literature Review

This paper is related to two streams of literature, including the applications of carbon emission regulations in procurement management, and supply chain contract design with asymmetric information.

2.1 Carbon Emissions Regulations in Procurement Management

To reduce global GHG emissions, a series of environmental regulations have been proposed and implemented all over the world. Several researchers have quantified these mechanisms from the procurement management aspect as shown in Table 1.

<Insert Table 1 around here>

The first group of researchers applied the economic order quantity (EOQ) model. Hua et al. (2011) studied the single-product procurement issue with emissions trading, and examined the impacts of the carbon price and carbon cap on the order quantity. Their results show that the emissions trading mechanism was an effective way to help retailer reduce emissions, but increase the total cost. Wahab et al. (2011) determined the optimal production-shipment policy while considering the carbon emissions. The authors revealed that incorporating the environmental impact into the supply chain decisions reduces the frequency of shipments. Bouchery et al. (2012) developed a multi-objective EOQ model by integrating sustainability criteria into the classical EOQ model. The authors proved that the model can help decision makers to determine the effectiveness of different regulatory policies to control carbon emissions, and then identify the best option quickly. Chen et al. (2013) developed a carbon-constrained EOQ model to analyze the impacts of emission regulations, including carbon cap-and-offset, carbon caps, carbon taxes, and emissions trading, on the optimal order quantity. They provided conditions under which the emissions can be reduced significantly without significantly increasing cost.

The second group of researchers used the mixed integer linear programming model. Benjaafar et al. (2013) analyzed the effect of different emission regulations on the procurement, production, and inventory management. The results indicated that firms could effectively reduce carbon emissions without significantly increasing costs by making only operational adjustments and by collaborating with other members of their supply chain. Jaber et al. (2013) studied the procurement and production optimization problems in a two-level supply chain in consideration of the different emission trading schemes. The authors proved that the model can help decision makers to jointly minimize the inventory-related and carbon emissions costs of their supply chains when penalties for exceeding emissions limits are considered. Hammami et al. (2015) studied the impacts of carbon tax and emissions cap schemes on procurement, production, and inventory decisions. The authors demonstrated that individual caps can achieve significant lower emissions but can paradoxically lead to increasing the per unit emissions.

The following researchers adopted the dynamic programming model. Gong and Zhou (2013) analyzed the impact of emissions trading on optimal production planning, where the manufacturing can use a more costly but cleaner green technology or a less costly but more polluting regular technology, or both, to carry out production. Their results show that the optimal technology selection is determined by the relationship between the additional cost per allowance saved and the trading prices. Ma et al. (2016) studied the impact of a carbon tax on calculating the optimal order quantity over the finite time horizon. An effective range for the carbon tax was established to assist the government in calculating an appropriate carbon tax for the manufacturing industry.

Overall, there are two commonalities among the aforementioned articles. First, the environmental cost was considered as a fixed cost, and calculated passively. As the emissions information regarding the materials from suppliers is private to manufacturers, the quantification of environmental costs is difficult and the manufacturers have to calculate passively and indirectly. Second, the aforementioned articles only focus on the profit maximization of the manufacturers. However, the suppliers' perspective was not studied, and interaction behaviors between suppliers and manufacturers were neglected. To help the manufacturer reduce emissions, especially using sustainable materials, our paper quantifies the green degrees of materials from suppliers, which could provide an effective way to control GHG emissions from the sources of a supply chain. In addition, this paper develops a game model to study the interaction behaviors between the manufacturer and suppliers.

2.2 Supply chain contract design with asymmetric information

Several researchers studied the supply chain contract design with asymmetric information as summarized in Table 2. First, most of the researchers considered asymmetric cost information in their supply chain contracting models (Corbett et al., 2004; Mukhopadhyay et al., 2009; Chaturvedi and Martínez-de-Albéniz, 2011; Özer and Raz, 2011; Çakanyıldırım et al., 2012; Fang et al., 2014; Li et al., 2015; Wagner 2015). Comparatively, the supply chain contract design with asymmetric demand information has attracted less attention (Cachon, 2003; Chen, 2007; Kalkanci and Erhun, 2012; Lee and Yang, 2013).

<Insert Table 2 around here>

Second, with respect to the characteristics of asymmetric information, there are more researchers considering the binary opposite asymmetric information for both suppliers and manufacturers (Cachon, 2003; Özer and Raz, 2011; Çakanyıldırım et al., 2012; Lee and Yang, 2013; Fang et al., 2014; Li et al., 2015; Wagner 2015) than the continuous asymmetric information (Corbett et al., 2004; Chen, 2007; Mukhopadhyay et al., 2009; Chaturvedi Martínez-de-Albéniz, 2011; Kalkanci and Erhun, 2012).

Third, with respect to the number of players involved in the supply chain contracting model, there are two groups of studies. The majority of the studies focuses on one buyer/manufacturer-two/multiple suppliers (Chen, 2007; Chaturvedi and Martínez-de-Albéniz, 2011; Özer and Raz, 2011; Kalkanci and Erhun, 2012; Lee and Yang, 2013; Fang et al., 2014; Li et al., 2015). The other group of studies focuses on one buyer/manufacturer-one supplier (Cachon, 2003; Mukhopadhyay et al., 2009; Çakanyıldırım et al., 2012; Wagner 2015).

The study that is most similar to ours is that of Fang et al. (2014), in which the author studied the supply-side competition with a newsvendor model. The key difference from our model is that Fang et al. (2014) assumes suppliers belong to two specific types or binary opposite. In our paper, the buyer or the manufacturer can process the asymmetric information regarding the green degree of multiple suppliers and design attractive contract for suppliers. To achieve this goal, the private information of suppliers is extended as a continuous type in our model. The second difference is that Fang et al. (2014) considered the asymmetric cost information, that is, the unit production cost of each supplier was privately informed. In our paper, we shed a new light on the sustainable procurement decision in a supply chain, that is, we aim to study the impact of the asymmetric information about the green degrees of materials from suppliers on the supply chain contract design, as shown in Table 2.

The contributions of this paper can be summarized as follows. First, this paper is the first to study the constrained procurement decision issue for a manufacturer with asymmetric information about the green degrees of materials from a supplier under stochastic demand. In addition, different types of auctions, including price auctions with an emissions target and performance-based auctions, are designed to achieve a win-win situation for both the supplier and manufacturer. Second, besides studying the interaction behaviors between one manufacturer and one supplier, we extend the basic model to further study the case of multiple suppliers. Third, this study is also the first to analyze the impact of an emissions trading scheme on contract design in the presence of asymmetric information for the manufacturer. To overcome limited types of asymmetric information, the assumption about asymmetric information is extended as a continuous type. In addition, the effective emissions trading policy is derived based on the optimal procurement contract with asymmetric information to assist the manufacturer in balancing buying and selling emission allowances.

3. Model Setup

3.1 Model Description

Due to the pressures of uncertain demand and environmental regulations, a manufacturer or a leader of a supply chain has to make adjustments. For instance, HP collaborates with its production and non-production suppliers to reduce the GHG emissions of their entire supply chain (HP, 2014). In this paper, we aim to assist a manufacturer in designing an attractive and efficient procurement contract sourcing sustainable materials from different types of suppliers such that the profits of both the manufacturer and its suppliers can be maximized. Herein, the green degree of materials is private and known only to a supplier, thus, the manufacturer needs to identify the private information during the decision making process. In order to comprehensively describe the aforementioned practical and complex issues, this paper will develop a mechanism design model with asymmetric information and multiple agents. The details of the model setting are described in the following section. The notation used in the model is summarized in Table 3.

<Insert Table 3 around here>

3.2 The Model

This section considers a procurement issue in a supply chain with a manufacturer and n ($n \geq 1$) potential suppliers to satisfy the random demand. To control the emission volumes from suppliers, the manufacturer needs to use and purchase environmentally focused materials from 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 raw materials from supplier i. The green degree is also characterized by its type, which is known only by the supplier. Specifically, cooperation with a supplier of type θ_i directly impacts the emission volumes of the manufacturer.

However, the manufacturer only observes that the type of supplier has 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 the suppliers are risk-neutral. The manufacturer aims at maximizing its expected profit by seeking an optimal procurement strategy. The different strategies are studied under two scenarios, procurement from a single supplier (n = 1) and competitive procurement among multiple suppliers ($n \geqslant 2$).

Next, 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 emission 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 emission 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 brief analysis above, the objective functions of the manufacturer, Π_m, and the supplier, Π_s, can be formulated as follows.

$$\Pi_m = R(Q(\theta)) + T(Q(\theta), C) - M(Q(\theta)), \tag{1}$$

$$\Pi_s = M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta), \tag{2}$$

where

$$R(Q(\theta)) = p\,\mathrm{E}\min(D, Q(\theta)) + r_v\,\mathrm{E}(Q(\theta) - D)^+ - c_p Q(\theta), \tag{3}$$

$$T(Q(\theta), C) = w_1 \mathrm{E}\min(C - \beta Q(\theta))^+ - w_2 \mathrm{E}\min(\beta Q(\theta) - C)^+. \tag{4}$$

Equation (1) describes the payoff function of the manufacturer. The first item in Equation (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 (3). The sales revenue equals the unit price times the expected quantity of sale. 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 (1) illustrates the expected revenue from emissions trading activity. During the production processes, the unit emission factor of the manufacturer is denoted by the coefficient β. Thus, the total emissions amount of the manufacturer equals the product of β and $Q(\theta)$, which is determined by the production technology of the manufacturer. Krass et al. (2013) also adopted a linear function to calculate the emissions of the production process. For a certain period, if the emission allowances (C) of the manufacturer are greater than the total emissions amount, then the manufacturer could benefit from selling unneeded emissions allowances; otherwise, the manufacturer should purchase the insufficient allowances from the carbon market. In Equation (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 (Gong and Zhou, 2013). Regarding the uncertainty of emission 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 (1) is the cash transfer from the manufacturer to the supplier. Equation (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 product of the coefficient α, the green degree θ, 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, as a typical real-world example, implemented an innovative stage in producing iPhone models that may help its suppliers, especially those in China, cut carbon emissions (Xinhua News, 2015). 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 (Handfield et al. 2002). Thus, in this paper, we denote the environmental quality function by $W(Q(\theta))$, which is the impact on the suppliers' type, θ, without loss of generality, and $W(Q(\theta))$ is assumed to be an increasing concave function. The last term is the production cost, which is the material 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, the *incentive compatibility (IC)* constraint must be satisfied as shown in equation (5). This constraint indicates that each supplier prefers to choose the contract that is designed for him. That is, if a supplier's type is θ and the contract designed for him is ($Q(\theta)$, $M(Q(\theta))$), then, the utility of the supplier choosing $Q(\theta)$ is larger than choosing any other contract, ($Q(\theta')$, $M(Q(\theta'))$).

$$M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \geq M(Q(\theta')) + \alpha\theta W(Q(\theta')) - c_s Q(\theta'). \quad (5)$$

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

$$\begin{aligned} \max \Pi_m(\theta, Q(\theta)) &= \max \mathrm{E}[R(Q(\theta)) + T(Q(\theta), C) - M(Q(\theta))] \\ &= \int_{\underline{\theta}}^{\overline{\theta}} [R(Q(\theta)) + T(Q(\theta), C) - M(Q(\theta))] f(\theta) d\theta \\ s.t. \quad & M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \geq \Pi_0 = 0, \textit{ for all } \theta, \\ & M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \geq M(Q(\theta')) + \alpha\theta W(Q(\theta')) - c_s Q(\theta'), \textit{ for all } \theta \textit{ and } \theta'. \end{aligned} \quad (6)$$

In the following section, the properties of the manufacturer's decision issue in Equation (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. Contract Analysis and Implications

To reduce GHG emissions during the production process, the manufacturer prefers to use sustainable materials. However, for suppliers, offering the environmental materials to meet sustainable requirements is costly. Therefore, there exists a conflict between a manufacturer and suppliers. Besides, the green degree of material is private and known only to a supplier. This private information can significantly affect the profitability, brand value, and reputation of the manufacturer or buyer as we discussed the brand scandal case (Genasci, 2012) in Section 1.

To study how an attractive and efficient procurement mechanism can be effectively designed under constrains of the asymmetric information (e.g., the green degree, θ) and an emissions trading scheme, this section examines the properties of the manufacturer's decision problem specified by Equation (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. All of the proofs can be found in the Appendix.

The decision problem specified by Equation (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 (i.e., the profit of choosing nothing), but this type of behavior may lead to increases in the emissions volume of the manufacturer. However, information rent can be used appropriately to illustrate this phenomenon. The information rent is denoted as follows:

$$r(\theta) = M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta). \tag{7}$$

The first order derivative of the information rent $r'(\theta)$ is $\alpha W(Q(\theta))$, which is greater than or equal zero. Thus, the information rent $r(\theta)$ must be an increasing function with respect to θ, and $r(\underline{\theta})$ should equal 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:

$$\begin{aligned}\Pi_m &= \int_{\underline{\theta}}^{\overline{\theta}} [R(Q(\theta)) + T(Q(\theta), C) - M(Q(\theta))] f(\theta) d\theta \\ &= \int_{\underline{\theta}}^{\overline{\theta}} [R(Q(\theta)) + T(Q(\theta), C) - r(\theta) + \alpha\theta W(Q(\theta)) - c_s Q(\theta)] f(\theta) d\theta\end{aligned} \tag{8}$$

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 (8) can be re-written as follows:

$$r(\theta)=\int_{\underline{\theta}}^{\overline{\theta}}\alpha W(Q(\theta))d\theta \tag{9}$$

$$\Pi_m=\int_{\underline{\theta}}^{\overline{\theta}}[R(Q(\theta))+T(Q(\theta))-\alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)}+\alpha\theta W(Q(\theta))-c_sQ(\theta)]f(\theta)d\theta \tag{10}$$

Maximization of Π_m corresponds to maximization of the integrand function in Equation (10). Thus,

$$\begin{aligned}G(Q(\theta))&=R(Q(\theta))+T(Q(\theta))-\alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)}+\alpha\theta W(Q(\theta))-c_sQ(\theta)\\&=p\,\mathrm{E}\min(Q(\theta),D)+r_v\,\mathrm{E}(Q(\theta)-D)^+-c_pQ(\theta)+w_1\,\mathrm{E}(C-\beta Q(\theta))^+\\&\quad-w_2\,\mathrm{E}(\beta Q(\theta)-C)^+-\alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)}+\alpha\theta W(Q(\theta))-c_sQ(\theta).\end{aligned} \tag{11}$$

Proposition 1. *The characteristics of Q(θ) and G(Q(θ)) include the following:*

(i) Q(θ) is an increasing function in θ;

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

In Proposition 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 (11), the second property in Proposition 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 2. *Given the condition of an increasing failure rate,* $G(Q(\theta))$ *is supermodular in* θ, $Q(\theta)$ *and* w_1 *and is submodular in* $Q(\theta)$ *and* w_2.

Based on the results described in Proposition 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; regarding the supplier, becoming more green results in increased competitive power because the supplier can claim a greater market share. In addition, the modularity of $G(Q(\theta))$ with respect to trading prices indicate that the manufacturer prefers to source greener materials if the selling price of emission allowances is increasing, that is, the manufacturer can gain profit from emissions trading by selling its redundant emission allowances. Following the 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 3. *The characteristics of the optimal contract and the payoff function of the supplier include the following:*

(*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*

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

where $Q^*(\theta)$ = argmax $G(Q(\theta))$;

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

The first property described in Proposition 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 supplier can maximize their payoff functions simultaneously. Regarding the manufacturer, this optimal contract not only can assist them in controlling the emission 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 (θ, $Q(\theta)$) 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.

5. Decisions when Multiple Suppliers Are Available

This section extends the basic model presented in Section 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 that 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 the 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:

$$\tilde{\Pi}_m = \mathrm{E}[R(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1,\ldots,\theta_n))], \tag{12}$$

$$\tilde{\Pi}_{s_i} = m_i(q_i(\theta_i)) + \alpha_i\theta_i W(q_i(\theta_i)) - c_s q_i(\theta_i), \tag{13}$$

where

$$\begin{aligned} R(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) = p\,\mathrm{E}\min(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n), D) \\ + r_v\,\mathrm{E}(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n) - D)^+ - c_p \sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n) \end{aligned} \tag{14}$$

$$T(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) = w_1\,\mathrm{E}(C - \beta\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n))^+ - w_2\,\mathrm{E}(\beta\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n) - C)^+. \tag{15}$$

In the multiple-supplier scenario, Equation (14) consists of three items, the sales revenue, the salvage value of leftover products, and the production cost. The parameters in Equation (14) have same meaning as the parameters in Equation (3). Equation (15) describes the revenue or expenditure obtained by selling or purchasing the carbon emissions allowances of the manufacturer. The emissions volume of the manufacturer is determined by the total order quantity and the unit emission rate, β. The supplier i payoff function in Equation (13) has the same meaning as in Equation

(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 $\mathrm{E}_{\theta_{-i}} Q_i(\theta_i, \theta_{-i})$; then, the payment is $\mathrm{E}\, M_i(Q_i(\theta_i, \theta_{-i}))$.

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,…, *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:

$$m_i(q_i(\theta_i)) + \alpha_i \theta_i W(q_i(\theta_i)) - c_s q_i(\theta_i) \ge m_i(q_i(\theta_i)) + \alpha_i \delta W(q_i(\theta_i)) - c_{s_i} q_i(\theta_i) . \tag{16}$$

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

$$\begin{aligned} \tilde{\Pi}_m &= \mathrm{E}[R(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1, \ldots, \theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1, \ldots, \theta_n))] \\ s.t.\quad & m_i(q_i(\theta_i)) + \alpha_i \theta_i W(q_i(\theta_i)) - c_s q_i(\theta_i) \ge 0, \\ & m_i(q_i(\theta_i)) + \alpha_i \theta_i W(q_i(\theta_i)) - c_s q_i(\theta_i) \ge m_i(q_i(\theta_i)) + \alpha_i \delta W(q_i(\theta_i)) - c_{s_i} q_i(\theta_i), \\ & \textit{for all } \delta \textit{ and } \theta_i. \end{aligned} \tag{17}$$

We denote the information rent as $r_i(\theta_i) = m_i(q_i(\theta_i)) + \alpha_i \theta_i W(q_i(\theta_i)) - c_s q_i(\theta_i)$. The first order derivative of the information rent $r_i'(\theta_i)$ is then $\alpha_i W_i(q_i(\theta_i))$, which is greater than or equal zero. Thus, the information rent $r_i(\theta_i)$ must be increasing, and $r_i(\underline{\theta})$ should equal zero; consequently, the *IR* condition is automatically satisfied. The expected payment from the manufacturer is given by Equation (18).

$$\begin{aligned}
&\mathrm{E}[\sum_{i=1}^{n} M_i(Q_i(\theta_1,\ldots,\theta_n))] = \mathrm{E}[\sum_{i=1}^{n} m_i(q_i(\theta_1,\ldots,\theta_n))] \\
&= \sum_{i=1}^{n}\int_{\underline{\theta}}^{\overline{\theta}} [r_i(\theta_i) - \alpha_i\theta_i W_i(q_i(\theta_i)) + c_{s_i} q_i(\theta_i)] dF(\theta_i) \\
&= \int_{\underline{\theta}}^{\overline{\theta}} \cdots \int_{\underline{\theta}}^{\overline{\theta}} [c_{s_i} Q_i(\theta_i) - \alpha_i W_i(q_i(\theta_i))(\theta_i - \frac{1-F_i(\theta_i)}{f_i(\theta_i)})] dF(\theta_i),
\end{aligned} \tag{18}$$

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:

$$\begin{aligned}
\tilde{\Pi}_m &= \int_{\underline{\theta}}^{\overline{\theta}} [R(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1,\ldots,\theta_n))] dF(\theta_i) \\
&= \int_{\underline{\theta}}^{\overline{\theta}} [R(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) - r_i(\theta_i) + \alpha_i\theta_i W_i(q_i(\theta_i)) \\
&\quad - c_{s_i} q_i(\theta_i)] dF(\theta_i) \\
&= \int_{\underline{\theta}}^{\overline{\theta}} [R(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) - c_{s_i} Q_i(\theta_i) \\
&\quad + \alpha_i W_i(q_i(\theta_i))(\theta_i - \frac{1-F_i(\theta_i)}{f_i(\theta_i)})] dF(\theta_i)
\end{aligned} \tag{19}$$

Maximization of the manufacturer’s payoff corresponds to maximization of the integrand function in Equation (19), which implies

$$\begin{aligned}
&K(Q_i(\theta_1,\ldots,\theta_n)) \\
&= R(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) + T(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n)) - \sum_{i=1}^{n} M_i(Q_i(\theta_1,\ldots,\theta_n)) \\
&= p\,\mathrm{E}\min(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n), D) + r_v\,\mathrm{E}(\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n) - D)^+ - c_p \sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n) \\
&\quad w_1\,\mathrm{E}(C - \beta\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n))^+ - w_2\,\mathrm{E}(\beta\sum_{i=1}^{n} Q_i(\theta_1,\ldots,\theta_n) - C)^+ - c_{s_i} Q_i(\theta_i) \\
&\quad + \alpha_i W_i(Q_i(\theta_i))(\theta_i - \frac{1-F_i(\theta_i)}{f_i(\theta_i)}).
\end{aligned} \tag{20}$$

Proposition 4. *For the scenario of multiple suppliers,*

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

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

The first property of Proposition 4 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 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 order quantity increases. Therefore, the manufacturer should follow this rule to design the appropriate contracts.

Proposition 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* $Q_i(\theta_1,\ldots,\theta_n)$.

With respect to the monotonicity, Proposition 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 θ_i and $Q_i(\theta_1,\ldots,\theta_n)$. 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 6. *In a scenario with multiple suppliers,*

(i) if $\theta_1 \le \theta_2 \le \cdots \le \theta_n$*, 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*

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

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

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

In Proposition 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 θ_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 $Q^*(\theta_j) = 0, j = 1,2,\ldots,n-1$. $Q^*(\theta_n)$ is the maximizer of the concave function $K(Q_i(\theta_1,\ldots,\theta_n))$. The second property of Proposition 6 implies that the suppliers' payoff is 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, 5, and 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 3. Under a scenario with multiple independent suppliers, the robustness of the results were studied, and the results indicate that the scenario with multiple independent suppliers yield similar results as the optimal contract for a single supplier.

6. Model Extensions

6.1 Emissions Trading Policy

Based on the structured 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 7. *Given an order quantity Q(θ), 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(θ).*

$$C^{*}=\begin{cases} L(Q(\theta)), & \text{if } C\leq L(Q(\theta)) \\ C, & \text{if } L(Q(\theta))\leq C\leq U(Q(\theta)) \\ U(Q(\theta)), & \text{if } C\geq L(Q(\theta)) \end{cases},$$

where

$$U(Q(\theta))=\arg\max_{C}\{R(Q(\theta))-M(Q(\theta))+w_1\,\mathrm{E}(C-\beta Q(\theta))^{+}\}$$
$$L(Q(\theta))=\arg\max_{C}\{R(Q(\theta))-M(Q(\theta))-w_2\,\mathrm{E}(\beta Q(\theta)-C)^{+}\}.$$

Proposition 7 specifies the optimal emissions trading policy, which consists of the lower ($L(Q(\theta))$) and upper ($U(Q(\theta))$) bounds based on the emissions allowances of the manufacturer. The "trading policy" for the manufacturer can be summarized as follow. 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 emission 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 its emission allowances in a timely manner to maximize its profit by holding appropriate emission allowances.

6.2 Price Auction with a Carbon Emission Target

Facing a carbon emission 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 δ(·); let *p* denote the bidding price for supplier *i*. Assume that δ(·) 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 emission cost and the production cost for supplier *i* is $\mu(\theta_i)$ times *p*. Therefore, supplier *i*'s expected profit can be formulated as follows:

$$\Pi_i = (x - \mu(\theta_i)p)\Pr(p_j > \delta^{-1}(p)) \tag{21}$$

Proposition 8. *Consider a price auction with an emission target. With n independent suppliers, the symmetric Bayesian-Nash equilibrium bidding strategy on the first price bid is* $\frac{\mathrm{E}(P \mid P \leq p)}{\mu(\theta_i)}$, *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* $\frac{x}{\mu(\theta_i)}$.

In a price auction with a carbon emission target, the required order quantity is first determined by the emissions capacity of the manufacturer. That is, the manufacturer establishes the target objectives for cooperation with a certain type of supplier. 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.

6.3 A Performance-Based Auction

In a performance-based auction, the 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 a 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:

$$V(\theta, p) = M(Q(\theta)) + c_m Q(\theta) \quad (22)$$

Proposition 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* $M^* = \delta(\theta^*) - c_m Q^*(\theta)$, $\delta(\theta^*) = \mathrm{E}[Z(\theta^*) \mid Y < v]$, $Y = \max\{v_1, v_2, \ldots, v_{n-1}\}$, $Z(\theta^*) = (c_s + c_m)Q(\theta^*) - \alpha\theta^* W(Q(\theta^*))$.

The intuition of Proposition 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.

7. Numerical Example and 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 contract design with asymmetric information. The research results provide meaningful managerial implications 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 also can benefit from our findings by understanding the outcomes of adopting flexible strategies in different auction types. Next, we design a numerical example to present analytical results and summary a few managerial guidelines for practitioners.

We assume that the demand, D, the emission allowances, C, and the green degree, θ, of the manufacturer are uniformly distributed over the interval (0, 1). The $W(Q(\theta))$ function is assumed to be a linear case, $kQ(\theta)$. All the other parameters are given as follows, p=40, w_1=20, w_2=30, c_p=15; c_s=20; α=10, β=0.2, k=2, r_v=4.5, $\theta \in [0.1,1]$. Based on the analytical results, the optimal contract, ($Q^*(\theta)$, $M(Q^*(\theta))$), and the optimal emissions trading thresholds are presented in Figure 1 and 2, respectively.

<Insert Figure 1 around here>

<Insert Figure 2 around here>

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 indicate that θ brings a different concern to the manufacturer's decision and the payoffs of the manufacturer. Regarding the payoffs for the members of the supply chain, our research results also indicate that the manufacturer prefers to offer a higher ordering quantity $Q(\theta)$ is greater when θ is greater as shown in Figure 1. Based on the numerical example outcome as shown in Figure 2, managerial guidelines for the manufacturer can be summarized as follows.

- The manufacturer needs to cooperate with a greener supplier with sufficient emissions allowances because the manufacturer can spend less money to hold emission allowances.
- The manufacturer also can select the supplier with the lower green degree and

lower price if he has larger emissions allowances. This reduces the procurement cost that can be used to purchase emissions allowances from the carbon market.

The effective emissions trading policy was established to guide the manufacturer in making reasonable trading decisions. As an example of a typical case in China, Beijing Eastern Petrochemical Co. Ltd. earned half a million RMB in profit from emissions trading in 2015 (BEP, 2015).

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 the green degrees and supply quantities. 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. Regarding 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. For a performance-based auction, the performance of suppliers is a key factor for the manufacturer in making procurement decisions. In such scenario, the bidding information not only includes the green degree but also involves the price because these two factors operate simultaneously. The managerial guidelines for suppliers can be summarized as follows.

- A supplier can enlarge its market share by providing sustainable raw materials, which can be a strong competitive advantage for a supplier, as shown in Figure 1.

- For a price auction with a carbon emissions target, a supplier only aims at bidding by providing the most attractive price.
- In a performance-based auction, a supplier has to bid by providing both attractive prices in consideration of its production cost and green degree simultaneously.

In general, to achieve the goal of mutual benefit of profit maximization and carbon emissions control, the research outcomes in our paper provide an effective method to promote sustainable operations for the upstream of a supply chain.

8. Conclusions

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 work. Based on literature review in section 2.1, several studies studied the emissions control with perfect information using some classical operations research models to assist the manufacturer in making the optimal decision. However, the interaction behaviors between the manufacturer and suppliers are neglected. We shed a new light on the sustainable procurement decision in a supply chain using a mechanism design model with asymmetric information (e.g., the green degree) to maximize the profits of both the manufacturer and suppliers and to reduce the GHG emissions for the manufacturer. Regarding the confidential information for the green degree of the raw materials of suppliers, the manufacturer needs to adopt effective procurement strategies to earn profit and control its emissions volumes under the emissions trading policy.

First, the 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 profit by trading its emissions allowances. The optimal procurement contract was derived with asymmetric information. The relationship between the green degree of a supplier and the optimal structure of the contract were further analyzed. Unlike the research results summarized in section 2.1, the optimal contract is profitable for both the manufacturer and the supplier with asymmetric information and emissions constraints.

Second, as shown in Table 2, we can find that the majority of studies focus on one buyer/manufacturer-two/multiple suppliers. In our paper, the impact of multiple independent suppliers on the manufacturer's decisions is studied. Therefore, the second model in our paper for the general setting of multiple suppliers' competition based on the basic model was formulated, and the robustness of the characteristics of a single supplier was analyzed.

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

In summary, this paper analyzed an interesting procurement mechanism design issue for the manufacturer subjects to information asymmetry regarding its suppliers' green degrees. Our research outcomes provide insight into this procurement issue. Future research may investigate how the key factors, such as emissions trading prices and carbon taxes, 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 emissions regulations.

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APPENDICES

PROOF OF PROPOSITION 1.

(i) Based on the *IC* condition in Equation (5), the payoff function of the supplier Π_s can be maximized when θ' equals θ, that is, the result of the first order derivative of the right hand-side of Equation (5) for θ' equals zero when $\theta' = \theta$, i.e.,

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

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

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

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

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

The above analysis implies that the necessary condition is $\alpha W'(Q(\theta))Q'(\theta) \ge 0$. It is because $W(Q(\theta))$ is assumed as an increasing function, that is, $W'(Q(\theta))$ is greater than or equal zero. Therefore, the necessary condition becomes that $Q'(\theta)$ is greater than or equal zero. That is, $Q(\theta)$ is an increasing function in θ.

(ii) The second order derivative of the function in Equation (11) for $Q(\theta)$ is shown as:

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

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

Q.E.D.

PROOF OF PROPOSITION 2.

Taking the cross partial derivative of $G(Q(\theta))$ with respect to $Q(\theta)$ and θ, we can get

$$\frac{\partial^2 G(Q(\theta))}{\partial Q(\theta)\partial\theta} = \alpha W'(Q(\theta))[\frac{f(\theta)(1-F(\theta))+f^2(\theta)}{f^2(\theta)}+1] \quad \text{(A.5)}$$

Therefore, under the condition of increasing failure rate, Equation (A.5) is greater than or equal zero. Because $W(Q(\theta))$ is an increasing function and other parts in Equation (A.5) is greater than zero.

Taking the cross partial derivative of $G(Q(\theta))$ with respect to $Q(\theta)$ and w_1, we can get

$$\frac{\partial^2 G(Q(\theta))}{\partial Q(\theta)\partial w_1} = \beta H(\beta Q(\theta)) > 0, \quad \text{(A.6)}$$

Similarly, taking the cross partial derivative of $G(Q(\theta))$ with respect to $Q(\theta)$ and w_2, we can get

$$\frac{\partial^2 G(Q(\theta))}{\partial Q(\theta)\partial w_2} = -\beta H(\beta Q(\theta)) < 0. \quad \text{(A.7)}$$

Because $H(\beta Q(\theta))$ is an increasing function, thus, Equations (A.6) and (A.7) are greater and smaller than zero, respectively. Based on the theory on lattice and modularity (Topkis, 1998), $G(Q(\theta))$ is supermodular in ($Q(\theta)$, θ, w_1) and submodular in ($Q(\theta)$, w_2) under the condition of increasing failure rate.

Q.E.D.

PROOF OF PROPOSITION 3.

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

$$\frac{\partial G(Q(\theta))}{\partial Q(\theta)} = p - \beta w_1 - c_p - c_s + (r_v - p)\Phi(Q(\theta)) + \beta(w_1 - w_2)H(\beta Q(\theta)) \\ + \alpha W'(Q(\theta))(\theta - \frac{1-F(\theta)}{f(\theta)}). \tag{A.8}$$

Let

$$\frac{\partial G(Q(\theta))}{\partial Q(\theta)} = 0 \tag{A.9}$$

Then, the optimal $Q^*(\theta)$ can be derived from Equations (A.8) and (A.9). In addition, the optimal cash transfer can be obtained as follows:

Because

$$\int_{\underline{\theta}}^{\theta} \alpha W(Q^*(\xi))d\xi = r(\theta) = M(Q^*(\theta)) + \alpha\theta W(Q^*(\theta)) - c_s Q^*(\theta). \tag{A.10}$$

Thus,

$$M(Q^*(\theta)) = \int_{\underline{\theta}}^{\theta} \alpha W(Q^*(\xi))d\xi + c_s Q^*(\theta) - \alpha\theta W(Q^*(\theta)). \tag{A.11}$$

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

(ii) Substituting Equation (A.11) 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 zero, because both $W(Q(\theta))$ and $Q(\theta)$ are increasing functions. Thus, Π_s is supermodular in (θ, $Q(\theta)$).

Q.E.D.

PROOF OF PROPOSITION 4.

(i) In order to guarantee the *IC* condition in Equation (16), we take the first order derivative for θ_i, which aims at maximizing the payoff of the supplier *i*. Then,

$$[m_i'(q_i(\theta_i))+\alpha_i\theta_i W_i'(q_i(\theta_i))-c_{s_i}]q_i'(\theta_i)=0. \tag{A.12}$$

Thus, the second order derivative for θ_i is:

$$\begin{aligned}&m_i''(q_i(\theta_i))(q_i'(\theta_i))^2+m_i'(q_i(\theta_i))q_i''(\theta_i)+\alpha_i W_i'(q_i(\theta_i))q_i'(\theta_i)+\alpha_i\theta_i W_i''(q_i(\theta_i))(q_i'(\theta_i))^2\\&+\alpha_i\theta_i W_i'(q_i(\theta_i))q_i''(\theta_i)-c_{s_i}q_i''(\theta_i)=0.\end{aligned} \tag{A.13}$$

The first order derivative for θ_i should be maximized by:

$$\begin{aligned}&m_i''(q_i(\theta_i))(q_i'(\theta_i))^2+m_i'(q_i(\theta_i))q_i''(\theta_i)+\alpha_i\theta_i W_i''(q_i(\theta_i))(q_i'(\theta_i))^2\\&+\alpha_i\theta_i W_i'(q_i(\theta_i))q_i''(\theta_i)-c_{s_i}q_i''(\theta_i)\le 0.\end{aligned} \tag{A.14}$$

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

(ii) Taking the second order derivative for the integrand function in Equation (20) with respect to $Q_i(\theta_1,\ldots,\theta_n)$, we can obtain the following result as shown in Equation (A.15):

$$\begin{aligned}\frac{\partial^2 K(Q_i(\theta_1,\ldots,\theta_n))}{\partial Q_i^2(\theta_1,\ldots,\theta_n)}&=(r_v-p)\phi(Q_i(\theta_1,\ldots,\theta_n))+\beta^2(w_1-w_2)h(Q_i(\theta_1,\ldots,\theta_n))\\&+\alpha_i W_i''(Q_i(\theta_1,\ldots,\theta_n))(\theta_i-\frac{1-F_i(\theta_i)}{f_i(\theta_i)})\end{aligned} \tag{A.15}$$

Because the pdf function is greater than zero and the coefficient of the first two items in Equation (A.15) are negative, in addition, $W(Q_i(\theta_1,\ldots,\theta_n))$ is an increasing concave function, therefore, the result of the second order condition of $K(Q_i(\theta_1,\ldots,\theta_n))$ is negative if $\theta_i\ge\frac{1-F_i(\theta_i)}{f_i(\theta_i)}$. That is, $K(Q_i(\theta_1,\ldots,\theta_n))$ is a concave function in $Q_i(\theta_1,\ldots,\theta_n)$ if $\theta_i\ge\frac{1-F_i(\theta_i)}{f_i(\theta_i)}$. Q.E.D.

PROOF OF PROPOSITION 5.

Taking the mixed partial differential in terms of $Q_i(\theta_1,\ldots,\theta_n)$ and θ_i for Equation (20), we obtain the following result as shown in Equation (A.16):

$$\frac{\partial^2 K(Q_i(\theta_1,\ldots,\theta_n))}{\partial Q_i(\theta_1,\ldots,\theta_n)\partial\theta_i} = \alpha_i W_i'(Q_i(\theta_1,\ldots,\theta_n))(\frac{f_i^2(\theta_i) - f_i'(\theta_i)(1-F_i(\theta_i))}{f_i^2(\theta_i)}+1) \quad (A.16)$$

Thus, under the condition of increasing failure rate, Equation (A.16) is no less than zero, it is 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 (θ, $Q(\theta)$) under the condition of increasing failure rate.

Q.E.D.

PROOF OF PROPOSITION 6.

(i) Following the results in Proposition 4, $K(Q_i(\theta_1,\ldots,\theta_n))$ is a concave function in $Q_i(\theta_1,\ldots,\theta_n)$. If $\theta_1 \le \theta_2 \le \cdots \le \theta_n$, then, the optimal mechanism is $Q^*(\theta_1,\ldots,\theta_n) = Q^*(\theta_n)$ and $Q^*(\theta_j) = 0,\ j = 1,\ldots,n-1.$ is the maximizer of the concave function $K(Q_i(\theta_1,\ldots,\theta_n))$. Therefore, the optimal payment can be characterized as follows:

$$M_i(Q^*(\theta_n)) = \alpha_i W_i(Q^*(\theta_n))(\frac{1-F_i(\theta_n)}{f_i(\theta_n)} - \theta_n) + c_{s_i} Q^*(\theta_n) \quad (A.17)$$

Because

$$\int_{\underline{\theta}}^{\theta} \alpha_n W_n(q_n^*(\xi))d\xi = r_n(\theta_n) = m_n(q_n^*(\theta_n)) + \alpha_n\theta_n W_n(q_n^*(\theta_n)) - c_{s_n} q_n^*(\theta_n). \quad (A.18)$$

Thus,

$$M_n(q_n^*(\theta_n)) = \int_{\underline{\theta}}^{\theta} \alpha_n W_n(q_n^*(\xi))d\xi + c_{s_n} q_n^*(\theta_n) - \alpha_n\theta_n W_n(q_n^*(\theta_n)). \quad (A.19)$$

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

(ii) Substituting Equation (A.19) into the payoff function of the supplier, then, the profit of supplier equals $r(\theta)$. The result of the mixed partial differential in terms of θ_n and $Q^*(\theta_n)$ is greater than or equal zero, because $W(Q_i(\theta_1,\ldots,\theta_n))$ is an increasing function.

Q.E.D.

PROOF OF PROPOSITION 7.

Based on the integrated function of the manufacturer,

$$\begin{aligned} G(Q(\theta)) &= R(Q(\theta)) + T(Q(\theta)) - \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta) \\ &= p\,\mathrm{E}\min(Q(\theta), D) + r_v\,\mathrm{E}\min(Q(\theta)-D)^+ - c_p Q(\theta) + w_1\,\mathrm{E}(C-\beta Q(\theta))^+ \\ &\quad - w_2\,\mathrm{E}(\beta Q(\theta)-C)^+ - \alpha W(Q(\theta))\frac{1-F(\theta)}{f(\theta)} + \alpha\theta W(Q(\theta)) - c_s Q(\theta). \end{aligned} \tag{A.20}$$

Thus, above equation can be rewritten as:

$$\begin{aligned} G(Q(\theta)) = \max\{&R(Q(\theta)) - M(Q(\theta)) + w_1\,\mathrm{E}(C-\beta Q(\theta)), \\ &R(Q(\theta)) - M(Q(\theta)) - w_2\,\mathrm{E}(\beta Q(\theta)-C)^+\}, \end{aligned} \tag{A.21}$$

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

Define

$$U(Q(\theta)) = \arg\max_{C}\{R(Q(\theta)) - M(Q(\theta)) + w_1\,\mathrm{E}(C-\beta Q(\theta))^+\}$$
$$L(Q(\theta)) = \arg\max_{C}\{R(Q(\theta)) - M(Q(\theta)) - w_2\,\mathrm{E}(\beta Q(\theta)-C)^+\}$$

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

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

Because both Equations (22) and (23) are greater than zero, thus, $w_1\,\mathrm{E}(C-\beta Q(\theta))^+$ and $w_2\,\mathrm{E}(\beta Q(\theta)-C)^+$ are supermodular in (θ, $Q(\theta)$). In addition,

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

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

Following the above analysis and the Theorem 2.6.4 (Topkis, 1998), both $T_1(Q(\theta), C)$ and $T_2(Q(\theta), C)$ are supermodular in (θ, $Q(\theta)$). Therefore, following the above analysis and the Theorem 2.7.6 and Theorem 2.8.2 (Topkis, 1998), both $L(Q(\theta))$ and $U(Q(\theta))$ are increasing in $Q(\theta)$. Q.E.D..

PROOF OF PROPOSITION 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 their 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, the supplier i's expected profit is $\Pi_i = (x - \mu(\theta_i)p)\Pr(p_j > \delta^{-1}(p))$, $\delta(\cdot)$ is a Bayesian-Nash equilibrium only if Π_i is maximized by $p = \delta(x)$. The first order condition for optimal p should satisfy:

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

The above equation can be written as:

$$(\mu(\theta)\delta(x)F(x)^{n-1})' = x(F(x)^{n-1})' \qquad \text{(A.26)}$$

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

$$\delta(x) = \frac{1}{F(x)^{n-1}} \int_{\underline{x}}^{x} z dF(z)^{n-1} = \frac{1}{\mu(\theta_i)} \mathrm{E}(P \mid P \le p), \qquad \text{(A.27)}$$

where $P = \max\{p_j\}, j = i.$ Q.E.D.

PROOF OF PROPOSITION 9.

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

$$\max_{\theta,M} \Pi_s = M(Q(\theta)) + \alpha\theta W(Q(\theta)) - c_s Q(\theta)$$
$$s.t. \quad M(Q(\theta)) + c_m Q(\theta) = v \qquad \text{(A.28)}$$

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

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

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

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

The first order derivative for the optimal v should satisfy:

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

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

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

which implies:

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

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

$$\frac{\delta^*(\theta)}{H(\theta)}\int_{\underline{\theta}}^{\theta}[(c_s+c_m)Q(\xi) - \alpha\theta W(Q(\xi))]h(\xi)d\xi = \mathrm{E}[Z(\theta^*) \mid Y < v], \qquad \text{(A.34)}$$

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.

Table 1. Carbon emissions regulations in procurement management

Authors	Specific problems	Approaches
Hua et al. (2011)	A single-product procurement issue with emissions trading	EOQ model
Wahab et al. (2011)	The optimal production-shipment policy with carbon emissions	EOQ model
Bouchery et al. (2012)	Inventory and emissions control	Multi-objective EOQ model
Benjaafar et al. (2013)	Coordination of procurement, production, and inventory with emissions regulations	Mixed integer linear programing model
Chen et al. (2013)	The optimal order quantity with emissions regulations	EOQ model
Gong and Zhou (2013)	The optimal production and inventory planning with carbon emissions trading	Dynamic programming model
Jaber et al. (2013)	Coordination of procurement and production with emissions trading schemes	Mixed integer linear programing model
Hammami et al. (2015)	Coordination of procurement, production, and inventory with carbon tax and emissions cap	Mixed integer linear programing model
Ma et al. (2016)	The optimal order quantity with carbon tax	Dynamic programming model

Table 2. Supply chain contract design with asymmetric information

Authors	Asymmetric information	Information characteristics	Players in the game
Cachon (2003)	Demand	Binary opposite	One manufacturer-one supplier
Corbett et al. (2004)	Production costs	Continuous	Two buyers-one supplier
Chen (2007)	Production costs	Continuous	One manufacturer-multiple suppliers
Mukhopadhyay et al. (2009)	The cost of effort	Continuous	One manufacturer-one sales agent
Chaturvedi Martínez-de-Albéniz (2011)	Production costs	Continuous	One buyer-multiple suppliers
Özer and Raz (2011)	Production costs	Binary opposite	One manufacturer-two suppliers
Çakanyıldırım et al. (2012)	Production costs	Binary opposite	One retailer-one supplier
Kalkanci and Erhun (2012)	Demand	Continuous	One manufacturer-two suppliers
Lee and Yang (2013)	Demand	Binary opposite	One retailer-two suppliers
Fang et al. (2014)	Production costs	Binary opposite	One assembler-multiple suppliers
Li et al. (2015)	Production costs	Binary opposite	One manufacturer-two suppliers
Wagner (2015)	Production costs	Binary opposite	One retailer-one supplier
Our paper	The green degrees of materials	Continuous	One manufacturer-one supplier; One manufacturer-multiple suppliers

Table 3. Notation

n	the number of suppliers, $n \geq 1$
D	the demand of the manufacturer
$\Phi()$	the cumulative distribution function (cdf) of the demand
$\phi()$	the probability density function (pdf) of the demand
θ	the green degree of the raw materials from a supplier
$F(\theta)$	the cdf of θ
$f(\theta)$	the pdf of θ
$Q(\theta)$	the order quantity offered to a supplier with the green degree of θ
$M(Q(\theta))$	the revenue from the manufacturer
Π_m	the payoff function of the manufacturer
Π_s	the payoff function of the supplier
$R(Q(\theta))$	the sales revenue of the manufacturer
p	the unit price
r_v	the unit salvage revenue
c_p	the unit production cost
C	the emission allowances of the manufacturer
$T(Q(\theta),C)$	the expected revenue from emissions trading
w_1	the selling prices of carbon emissions
w_2	the buying prices of carbon emissions
β	the unit emission factor of the manufacturer
$H()$	the cdf of the emission allowances of the manufacturer
$h()$	the pdf of the emission allowances of the manufacturer
$W(Q(\theta))$	the environmental quality function
c_s	the material of the unit production cost

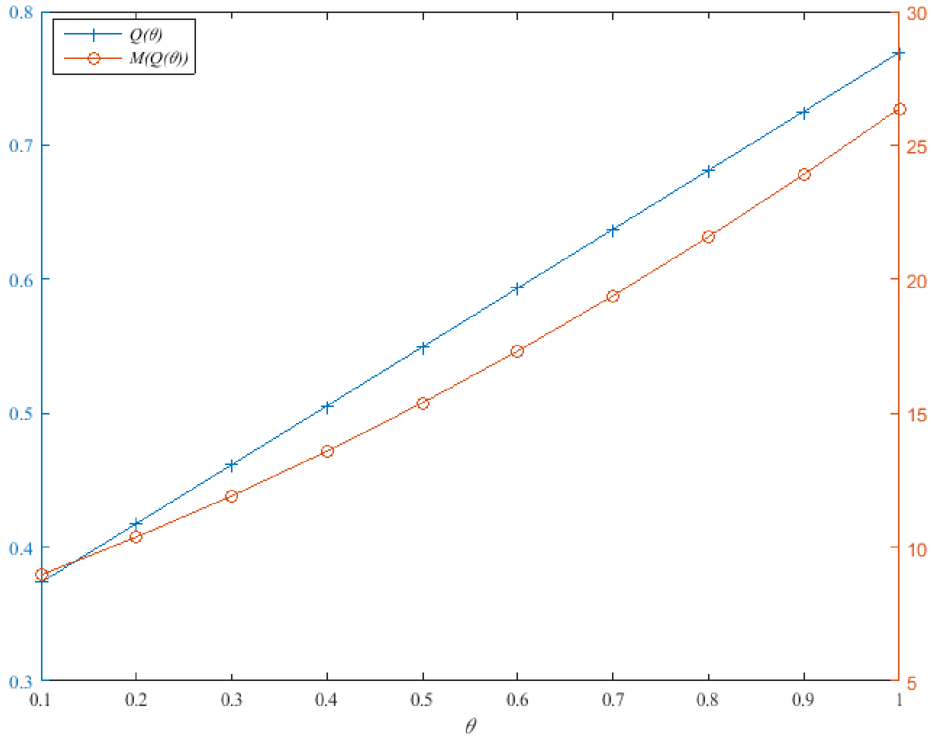

Figure 1. The relationship between the optimal contract and the green degree

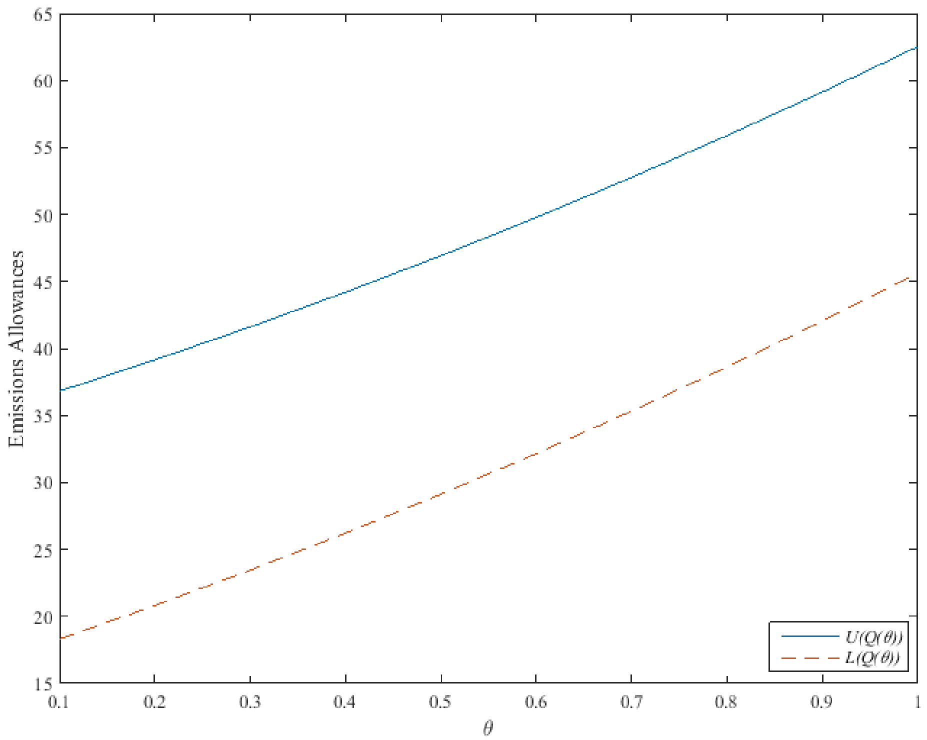

Figure 2. The optimal emission trading thresholds for the manufacturer