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Production decisions in a hybrid manufacturing–remanufacturing system with carbon cap and trade mechanism

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ABSTRACT

We study a monopolist manufacturer who makes new products in the first period and makes new and remanufactured products simultaneously in the second period. The manufacturing and remanufacturing activities in the two-period planning horizon are limited by carbon cap and trade mechanism (CCT-mechanism), and the manufacturer has to determine the optimal production quantities for each period. With the consideration of CCT-mechanism, we propose two profit-maximization models for the independent demand market (ID-market) and the substitutable demand market (SD-market), respectively, and characterize the corresponding optimal production decisions. Based on the theoretical and numerical studies, we analyze the impacts of the CCT-mechanism and carbon related parameters. The results show that the CCT-mechanism has a great influence on firm's production decisions of manufacturing and remanufacturing. In specific, the carbon price is more effective in controlling productions and emissions compared with the carbon cap in both types of market. In the ID-market, the CCT-mechanism cannot induce the firm to choose the low-carbon remanufacturing technology, while in the SD-market, it may induce the firm to choose the low-carbon remanufacturing technology.

1. Introduction

With growing concerns over greenhouse gases (GHGs) and environmental protection in recent years, many countries and districts have enacted a diverse of legislations such as carbon tax, carbon cap and trade, to help quelling the emissions of CO_2 and other GHG. For example, European Union (EU) launched the European Union Emission Trading System (EU-ETS) in 2005, California's cap and trade regulation was adopted in October 2011, and Sweden and Finland started to levy carbon tax in 1991 and 1990, respectively.

Among different regulations of GHG emissions, market-based carbon cap and trade mechanism (CCT-mechanism) for CO_2 is attracting widespread attention. Kyoto Protocol in 1997 aimed to establish a carbon cap and trade system on international scale. EU-ETS has grown to be the world's largest carbon trading market (Zhang and Xu, 2013). Similar famous carbon trading markets are Chicago Climate Exchange (CCX) and Australia Climate Exchange (ACX). In China, the biggest GHG emitters in the world, carbon emission concerns have simulated a number of potential policy responses, including a proposal to cap CO_2 emissions for each province, and seven pilot emission trading markets established in five cities (Beijing, Tianjin, Shanghai, Chongqing and Shenzhen) and two provinces (namely Guangdong and Hubei).

The CCT-mechanism means a quota of carbon emission (carbon cap) is allocated to a 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 and Chicago Climate Exchange (Zhang and Xu, 2013).

Production manufacturing activities produces GHG emissions directly and indirectly by using fuels and consuming resource and energy. It can be predicted that CCT-mechanism of carbon emission constraint will make it costly to emit carbon, which will put pressure on manufacturers and encourage them to incorporate the lower-carbon emission technologies into their production activities significantly.

Remanufacturing, as a specific type of eco-efficiency technology, is the process by which used products are recovered, processed and sold as like-new products in the same or separate markets (Lund and Skeels, 1983; Thierry et al., 1995; Fleischmann et al., 2000). Remanufacturing efficiency could significantly reduce energy consumption and associated GHG emissions due to fewer raw materials and fewer manufacturing procedures (Sutherland et al., 2008). For example, the remanufacturing of photocopiers and diesel engines can obtain eco-efficiency (Kerr and Ryan, 2001; Sutherland et al., 2008).

For manufacturers who engage in both manufacturing and remanufacturing, carbon emission constraint will lead them to make decisions on managing the new and remanufactured products with the consideration of both profit and carbon emission.

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This leads to some interesting research questions: how to make optimal production decisions for manufacturers to maximize the profit under the constraint of carbon emission? How will carbon emission constraint affect production decisions? Can the regulations lead to carbon emission reduction and induce the manufacturer to choose lower-carbon remanufacturing technology?

There is a growing literature on operations and supply chain management considering the constraint of carbon emission or environment protection, such as carbon regulated supply chains (Akker, 2009; Boere, 2010; Shaw et al., 2013), carbon emission regulations on transport activities (Hoen et al., 2011), low carbon network design and location problem (Sadegheih, 2011; Diabat et al., 2013; Elhedhli and Merrick, 2012; Giarola et al., 2012; Chaabane et al., 2012), carbon footprints and inventory management (Hua et al., 2011), and environmental considerations and optimal product mix (Letmathe and Balakrishnan, 2005).

In the research field of production and pricing, Ferrer and Swaminathan (2006) propose two-period and multi-period production planning models in which the remanufactured and the original products are indistinguishable. Later, they extend their model to the situation where the remanufactured and original products are distinguishable in the setting of two-period, multi-period (three, four and five) and infinite planning horizons (Ferrer and Swaminathan, 2010). Debo et al. (2005) discusses the issue of joint pricing and production technology selection for remanufacturable products. Kaya (2010) investigates the optimal value of several incentives and the optimal production quantities of new and remanufactured products in a stochastic demand market. Zanoni et al. (2012) study the multi-product economic lot scheduling problem with manufacturing and remanufacturing. Similarly, the issues of manufacturing–remanufacturing production and pricing decisions are also researched by Akcali and Cetinkaya (2011), Chen and Chang (2013), Karakayali et al. (2007), Kenne et al. (2012), Mahmoudzadeh et al. (2013), Shi et al. (2011) and Xiong et al. (2014). These researches focus on the minimization of costs subject to operational constraints and draw some unique results, but they do not consider carbon emission constraint regulations. The integration of carbon emission constraints into production and pricing issues will lead to new problems and novel optimization models. However, the literature on this topic is rather scarce. Absi et al. (2013) study multi-sourcing lot-sizing problems considering several carbon emission constraint policies rather than CCT-mechanism. Drake (2012) studies the carbon tariffs' effects with production technology choice, but does not consider remanufacturing issues and carbon cap and trade policy. Similarly, Considine and Larson (2012) investigate the issue of electric production technology switching without considering remanufacturing under carbon cap and trade. Zhang and Xu (2013) analyze the optimal policy of multi-item production decisions with CCT-mechanism, assuming the demands of different products are independent.

In this paper, we address the production issues in a hybrid manufacturing–remanufacturing system under the CCT-mechanism. We study a monopolist manufacturer that produces new products using virgin materials in the first period and uses returned/recycled products from market to produce remanufactured products in the second period. The manufacturing and remanufacturing activities in the two-period planning horizon are limited by the CCT-mechanism, and the manufacturer must determine the optimal production quantities and product prices for each period.

As the remanufacturing product and the new product may or may not be homogenous in the real world, we consider two types of markets: independent demand market (ID-market) and substitutable demand market (SD-market), and propose two two-period profit-maximization models for ID-market and SD-market, respectively. We characterize the optimization production problem, and analyze the impacts of CCT-mechanism on production decision-making and reducing carbon emissions. For the former case, the new product and the remanufactured product are sold in the separate markets, and have their own demands respectively. So the product demand of the new product and the remanufactured product are independent. There are many practical examples of independent demand of new products and remanufactured products. As described in the research by Karakayali et al. (2007), in the automotive industry, an original equipment manufacturer (OEM) typically provides service parts for vehicles that are about 7 years old or younger, while the remanufactured parts cannot be used to provide service parts for younger vehicles and typically be used for vehicles that are older than 10 years. Therefore, the OEM's service parts market and the remanufactured service parts market are non-overlapping and independent. For the latter case, the new product and the remanufactured product are sold in the same market. They are competitive and substitutable for each other. So the product demand functions of the new product and the remanufactured product are substitutable. This consideration is valid in a lot of practical situations. For example, Amazon often provides the products of the same brand and model at different quality levels and prices on Amazon's website at www.amazon.com. When a consumer wants to purchase a product like GPS navigator of a certain brand and a certain model, she can locate a new one, a used one and a refurbished/remanufactured one at different prices. In this kind of market, the new product and the remanufactured one, as two competing products, substitute to each other.

Our modeling framework stems from Ferrer and Swaminathan (2010) and we extend it in the following manner. First, we integrate CCT-mechanism into traditional manufacturing and remanufacturing production and price models and propose novel optimization models. Second, we study two models for ID-market and SD-market, respectively. Third, we extend the analysis to study the impacts of CCT-mechanism and carbon related parameters on manufacturing and remanufacturing production decisions.

The paper is organized as follows: Section 2 describes the problem and assumptions. Section 3 presents models and solutions. In Section 4, the impacts of CCT-mechanism and other carbon related parameters on manufacturing and remanufacturing production decision-making are analyzed by theoretical and numerical analysis. Comparisons and main conclusions are drawn in Section 5. All proofs are presented in Appendix A.

2. Problem statement and assumption

We consider a hybrid manufacturing–remanufacturing system consisting of a monopolist manufacturer over two periods. In the first period, the monopolist manufacturer produces new products using virgin materials and sells the new products to the market. In the second period, a certain ratio of end-of-life products can be collected from the market for remanufacturing, so the monopolist manufacturer can use collected returns derived from the first period to produce remanufactured products in the second period.

For each production period, a quota of carbon emission (carbon cap) is allocated to the manufacturer by an external regulatory body. The manufacturer can buy or sell carbon credit on a trading market of carbon emission to meet its production needs and to maximize his profit.

Limited by the CCT-mechanism, the manufacturer needs to make decisions of the optimal production plans in a two-period horizon. Should the manufacturer make new products in both periods or just in the first period? Should the manufacturer make remanufacturing in the second period? How much collected returns should be used for remanufacturing, all collected returns or some of them? How are these production decisions affected by the CCT-mechanism?