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Multi-item production planning with carbon cap and trade mechanism

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ABSTRACT

Carbon emission control becomes a challenge in recent years, and carbon emission trading is an effective way to curb carbon emission. This paper investigates the multi-item production planning problem with carbon cap and trade mechanism, in which a firm uses a common capacity and carbon emission quota to produce multiple products for fulfilling independent stochastic demands, and the firm can buy or sell the right to emit carbon on a trading market of carbon emission. A profit-maximization model is proposed to characterize the optimization problem. The optimal policy of production and carbon trading decisions is analyzed, and an efficient solution method with linear computational complexity is presented for solving the optimal solution. The impacts of carbon price, carbon cap on the shadow price of the common capacity, production decisions, carbon emission and the total profit are investigated. The comparisons of the carbon cap and trade policy and the taxation policy are given to show the effectiveness of the policies. Numerical analyses are presented for illustrating our findings and obtaining some managerial insights and policy implication.

1. Introduction

Research has already shown that global warming has a direct relationship with the emission of carbon and other greenhouse gases. Many countries have attempted to enact legislation or design market-based carbon trading mechanism for controlling carbon emission. In comparison with the command-and-control standards, the carbon cap and trade mechanism is more effective in carbon emission reduction (Stavins, 2008; Hua et al., 2011). In past decades, some carbon emission control mechanisms have been launched, such as Kyoto Protocol in 1997 which aims to establish a carbon cap and trade system on international scale. The European Union Emission Trading System (EU-ETS), which is launched by European Union on January 2005, is a cornerstone of European Union climate policy toward its Kyoto commitment and beyond. The EU-ETS has grown to be the world largest carbon trading market, greatly advancing Chicago Climate Exchange (CCX) and Australia Climate Exchange (ACX), etc. As the World Bank report "State and Trends of the Carbon Market Report 2011" shows, the carbon trading volume of EU-ETS carbon allowances reaches 119.8 billion dollars in 2010 and will continue to increase.

Not only applied in the carbon footprint cutting, the cap and trade mechanism is also used to control the emission of other pollutants, e.g., industrial waste and sewage. The most notable case is the SO_2 trading system under Acid Rain Program which is launched by the U.S. Government to curb the emission of sulfur dioxide. This program covers 263 power stations in America at the first stage and expends to all of which the capacity is larger than 25 MW. According to the report from U.S. Environmental Protection Agency (2007),[1] this program curbs 40% of the sulfur emission from 1990 to 2006 with a 37% increase of total electricity generated.

Apart from the emission policy regulation, the customer awareness about climate change has been another factor to drive firms to be greener. According to a U.S. customer survey (Klassen and McLaughlin, 1996), almost 85.7% of the investigated have strong willingness to pay more for products that are environment friendly; shareholders reflect a similar opinion, recommending that the top priority for corporate expenditures be cleaning up the environment. The enterprises in China are feeling significant pressure to introduce green supply chain principles and practices because they keep encountering green barriers when exporting commodity (Zhu et al., 2005). Zhu et al. (2007) investigated 89 automotive enterprises in China, and they found that these enterprises experienced both government regulatory and market pressure to adopt green supply chain practices.

To respond to government regulatory on carbon emission and environment concerns from customers, many firms have tried to improve their products' design or adopt more energy efficient equipments, facilities and carbon-reducing technologies. As a

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[1] The report: The Experience with Emissions Control Policies in the United States, U.S. Environmental Protection Agency, Office of Atmospheric Programs, 2007, p42. http://www.epa.gov/airmarkets/international/china/JES_USexperience.pdf.

result, green supply chain management, which defined as integrating environment concern into supply chain management, has caught attention in academic area. Many research on green supply chain investigated closed-loop supply chain or sustainable usage of material, such as Srivastava (2007), Chaabane et al. (2012) and Shi et al. (2011). Other works have been done to design efficient reverse logistics networks, e.g., Lieckens and Vandaele (2007) and Lee et al. (2010).

Although these actions are very valuable to curb carbon emission, they often need long lead time and costly investments. In fact, some carbon emission can be reduced by incorporating carbon emission concern into operational decision-making, which requires much less or no implementing cost. Up to now, less work has been done to incorporate carbon emission concerns into supply chain management, both in scientific research and in industry practice. Some works have been done for studying the measurement methods of carbon emission in supply chains, for examples see Cholette and Venkat (2009) and Sundarakani et al. (2010). Some works have attempted to study operations decisions in production planning and transportation management with carbon emission regulations. Penkuhn et al. (1997) incorporated carbon emission taxes into a joint production planning problem. Letmathe and Balakrishnan (2005) studied the product portfolio selection and production problems with deterministic demands in the presence of several different types of environmental constraints and production constraints. Kim et al. (2009) studied a tradeoff between carbon emission and transportation costs via multi-objective optimization. Hoen et al. (2010) investigated the effects of emission cost and emission constraint on the transport mode selection decision. Cachon (2011) studied the impact of carbon emission cost on the design of supply chain.

Recently, several papers incorporated carbon emission concern into some classical production and inventory management models. Benjaafar et al. (2012) illustrated how some different carbon emission concerns could be integrated into operational decision-making in single-firm and multi-firm lot-size problems, and they provided a series of insights to highlight the impact of operational decisions on carbon emissions by analyzing numerical examples. Hua et al. (2011) studied the optimal order quantity under the carbon emission trading mechanism by integrating carbon emission concern into the classical economic order quantity model, and they derived some interesting observations. Li and Gu (2012) added the cost of environmental protection to the well-known Arrow–Karlin dynamic production–inventory model, in which the firm could either sell the emission permits in market or deposit for future use. They compared the optimal production–inventory strategies with and without emission permits, and investigated the effect of tradable emission permits with banking on the production–inventory strategy. Song and Leng (2012) studied the single-period production problem under carbon emission policies and obtained the optimum production quantity.

In practice, firms face the challenge of managing multi-product production system in the presence of carbon emission control. For instance, Walkers, the UK's largest snack foods manufacturer, now works with Carbon Trust, an independent organization aims to reducing carbon footprint in business, to manage the product portfolios and to reduce carbon emission. So does Trinity Mirror, the UK's largest newspaper publisher with some 240 local and regional newspapers and five national newspapers (Carbon Trust, 2006). However, the impact of carbon emission control on multi-item production planning is seldom investigated in literature.

In this paper, we study the multi-item production planning problem with carbon cap and trade mechanism, in which a common capacity and carbon emission quota are shared to produce multiple products for fulfilling independent stochastic demands. A certain amount of carbon emission (carbon cap) is allocated to the firm by an external regulatory body, and the firm can buy or sell carbon credit on a trading market of carbon emission, e.g., European Climate Exchange (ECX) and CCX. The carbon price is set by the trading market, and it is an exogenous variable to decisions made by the firm. The firm has to make the decisions on production quantities and the carbon trading quantity for maximizing the expected profit. We present a profit-maximization model to characterize the firm's decisions in the multi-item production planning problem with carbon cap and trade mechanism. We derive the optimal policy of production and carbon trading decisions, and give an efficient solution method solving the optimal solution to the studied problem. We obtain some managerial insights by theoretically and numerically analyzing the impacts of carbon price, carbon cap on the system performance.

In addition, we compare the impacts of the carbon cap and trade policy and the taxation policy on the carbon emission and profit of the regulated firm. Under the taxation policy, the regulated firm pays a carbon tax based on the amount of carbon footprint emitted. The comparison would provide some instructions to the implementation of carbon emission control policy. Although the discussion throughout this paper focuses on carbon footprint, the result can easily be applied to control emission of other pollutants.

The rest of the paper is organized as follows. Section 2 describes the problem. In Section 3, the optimal policy and a solution method are presented. The impacts of carbon cap and trade mechanism on the system performance are investigated in Section 4. Section 5 compares the two different emission control policies. Section 6 provides numerical examples to illustrate our results. Section 7 concludes the paper with a few future research directions. All proofs are presented in Appendix.

2. The problem

Product portfolio produced by a firm generally shares some common manufacturing process or resource while incur different carbon footprint for different products. For examples, the three products (Crisps, Quavers and Doritos) from Walkers satisfy similar consumer needs yet the manufacturing processes (e.g., frying and baking processes) are different for each of the three, which incur different amount of carbon emission (Carbon Trust, 2006); Trinity Mirror recognizes that a significant portion of the carbon emissions comes from its manufacturing processes. It uses two types of raw materials (50% recovered fiber and 100% recovered fiber) on paper manufacturing, and the energies consumed in manufacturing newspapers with the two kinds of fibers are 0.6 and 0.44 kW h per paper sold, respectively (Carbon Trust, 2006). In these examples, the snack foods from Walkers and newspapers from Trinity Mirror are typical newsvendor-type products.

We consider the multi-item production system that uses a common capacity and carbon emission quota to produce n different newsvendor-type products, and model the problem as an extended multi-item newsvendor problem with carbon emission control. Let $i=1,\dots,n$ be the index for all products. The production cost, selling price, and salvage value for one unit of product i is c_i, p_i and s_i, respectively. To avoid the trivial case, we assume $p_i>c_i>s_i$. Random demand for product i is D_i, and $f_i(x)$, $F_i(x)$ and $F_i^{-1}(x)$ are the probability density (positive) function, cumulative distribution and inverse distribution functions, respectively. It is common to assume that all demands are nonnegative, so we assume that $F_i(x)=0$ for all $x\le 0$, $i=1,\dots,n$. The total common capacity is t, and τ_i unit of common capacity is