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A Newsboy Model with Quick Response under Sustainable Carbon Cap-N-Trade

Jinpyo Lee *, **Mi Lim Lee** and **Minjae Park**

College of Business Administration, Hongik University, 94 Wausan-ro, Mapo-gu, Seoul 121-791, Korea; mllee@hongik.ac.kr (M.L.L.); mjpark@hongik.ac.kr (M.P.)
* Correspondence: jinpyo.lee@hongik.ac.kr; Tel.: +82-2-320-1734

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Abstract: In this study, we consider a carbon emission cap-and-trade system in which the policymaker decides the cap for carbon emissions for each company and also has the power to regulate the carbon price in the carbon trading market for the purpose of minimizing total carbon emissions. We assume that there are n companies regulated in terms of carbon emissions by the policymaker, each of which emits carbon when producing its own product. After learning the carbon cap and carbon price regulated by the policymaker, each company makes simultaneous pricing and production decisions using the quick response strategy, and can trade some of its carbon emissions in the carbon market at the carbon price set by the policymaker, if the carbon emissions are below the cap. We model this non-cooperative game between the policymaker and companies as a Stackelberg game in which the policymaker is the leader and the companies are the followers. We show that there exists an equilibrium for the policymaker's carbon pricing decisions and each company's production and pricing decisions. From this equilibrium, we derive a carbon cap for the company at which the amount of traded carbon emissions is zero. This implies that some company's production and pricing decisions, even under carbon emission restrictions, will be equal to those without the carbon emission restrictions. Also, we find that companies participating in the carbon cap-and-trade system would reduce their carbon emissions through reduced production, but can have a chance to improve profit through control of the product's selling price.

Keywords: carbon cap-and-trade; dynamic pricing; newsboy model; quick response; Stackelberg game; sustainable operation management

1. Introduction

In the area of operations management, many researchers have faced challenges in integrating issues of sustainability into their traditional areas of interest. As reported in Kleindorfer et al. [1], over the past 20 years there has been growing pressure on businesses to consider the environment in the products that they offer and the processes they deploy. One symptom of this pressure is the movement towards the triple bottom line (TBL) approach, which concerns the relationships between profit, people, and the planet. The resulting challenges include integrate environmental, health, and safety concerns along with sustainable operations. Moreover, to address climate change, which is an environmental concern, companies (especially in carbon emission-related businesses) have been forced to take responsibility for global warming and increasing concentrations of greenhouse gases.

In this context, the Kyoto Protocol aimed to encourage global efforts and the enforcement of its goals. This international treaty was adopted in Kyoto, Japan on 11 December 1997 and enforced on 16 February 2005. Despite doubts as to whether it would ultimately be adopted globally, it has definitely changed attitudes and policies both in the public and private sector with respect to greenhouse gas concentrations and carbon emissions, as well as the potential for trade of those reductions [2], with impacts on the global economy. Since the Kyoto Protocol was enforced, 192 nations have been involved in implementation of the objective of reducing greenhouse gas concentrations and carbon emissions in developed countries. The Kyoto protocol adopted three carbon reduction mechanisms: International Emissions Trading, the Clean Development Mechanism, and Joint Implementation [3].

In this study, we consider International Emissions Trading as a carbon emission control system which uses a cap-and-trade system for carbon reductions. The cap-and-trade system improves the welfare for all participants since marginal benefits will usually differ across participants so that the same overall emission level can be reached at lower costs [4]. For the cap-and-trade system, we consider the policymaker, who decides the cap for each company's carbon emissions, and who also has the power to regulate the carbon price in the carbon trading market for the purpose of minimizing total carbon emissions. After each company learns its own carbon cap (as set by the policymaker), each company simultaneously makes its product pricing and production decisions. The company can trade some of its carbon emissions in the carbon market at the carbon price set by the policymaker if the company's own carbon emissions are below its own cap. Generally, a policymaker does not make carbon pricing decisions since this is usually determined via a market-balancing mechanism. The policymaker's authority implementing the carbon price in the carbon market is an increasing necessity in order to stabilize the market to avoid market failures of the emissions trading system [5]. Hence, simple regulations are needed to ensure a fair and transparent carbon trading market [6]. Hence, for this reason in our model the policymaker is assumed to be able to regulate the carbon price in the carbon trading market.

For the company's operational decisions, the modified newsboy model is used to make the product pricing and production quantity decisions for each company. In the traditional newsboy model, each company sells a product to customers at a price of p per unit, which is assumed to be given exogenously. However, in this paper the price is endogenously decided simultaneously using the production quantity decision of each company. The quantity of products in demand during the selling season is uncertain and thus is assumed to be drawn from a random distribution. The company makes simultaneous pricing and production decisions which decide the product price and how many products to produce before the realization of actual demand during the selling season. Also, each company uses the so-called quick response strategy. The quick response strategy procures an additional quantity of products after obtaining updated demand information during the selling season, albeit at a higher unit procuring cost than its own unit production cost [7]. Excess units left after the selling season will be salvaged at the price or cost s per unit but cannot be saved and sold in the next selling season. As mentioned above, a restriction on the carbon emissions is influenced by the production quantity through the International Emissions Trading mechanism if it is over the carbon cap. That is, each company's carbon emissions are restricted by a pre-assigned allowance of carbon emissions, and any company that exceeds its own allowances can buy emission credit from other companies with surplus emission credit.

As mentioned above, our model considers uncertain demand managed by the company through a modified newsboy model, as well as carbon emissions through the cap-and-trade system and the policymaker's carbon price regulations. Moreover, as reviewed in the following literature review section, our model is the first to consider the issues of uncertain demand, carbon trade credit, carbon emissions, and the company's operational decisions (pricing and production quantity) with the quick response strategy.

The rest of this paper is organized as follows. Section 2 provides a literature review. Section 3 describes the model for the policymaker's carbon pricing and the company's pricing and production decisions with a quick response strategy. Section 4 establishes the model optimization and some results from our model. Section 5 provides a numerical example. Section 6 concludes this paper.

2. Literature Review

Many works on the carbon emission issue have dealt with macro issues of carbon emission permits and trading, such as environmental policy and the international trade of emission permits. However, although little attention is given to micro-aspects of emission trading, the operational management for carbon emission mechanism is also believed to be significant. Hence, most of the studies which are reviewed here are related to the operational management for carbon emission.

First, there are some works which provide a general review and summary regarding the environmentally sustainable operation management. Kleindorfer et al. [1] review sustainability in the fields of production and operations management, and provide some thoughts on future research challenges in sustainable operations management integrating environmental, health, and safety concerns with the closed-loop supply chains for green product design and lean operations. Linton et al. [8] review the background to understand current trends in the operations management and the future research opportunities and challenges. Corbett and Klassen [9] argue that the environmentally sustainable operational system extends the horizons of analysis, which can be applied to both the theory and practice of operations management.

Second, we will go over the studies which provide the firm's operational model considering the carbon emission and summarize the differences with respect to our model. Many papers on inventory or production management decisions with respect to carbon emissions study the classic or modified economic order quantity (EOQ) model. Du et al. [10] address the impact of the emission cap-and-trade mechanism in a situation where, if the cap for the carbon emission is not sufficient for the emission-dependent firm's production objective, extra emission permits could be purchased via emission trading from the emission permit supplier. For this analysis, Du et al. [10] use a simple newsboy model for the emission-dependent firm's operational decision where the price is given exogenously, the salvage cost is disregarded, and the firm produces the product before the selling season but does not have opportunity to procure it in the spot market, and assumes that the emission-dependent firm can only buy the carbon permit but can not sell it. An and Lee [11] address how to allocate the carbon emission efficiently using a cap-and-trade mechanism in a situation where, given each firm's carbon allowances, a policymaker accumulates all remaining and exceeding carbon emission allowances in the industry, and address the firm's operational management using a classic newsboy model which simulates the firm's production decision at the exogenous price before the selling season without an opportunity to procure extra needs in the spot market. Hua et al. [12] investigate how firms manage carbon footprints in inventory control under the cap-and-trade system using the Economic Ordering Quantity (EOQ) model for their operational decisions on is the production quantity with an exogenous product price and exogenous carbon credit price. Chen et al. [13] use the EOQ model for the firm's operational decisions, which are based on the production quantity with an exogenous product price and exogenous carbon credit price to provide a condition under which it is possible to reduce emissions by modifying ordering quantities, and also provide conditions under which the relative reduction in carbon emissions is larger than the relative increase in cost. Hovelaque and Bironneau [14] propose an EOQ model that considers the link between inventory management, total carbon emissions through carbon tax and product price, and environment-dependent demands. The modified EOQ model used in Hovelaque and Bironneau [14] is used as a firm's operational management tool optimizing its profit through EOQ only and through both EOQ and pricing decisions. Chaabane et al. [15] introduce a mixed-integer linear optimization tool for sustainable supply chain design considering life cycle assessment principles in addition to the traditional material balance constraints at each node in the supply chain. By applying it to the aluminum industry, they conclude that the present emission trading scheme must be strengthened. Letmathe and Balakrishnan [16] present both linear and mixed-integer linear models that can be used by firm to determine its optimal product mix and production quantities subject to several environmental constraints, in addition to typical production constraints. They also introduce a linear and a mixed-integer program for firms to determine the optimal product mix and production quantities under environmental constraints in addition to the production constraints. Cachon [17] developed a model in which a retailer chooses the size, location, and number of stores to serve a region of customers which integrates an emissions cost (due to the consumption of fuel) in its total cost objective function. They show that improving consumer fuel efficiency is more effective in reducing environmental externalities than imposing a carbon tax. Caro et al. [18] introduce a model where a product's carbon emissions result from a supply chain's joint effort—i.e., the emissions from at least one process are differentiated by each combination of firms. They find that, in such settings, emissions must be over-allocated to achieve welfare maximizing abatement efforts. Benjaafar et al. [19] present simple models to show how carbon emission concerns could be integrated into operational decisions such as procurement, production, and inventory control decisions under strict carbon emission restrictions. Cramton and Kerr [20] recommend an auction model which is preferable to giving companies permits based on historical output or emissions (which is called as grandfathering), because it provides more flexibility in distribution of costs, provides greater incentives for innovation, allows reduced tax distortions, and reduces the need for politically contentious arguments over the allocation of rents. Böhringer and Lange [21] use a simple multi-period partial equilibrium model to derive optimal schemes for the free allocation of emission allowances in a dynamic context considering emissions-allocation rule which allows for updating of the basis of allocation over time. Hong et al. [22] develop a predictive regression model of carbon pricing movements with past returns of various commodities and financial products. Additionally, Kim et al. [23] investigate a dynamic programming model to make joint pricing and inventory replenishment decisions in orer to optimize the firm's profit assuming that customers are loss averse and the firm is risk averse. Regarding the use of energy management techniques, Fera et al. [24] explain the effect of the electricity technology for renewable energy and the quality of the environment and in Fera et al. [25] the sustainability with new production technologies such as additive manufacturing is mentioned. Zhou and Wang [26] provide a review of carbon dioxide emission allocation, emphasizing the evolution of allocation methods, and then classify the existing allocation methods into four groups which are the indicator, optimization, game theoretic and hybrid approaches. Chen et al. [27] provide a review on the histories of China, USA, and India in terms of their respective carbon dioxide emissions, reflect on the motivations and mechanisms behind these changes, and predict whether these three major countries emitting carbon dioxide can control their coal consumption and reduced the global carbon dioxide emissions.

Table 1. Comparison of our research with other studies.

	[10,14]	[11]	[12–15,19,21]	**Our Research**
Production Quantity Decision	✓	✓	✓	✓
Endogenously Pricing Decision		✓		✓
Quick Response Strategy				✓
Carbon Credit Pricing	✓			✓
Carbon Emission Cap	✓	✓	✓	✓

The above literature review clearly shows that a systematic operational management planning considering carbon emission is important, and that several authors have provided mathematical models to address specific issues in this regard. However, as reviewed above and summarized in Table 1, to the best of our knowledge, there are no comprehensive models that simultaneously address multiple issues in production, especially regarding pricing, quick response, and carbon pricing decisions. Hence, to the best of our knowledge, there is no research for a model which considers the issues of uncertain demand, carbon trade credit, carbon emissions, and the company's operational decisions (pricing and production quantity), even with the widely used quick response strategy. Hence, our model is new and will bridge the research gap in the operational decision model under the carbon trading system.

3. Model

We consider n companies regulated with respect to carbon emissions by the policymaker, whose objective is to minimize the total quantity of carbon emissions. In the first stage, a policymaker makes pricing decisions on carbon per unit in a trading mechanism. Then, in the second stage, each company makes optimal pricing and production decisions given the carbon price. We model this non-cooperative game between the policymaker and companies as a Stackelberg game in which the policymaker is the leader and the companies are the followers. Hence, we can solve this Stackerberg game as follows:

1. In the second stage, each company makes its own operational decisions with the carbon price regulated by the policymaker in the first stage.
2. In the first stage, the policymaker makes a carbon pricing decision to minimize the total carbon emissions by considering companies' operational decisions.

More details on the policymaker and companies will be provided in the following subsections.

3.1. Model for Company i's Operational Decision Given a Carbon Cap and Carbon Price

In the second stage, given the carbon price regulated by the policymaker in the first stage, each company makes simultaneous pricing and production decisions. We assume that each company uses a quick response strategy. Quick response is nowadays a widely used strategy in which the company will procure the product in the spot market if the demand is larger than the quantity it produced before the selling season. However, the procuring cost during the selling season is generally higher than the production cost. Before the selling season, Q_i units need to be produced at a production cost of c_i per unit and an additional quantity of units demanded during the selling season uis procured at a procuring cost of $c_i' > c_i$ per unit if the demand is larger than what the company i expected (Q_i).

Company i faces a random price-dependent demand function. Specifically, demand is defined as $D_i(p_i, \epsilon_i) = y_i(p_i) + \epsilon_i$. $y_i(p_i) = a_i - b_i p_i$, where $a_i > 0$, $b_i > 0$, and ϵ_i is a random variable defined on $[A, B]$ for company i, which will be defined below. For a positive demand, A is a value such that $a_i - b_i p_i + A \geq 0$ for all i. Let F_i and f_i be the cumulative distribution function (CDF) and the probability density function (PDF) of ϵ_i, respectively. $F_i(\epsilon_i) = 0$ for all $\epsilon_i \leq A$; $F_i(\epsilon_i) = 1$ for all $\epsilon_i \geq B$; and F_i^{-1} is the inverse cumulative distribution function of F_i. Let μ_i and σ_i be the mean $E[\epsilon_i]$ and standard deviation $Var[\epsilon_i]$, respectively.

Thus, company i's profit for either $D_i(p_i, \epsilon_i) \leq Q_i$ or $D_i(p_i, \epsilon_i) > Q_i$ is as follows:

$$\Pi_i(Q, p) = \begin{cases} p_i D_i(p_i, \epsilon_i) - c_i Q_i + s_i[Q_i - D_i(p_i, \epsilon_i)] + c_e x_i & \text{if } D_i(p_i, \epsilon_i) \leq Q_i, \\ p_i D_i(p_i, \epsilon_i) - c_i Q_i - c_i'[D_i(p_i, \epsilon_i] - Q_i] + c_e x_i & \text{if } D_i(p_i, \epsilon_i) > Q_i, \end{cases} \quad (1)$$

where x_i refers to the carbon emissions of company i to be traded in the carbon market. The quantity of traded carbon emissions can be either positive or negative. A negative amount implies that the company i's carbon emissions are greater than its carbon allowance and the company i can buy that amount of carbon permitted on the carbon market at the price of c_e. A positive amount of traded carbon emissions implies that the company i's carbon emissions are lower than its carbon allowance and can be sold on the carbon market at the price of c_e. Hence, the amount of traded carbon emissions x_i should be constrained to be equal to $w_i - e_i Q_i$, in which w_i is the carbon allowance for company i and e_i is the carbon emission per unit production by company i. However, by substituting $D_i(p_i, \epsilon_i) = y_i(p_i) + \epsilon_i$ and defining $z_i = Q_i - y_i(p_i)$, we can find the company i's profit for either $D_i(p_i, \epsilon_i) \leq Q_i$ or $D_i(p_i, \epsilon_i) > Q_i$

$$\Pi_i(z_i, p_i) = \begin{cases} p_i[y_i(p_i) + \epsilon_i] - c_i[y_i(p_i) + z] + s_i[z - \epsilon_i] + c_e x_i & \text{if } \epsilon_i \leq z_i, \\ p_i[y_i(p_i) + \epsilon_i] - c_i[y_i(p_i) + z] - c_i'[\epsilon_i - z_i] + c_e x_i & \text{if } \epsilon_i > z_i, \end{cases} \quad (2)$$

The constraint for the amount of the company i's traded carbon emission in the carbon market is as follows:

$$e_i(y_i(p_i) + z_i) + x_i = w_i$$

Now, using the probability density function f_i of ϵ_i, company i's problem of expected profit and constraint is as follows:

$$\begin{aligned}
\max \quad & \int_A^{z_i} \left(p_i[y_i(p_i) + \epsilon_i] + s_i[z_i - \epsilon_i]\right) f_i(\epsilon_i) d\epsilon_i + \int_{z_i}^{B} \left(p_i[y_i(p_i) + z_i] - c_i'[\epsilon_i - z_i]\right) f_i(\epsilon_i) d\epsilon_i \\
& \quad - c_i[y_i(p_i) + z_i] + c_e x_i \\
s.t \quad & e_i(y_i(p_i) + z_i) + x_i = w_i \\
& Q_i \geq 0, \; p_i \geq 0
\end{aligned} \tag{3}$$

By the following Lemma, we can transform the company i's problem to a mathematically more manageable form.

Lemma 1. *Company i's problem in Equation (3) is equivalent to*

$$\begin{aligned}
\max \quad & (p_i - c_i - c_e e_i)[y_i(p_i) + \mu_i] - (c_i + c_e e_i - s_i) \int_A^{z_i} F_i(x) dx \\
& \qquad - (c_i' - c_i - c_e e_i) \int_{z_i}^{B} (1 - F_i(x)) dx + c_e w_i \\
s.t. \quad & z_i \geq 0, \; p_i \geq 0
\end{aligned} \tag{4}$$

Proof. The objective function in Equation (3) can be rearranged as follows:

$$\begin{aligned}
& \int_A^{z_i} \left(p_i[y(p_i) + \epsilon_i] + s_i[z_i - \epsilon_i]\right) f_i(\epsilon_i) d\epsilon_i + \int_{z_i}^{B} \left(p_i[y(p_i) + \epsilon_i] - c_i'[\epsilon_i - z_i]\right) f_i(\epsilon_i) d\epsilon_i - c_i[y(p_i) + z_i] + c_e x_i \\
= \quad & p_i[y(p_i) + \mu_i] - c_i[y(p_i) + \mu_i - \mu_i + z_i] + \int_A^{z_i} s_i[z_i - \epsilon_i] f_i(\epsilon_i) d\epsilon_i + \int_{z_i}^{B} -c_i'[\epsilon_i - z_i] f_i(\epsilon_i) d\epsilon_i + c_e x_i \\
= \quad & (p_i - c_i)[y(p_i) + \mu_i] - c_i[z_i - \mu_i] + \int_A^{z_i} s_i[z_i - \epsilon_i] f_i(\epsilon_i) d\epsilon_i + \int_{z_i}^{B} -c_i'[\epsilon_i - z_i] f_i(\epsilon_i) d\epsilon_i + c_e x_i \\
= \quad & (p_i - c_i)[y(p_i) + \mu_i] + \int_A^{z_i} \left(-c_i[z_i - \epsilon_i] + s_i[z_i - \epsilon_i]\right) f_i(\epsilon_i) d\epsilon_i + \int_{z_i}^{B} \left(-c_i[z_i - \epsilon_i] - c_i'[\epsilon_i - z_i]\right) f_i(\epsilon_i) d\epsilon_i + c_e x_i \\
= \quad & (p_i - c_i)[y(p_i) + \mu_i] - (c_i - s_i) \int_A^{z_i} [z_i - \epsilon_i] f_i(\epsilon_i) d\epsilon_i + (c' - c_i) \int_{z_i}^{B} [\epsilon_i - z_i] f_i(\epsilon_i) d\epsilon_i + c_e x_i
\end{aligned}$$

Then, by substituting the constraint $x_i = w_i - e_i(y_i(p_i) + z_i)$ into the objective function in Equation (3), we have

$$\begin{aligned}
\max_{z_i, p_i} \quad & (p_i - c_i)[y(p_i) + \mu_i] - (c_i - s_i) \int_A^{z_i} [z_i - \epsilon_i] f_i(\epsilon_i) d\epsilon_i + (c' - c_i) \int_{z_i}^{B} [\epsilon_i - z_i] f_i(\epsilon_i) d\epsilon_i \\
& + c_e \left(w_i - e_i(y_i(p_i) + z_i)\right)
\end{aligned}$$

By interchanging the order of integrations, the integrations for the second and third terms can rewritten as follows:

$$\int_A^{z_i} [z_i - \epsilon_i] f_i(\epsilon_i) d\epsilon_i = \int_A^{z_i} \int_{\epsilon_i}^{z_i} dx f_i(\epsilon_i) d\epsilon_i = \int_A^{z_i} \int_A^{x} f_i(\epsilon_i) d\epsilon dx = \int_A^{z_i} F_i(x) dx$$

and also

$$\int_{z_i}^{B} [\epsilon_i - z_i] f_i(\epsilon_i) d\epsilon_i = \int_{z_i}^{B} \int_{z_i}^{\epsilon_i} dx f(\epsilon_i) d\epsilon_i = \int_{z_i}^{B} \int_{x}^{B} f_i(\epsilon_i) d\epsilon_i dx = \int_A^{z_i} (1 - F_i(x)) dx$$

Then, we have

$$\max_{z_i,p_i} \quad (p_i - c_i)[y(p_i) + \mu_i] - (c_i - s_i)\int_A^{z_i} F_i(x)dx + (c' - c_i)\int_A^{z_i}(1 - F_i(x))dx + c_e\left(w_i - e_i(y_i(p_i) + z_i)\right)$$

By rearranging the objective function, the result holds as follows:

$$\max_{z_i,p_i} \quad (p_i - c_i - c_e e_i)[y_i(p_i) + \mu_i] - (c_i + c_e e_i - s_i)\int_A^{z_i} F_i(x)dx - (c_i' - c_i - c_e e_i)\int_{z_i}^{B}(1 - F_i(x))dx + c_e w_i$$

□

3.2. Model for Policy Maker's Carbon Pricing Decision

Considering the company i's decision on the production quantities Q_i and selling price p_i for its product for all $i \in \{1, ..., n\}$ in the second stage, the policymaker's objective in the first stage is to minimize the total carbon emissions by providing a proper carbon price per unit to the carbon market. Here, for all $i \in \{1, 2, ..., n\}$, each company's carbon emissions depends on each company's pricing decision and is given by

$$Q_i = y_i(p_i) + z_i$$

where z_i and p_i can be obtained using the result from Theorem 1, and $y_i(p_i) = a_i - b_i p_i$. Hence, the policymaker has the following problem to solve

$$\begin{aligned} \min \quad & \sum_{i=1}^{n} e_i Q_i \\ s.t. \quad & Q_i = y_i(p_i) + z_i \;\; \forall i \in \{1, 2, ..., n\} \\ & c_e \geq 0 \end{aligned}$$

Equivalently, this problem can be rewritten as follows:

$$\begin{aligned} \min \quad & \sum_{i=1}^{n} e_i\left(a_i - b_i p_i + z_i\right) \\ s.t. \quad & c_e \geq 0 \end{aligned} \tag{5}$$

4. Model Optimization and Results

First we solve for company i's problem in Equation (4) with the quick response strategy. Then, the company i's operational decision will be as in Theorem 1.

Theorem 1. *Suppose that the company i can procure the product at cost c_i' in the spot market during the selling season (which is the quick response strategy) and $c_i' > c_i$. Then, z^* for company i's optimal production decision is some value satisfying the following equation:*

$$F_i(z_i^*) = \frac{c_i' - c_i - c_e e_i}{c_i' - s_i}$$

The optimal pricing decision p^* for the company i should be

$$p_i^* = \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2b_i}$$

Proof. Using the result of Lemma 1, let the objective function in Equation (4) be $\Pi_i(z, p)$. Then, by taking the first and second partial derivative of $\Pi_i(z_i, p_i)$ with respect to z_i,

$$\begin{aligned} \frac{\partial \Pi_i(z_i, p_i)}{\partial z_i} &= -(c_i + c_e e_i - s_i)F_i(z_i) + (c_i' - c_i - c_e e_i)[1 - F_i(z_i)] \\ \frac{\partial^2 \Pi_i(z_i, p_i)}{\partial z_i^2} &= -(c_i' - s_i)f_i(z_i) \end{aligned}$$

where $\Pi_i(z_i, p_i)$ is concave in z_i since $c_i' \geq c_i \geq s_i$. Therefore, by the first order optimality condition of the objective function with respect to z_i, we have:

$$1 - F_i(z_i^*) = \frac{c_i + c_e e_i - s_i}{c_i' - s_i}$$

Now, for some $z_i \geq 0$, the first derivative of $\Pi_i(z_i, p_i)$ with respect to p_i is as follows:

$$\begin{aligned} &\frac{\partial \Pi_i(z_i, p_i)}{\partial p_i} \\ = \;& a_i - b_i p_i + \mu_i + (p_i - c_i - c_e e_i)(-b_i) - (c_i + c_e e_i - s_i)\frac{\partial z_i}{\partial p_i}F_i(z_i) + (c_i' - c_i - c_e e_i)\frac{\partial z_i}{\partial p_i}(1 - F_i(z_i)) \\ = \;& a_i + b_i(c_i + c_e e_i) + \mu_i - 2b_i p_i \end{aligned}$$

where the first and second terms should be zero since z_i^* does not depend on p_i. Since

$$\frac{\partial^2 \Pi_i(z_i, p_i)}{\partial p_i^2} = -2b_i \leq 0,$$

$\Pi_i(z_i, p_i)$ is concave in p_i and the optimal price p_i^* is given by

$$p_i^* = \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2b_i}$$

□

Theorem 1 implies that the company i's operational decision is influenced by both carbon price c_e and carbon emission rate e_i. That is, company i's producing and pricing decision are a function of both carbon price c_e and carbon emission rate e_i. Moreover, while company i's production decision value is decreasing in the carbon price c_e and carbon emission rate e_i, company i's pricing decision is increasing in the carbon price c_e and carbon emission rate e_i. Theorem 1 shows that as the company i produces an environmentally friendly product by reducing the carbon emission through the production cut, the price for that product tends to increase.

Now, we need to solve the policymaker's problem (Equation (5)). Using

$$z_i = F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)$$

and

$$p_i = \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2b_i}$$

from Theorem 1, the policymaker's problem (Equation (5)) can be rewritten as follows:

$$\begin{aligned} \min \quad & \sum_{i=1}^{n} e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right) \\ s.t. \quad & c_e \geq 0 \end{aligned} \tag{6}$$

In Lemma 2, we find some property of the policymaker's objective function.

Lemma 2. *1.*

$$\sum_{i=1}^{n} e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right)$$

is decreasing in $c_e \in (0, \infty)$.

2. *Suppose that* $f(\epsilon)$ *is a decreasing function in* ϵ. *Then,*

$$\sum_{i=1}^{n} e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right)$$

is decreasing and convex in $c_e \in (0, \infty)$.

Proof. For all $i \in \{1, ..., n\}$, let's take the first derivative with respect to c_e and we have

$$\begin{aligned} & \frac{\partial}{\partial c_e} \left[e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right) \right] \\ = \quad & e_i \left(-\frac{b_i e_i}{2} + \frac{1}{f_i\left(F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)\right)} \left(\frac{-e_i}{c_i' - s_i} \right) \right) \\ = \quad & -e_i^2 \left(\frac{b_i}{2} + \frac{1}{f_i\left(F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)\right)} \left(\frac{1}{c_i' - s_i} \right) \right) < 0 \end{aligned}$$

Also, we know that $\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}$ is decreasing in c_e and thus $F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)$ is decreasing in c_e. Now, suppose that f is decreasing function. Let us take the second derivative with respect to c_e, and we have

$$\begin{aligned} & \frac{\partial}{\partial c_e} \left[e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right) \right] \\ = \quad & -e_i^2 \left(\frac{-f_i'(y)}{f_i^3\left(F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)\right)} \left(\frac{-e_i}{c_i' - s_i} \right) \left(\frac{1}{c_i' - s_i} \right) \right) \\ = \quad & -e_i^3 \left(\frac{f_i'(y)}{f_i^3\left(F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)\right)} \left(\frac{-e_i}{(c_i' - s_i)^2} \right) \right) \end{aligned}$$

where $y = F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i}\right)$. Since f is a decreasing function,

$$\frac{\partial}{\partial c_e} \left[e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right) \right] \geq 0$$

and

$$\sum_{i=1}^{n} e_i \left(a_i - \frac{a_i + b_i(c_i + c_e e_i) + \mu_i}{2} + F_i^{-1}\left(\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \right) \right)$$

is convex in c_e. The result holds. □

Lemma 2 shows that total carbon emissions are decreasing in the carbon price c_e. Moreover, the marginal effect of carbon price c_e tends to decrease if the probability density function $f(\epsilon)$ for the demand is a decreasing function in ϵ. Hence, for any probability density function $f(\epsilon)$, the optimal carbon price should be the largest possible value which the carbon price c_e can take. First, a policymaker provides a carbon price c_e and then companies will make their own operational decisions in the non-cooperative Stackelberg game between the policymaker and companies. The policymaker's decision should be optimized considering each company's operational decision and each company will make its own operational decision considering the policymaker's decision as in Theorem 2.

Theorem 2. *In the equilibrium, the optimal carbon price per unit is as follows:*

$$c_e^* = \min_{i \in \{1,...,n\}} \frac{c_i' - c_i}{e_i}$$

Moreover, the optimal production decision z_i^* for $i \in \{1, ..., n\}$ is given by

$$z_i^* = F_i^{-1}\left(\frac{c_i' - c_i - c_e^* e_i}{c_i' - s_i} \right)$$

and the optimal price of product p_i^* for $i \in \{1, ..., n\}$ is given by

$$p_i^* = \frac{a_i + b_i(c_i + c_e^* e_i) + \mu}{2b_i}$$

Proof. By the first result of Lemma 2, the optimal carbon credit price should be the largest possible value in its possible range. However, since for all $i \in \{1, ..., n\}$

$$\frac{c_i' - c_i - c_e e_i}{c_i' - s_i} \in (0, 1)$$

we have

$$c_e \in \left(-\frac{c_i - s_i}{e_i}, \frac{c_i' - c_i}{e_i} \right)$$

for all $i \in \{1, ..., n\}$. Therefore,

$$c_e \in \bigcap_{i \in \{1,...,n\}} \left(-\frac{c_i - s_i}{e_i}, \frac{c_i' - c_i}{e_i} \right)$$

and the optimal carbon credit price c_e^* should be

$$c_e^* = \min_{i \in \{1,...,n\}} \frac{c_i' - c_i}{e_i}$$

Now, using the result of Theorem 1, the optimal ordering decision z_i^* for $i \in \{1, ..., n\}$ is given by

$$z_i^* = F_i^{-1}\left(\frac{c_i' - c_i - c_e^* e_i}{c_i' - s_i}\right)$$

and the optimal price of product p_i^* for $i \in \{1, ..., n\}$ is given by

$$p_i^* = \frac{a_i + b_i(c_i + c_e^* e_i) + \mu}{2b_i}$$

Then, the result holds. □

Theorem 2 shows that there exists an equilibrium for the policymaker's carbon pricing decision and each company's production and pricing decisions. From this result, we can see that the company's production quantity decreases and the product selling price increases as the carbon price increases.

Theorem 3. *There exists a cap allowance w_i^* for a company i at which the amount of traded carbon emissions will be zero and w_i^* is given by*

$$e_i\left[a_i - b_i\frac{a_i + b_i(c_i + c_e^* e_i) + \mu}{2b_i} + F_i^{-1}\left(\frac{c_i' - c_i - c_e^* e_i}{c_i' - s_i}\right)\right]$$

Proof. By putting $p_i^* = \frac{a_i+b_i(c_i+c_e^*e_i)+\mu}{2b_i}$ and $z_i^* = F_i^{-1}\left(\frac{c_i'-c_i-c_e^*e_i}{c_i'-s_i}\right)$ into

$$w_i = e_i(y_i(p_i^*) + z_i^*)$$

the amount of carbon emission traded (x_i) in the carbon market becomes zero since x_i is given by

$$x_i = w_i - e_i(y_i(p_i^*) + z_i^*)$$

in company i's problem in Equation (3). □

Theorem 3 shows that there exists a carbon allowance for each company at which the quantity of carbon emissions traded in the carbon market becomes zero. This implies that at this carbon allowance the company's production and pricing decisions will be equal to those without the carbon cap-and-trade system, and thus its profit is culminated.

Theorem 4. *Suppose that z_i^N and p_i^N are the company i's production and pricing decisions without the restriction on carbon emissions. Then,*

1. *z_i^N is larger than the production decision with the restriction on the carbon emissions.*
2. *p_i^N is less than the pricing decision with the restriction on the carbon emissions.*

Proof. No restriction on the carbon emission implies that carbon credit on the carbon trading market is free. That is, c_e is thought as zero value. Then, the production decision z_i^N and pricing decision are given by

$$z_i^N = F_i^{-1}\left(\frac{c_i' - c_i}{c_i' - s_i}\right) \text{ and } p_i^N = \frac{a_i + b_i c_i + \mu}{2b_i}$$

From Theorem 2, we have

$$z_i^N = F_i^{-1}\left(\frac{c_i' - c_i}{c_i' - s_i}\right) \geq F_i^{-1}\left(\frac{c_i' - c_i - c_e^* e_i}{c_i' - s_i}\right) = z_i^*$$

and

$$p_i^N = \frac{a_i + b_i c_i + \mu}{2b_i} \leq \frac{a_i + b_i(c_i + c_e^* e_i) + \mu}{2b_i} = p_i^*$$

where $c_e^* \geq 0$. Hence, the result holds. □

Theorem 4 implies that, when each company participates in the carbon cap-and-trade system, each company tries to reduce carbon emissions by reducing the amount of production, but can squeeze in some profit through increasing the product's selling price. This is a widely-accepted strategy in the eco-friendly product market. This strategy considers the consumer's degree of interest in the product through the company's operational decision, which consists of its pricing decision and the carbon emissions to produce it. The latter is usually highlighted with eco-labeling on the product, e.g., carbon labeling on the product (showing the reduced carbon emissions to produce that product) by some countries in the EU as a sustainable marketing strategy (see [28–32]). Also, the eco-labeled products are usually sold in the market at a higher price. This mechanism might be explained by the result of Theorem 4.

Theorem 5. 1. *Suppose that company i^* is one such that*

$$i^* = \arg\min \left\{ i \in \{1, 2, ..., n\} : \frac{c_i' - c_i}{e_i} \right\}$$

Then, the company i^* would not produce any product.

2. *Suppose that $a_i = a, b_i = b, c_i = c, s_i = s, c_i' = c'$, and $F_i = F$ for all $i \in \{1, 2, ..., n\}$. Then, the only company which would not produce any product is the one with highest emissions for production.*

Proof. By the result of Theorem 2, we have

$$c_e = \frac{c_{i^*}' - c_{i^*}}{e_{i^*}}$$

and

$$z_{i^*} = F_i^{*-1}\left(\frac{c_{i^*}' - c_{i^*} - c_e^* e_{i^*}}{c_{i^*}' - s_{i^*}}\right) = F_i^{*-1}\left(\frac{c_{i^*}' - c_{i^*} - \frac{c_{i^*}' - c_{i^*}}{e_{i^*}} e_{i^*}}{c_{i^*}' - s_{i^*}}\right) = F_i^{*-1}(0) = 0$$

The first result holds. The second result holds directly from the first result by setting $a_i = a, b_i = b, c_i = c, s_i = s, c_i' = c'$, and $F_i = F$ for all $i \in \{1, 2, ..., n\}$. □

In Theorem 5, if company i's cost structure provides the smallest

$$\frac{c_i' - c_i}{e_i},$$

it will not survive in the market. That is, the company i could not produce any product and thus should close its business. Thus, to survive in the market, the company should decrease either the production cost c_i or its carbon emission rate e_i. This can be obtained through productivity improvement and energy-efficient production facilities.

5. Numerical Example

In this section, we provide a simple numerical example with three companies to show how our model actually works and how the company's expected profit changes over the various operational strategies. The parameters for each company that we consider as an example are shown in Table 2 and company i's probability for demand is as follows:

$$a_i - b_i p_i + \epsilon_i$$

where ϵ_i a truncated normal random variable with mean μ_i and standard deviation σ_i which makes $a_i - b_i p_i + \epsilon_i$ non-negative. For more detail regarding ϵ_i, its CDF at $\epsilon_i = x$ is given by $\frac{\Phi_i(x) - \Phi_i(\epsilon_{p_i})}{\Phi_i(\epsilon_i^U) - \Phi_i(\epsilon_{p_i})}$ where $\epsilon_{p_i} = -a_i + b_i p_i$, $\epsilon_i^U = a_i$ and $\Phi_i(\cdot)$ is the cumulative normal distribution function for each company. All companies can take one of the following strategies: (1) Dynamic pricing and quick response; (2) No dynamic pricing but quick response; and (3) No dynamic pricing and no quick response.

Table 2. Parameters for each company.

Company	c_i'	c_i	s_i	e_i	a_i	b_i	μ_i	σ_i	w_i
1	\$80	\$50	\$25	20	1,900	10	50	50	20,000
2	\$90	\$60	\$30	22	2,000	10	60	60	20,000
3	\$100	\$70	\$35	21	2,500	10	40	40	20,000

From Figure 1, we can see that the company's profit is culminated when it makes simultaneous pricing and production decisions with the quick response strategy. Also, we can see that its profit is the lowest when it makes only production decisions without the pricing decisions and quick response strategy. The expected profit from the simultaneous pricing and production decisions with the quick response strategy is about 5% higher that of no dynamic pricing, but quick response and about 16% higher than in no dynamic pricing and no quick response. From this numerical result, we can see that the addition of operational strategies such as quick response and pricing decisions makes the company's profit increase gradually even under the carbon cap restriction.

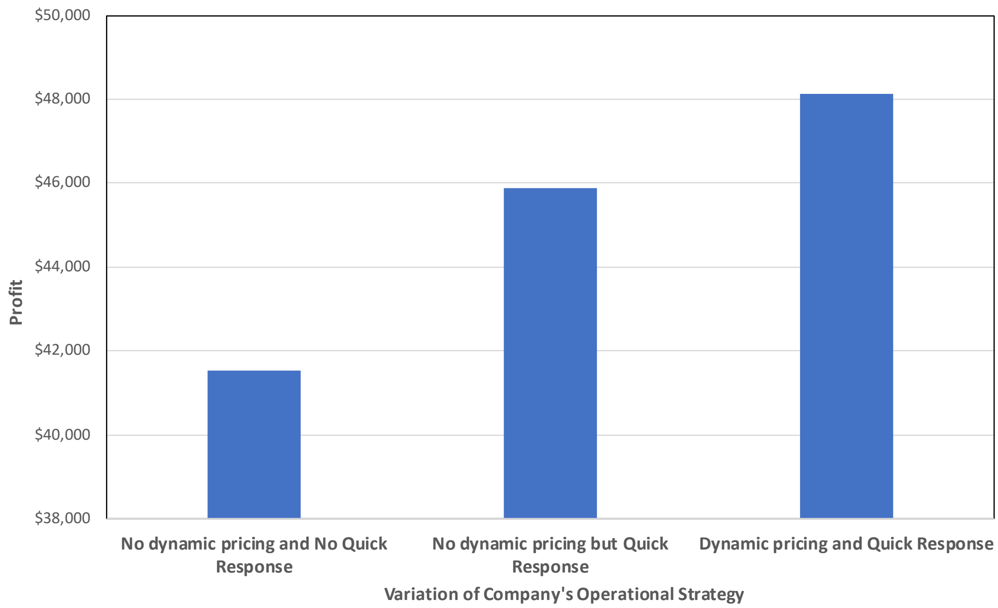

Figure 1. The company's profit for various operational strategies under the carbon cap-and-trade system.

As proven in Lemma 2, we can see the impact of carbon trading price on total carbon emissions in Figure 2 where total carbon emissions, which are the policymaker's objective function, decrease as the carbon price increases.

From Figures 3 and 4, we can see that the product selling price increases as the carbon price per unit increases. The company under the carbon cap-and-trade system tries to reduce the carbon emission by reducing the amount of production. This reduced amount of production might reduce the company's profit without the dynamic pricing operation. However, the company can sustain its profit by increasing the product's selling price through dynamic pricing operation. From this result, why the company's product under the carbon emission restriction increases can be explained. Moreover, we can observe the company's pricing behavior in the eco-friendly product (product manufactured with the consideration of carbon emissions) market in the EU as a sustainable marketing strategy [28,29].

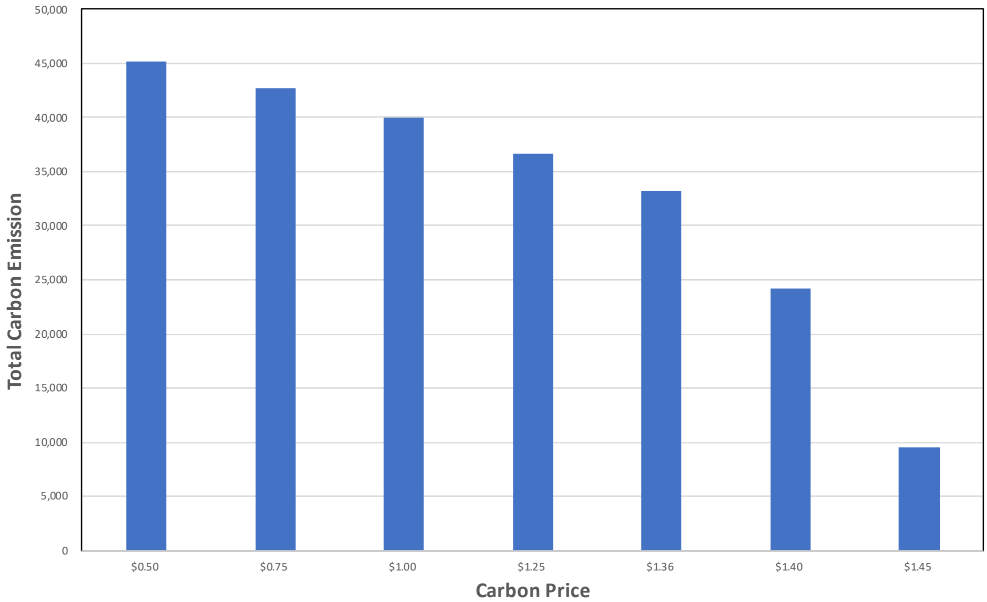

Figure 2. Total carbon emissions vs. carbon price.

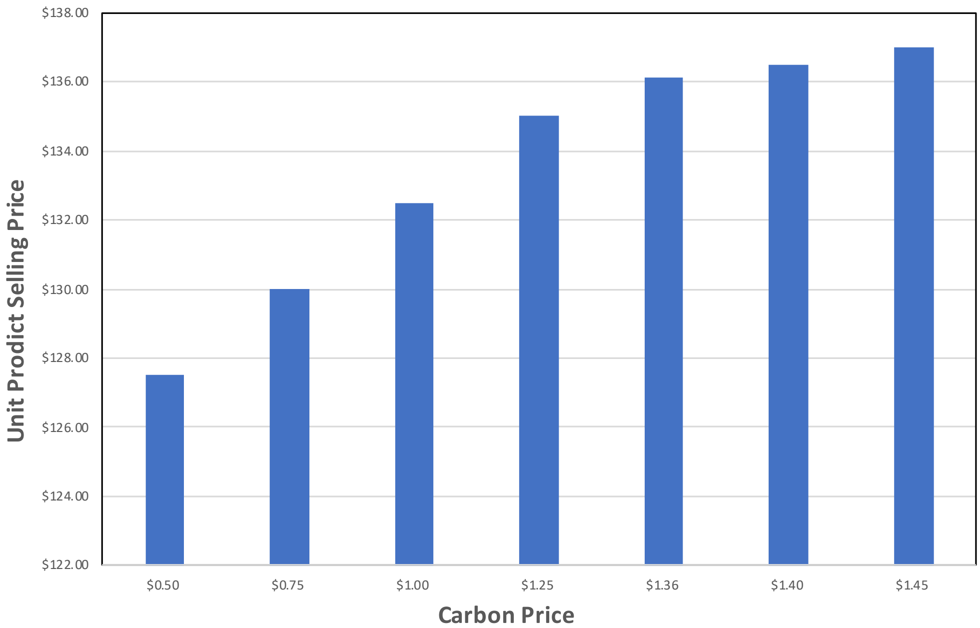

Figure 3. Unit product selling price vs. carbon price.

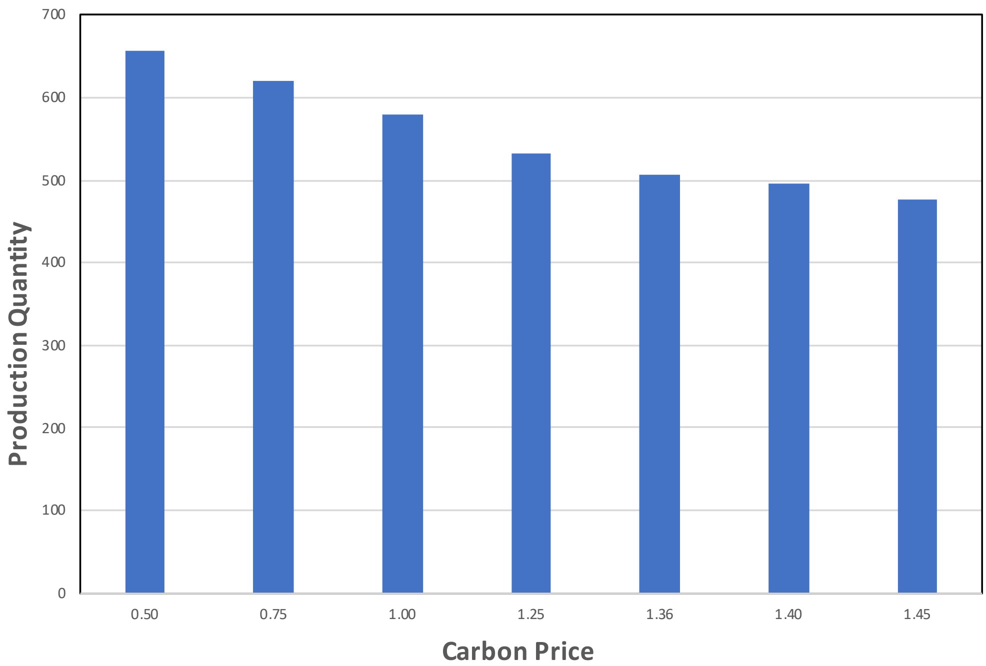

Figure 4. Production quantity vs. carbon price.

6. Conclusions

In this paper, we consider the following situation:

1. There are n companies in the market. Each company produces a product and for each product carbon is emitted into the environment.
2. Each company uses a newsboy model to make the producing and pricing decisions simultaneously with respect to its own product before the selling season.
3. Each company can also procure additional products in the spot market and deliver the procured product directly to the customer during the selling season if the demand is larger than what was produced before the selling season. This strategy is called as a quick response.
4. The policymaker determines a carbon price per unit emission which will be provided to the carbon market for trading carbon.

In the situation above, we find the optimal operational decisions for each company (the producing decision and pricing decision), and the policymaker's decision (the carbon pricing decision) for the cap-and-trade system. Also, we show that there exists an equilibrium for the policymaker's carbon pricing decision and each company's production and pricing decisions. Using the equilibrium for the company's pricing and production decisions and the policymaker's carbon pricing decisions, we find that companies participating in the carbon cap-and-trade system reduce carbon emissions through the reduction of production, but this reduced production abates their profit, so they try to improve their abated profit by increasing the product's selling price. This result is fairly intuitive since, in many markets eco-labeled products are usually sold at a higher price.

We show that the policymaker's objective decreases as the carbon prices increases. Since the policymaker's objective is focused on the reduction of total carbon emissions, total carbon emissions decrease as the carbon price increases. In addition, we show that, even under the carbon cap-and-trade system, there exists a carbon allowance for a company at which the amount of traded carbon emissions is zero. With this carbon allowance, this company's production and pricing decisions would be exactly equal to those without the carbon cap-and-trade system, and thus the company makes operational decisions as if it were not restricted in terms of carbon emissions.

We show that there exists a company which does not produce any products. Moreover, if all companies' production costs, salvage costs, and probability for demand are the same, then the company for which the carbon emission rate is highest would not produce any product. This result implies that if either the company's production efficiency in terms of production cost is very low, or the company does not have an efficient carbon-emission reducing capacity (high carbon emission rate), then it is better not to produce any product.

Given the findings in this paper, we provide a practical decision guideline for both the policymaker and the company under the cap-and-trade market system, and suggest the use of dynamic pricing and the quick response strategy to help the companies improve their profits. Despite our findings and practical implementations, our model in this study has several limitations that could require further investigation. First, it would be interesting to extend the model to incorporate the impact of the company's behavior regarding its carbon allowance.This analysis would enable us to anticipate the the managerial impact when the company is allowed to request its own carbon allowance. Second, the policymaker can be removed in our model. This means that the carbon price can be endogenously decided among the non-cooperative companies. We expect that such further research investigations will be performed in order to address environmental issues of concern globally.

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