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Optimal procurement decision with a carbon tax for the manufacturing industry

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ABSTRACT

A carbon tax, which has been implemented in several countries, is a cost-effective scheme for reducing carbon emission and developing sustainable supply chains. Two problems, how to make the optimal decision on order quantity and how to select appropriate suppliers for a manufacturer, are studied in this paper in consideration of a carbon tax. For the first problem, a dynamic programming model is developed to study the impact of the carbon tax on calculating the optimal order quantity. In reality, the manufacturer could choose a traditional or a greener supplier. The greener supplier is relatively expensive but yields lower emissions. To obey the emission regulations, the manufacturer should pay for the cost which is incurred by carbon emission. Firstly, in this paper, the expected emission cost is formulated, then, the structural properties of the model are derived. In particular, the optimal order quantity is characterized to minimize the expected total discounted cost. In addition, the effective range of the carbon tax is established to assist government to setup a reasonable carbon tax for a certain industry. For the second problem, a supplier evaluation procedure is proposed to select appropriate suppliers to satisfy the random market demand for the manufacturer. A numerical example from the metal industry is taken to illustrate the properties of the model and the procedure of supplier evaluation. Finally, possible extensions of the model are discussed.

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1. Introduction

Nowadays, many business firms have realized the need to improve their social responsibility, especially for the carbon-intensive firms. Facing environmental regulations, a firm needs to take a series of activities, such as, reducing pollutions, carbon emission, to promote sustainable development. In 2013, the Carbon Disclosure Project (CDP) conducted its annual investigation for managing carbon emission. In that project, more than 6000 suppliers participated in the survey. According to the results of that investigation, an increasing number of suppliers realized the benefits in both monetary savings and emissions reduction. In addition, the results show that 29% of suppliers reported emissions reduction in 2012, while one year ago, it was only 19%. In 2013, 69% of CDP members made investment in reducing greenhouse gas (GHG) emissions while this figure was only 39% in 2011 [5].

A carbon tax has been taken as a cost-effective scheme to reduce GHG emissions in a number of countries. As a typical example, British Columbia (B.C.) implemented the carbon tax on July 1, 2008 at a rate of C$10 per ton of CO_2. In July 2014, the B.C. carbon tax was increased to $25 per ton of CO_2 [6]. The implementation of this scheme could incent companies to improve themselves, such as adopting technologies for cleaner production, and using environment-friendly raw materials or products. It also directly impacts on their cost structure, production planning, procurement management and so on. With respect to the current situation, significant research questions should be considered: (i) how would the carbon tax affect the optimal order quantity for a manufacturer? (ii) How should a government implement an effective range of the carbon tax? (iii) How should a manufacturer select appropriate suppliers to satisfy the production demand? These practical questions are key factors to develop sustainable supply chains for the manufacturing industry.

First of all, in order to comply with the carbon tax scheme, the expected emission cost is formulated to describe the cost of emissions which is incurred during the production processes. The

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holding cost for leftover products and the penalty cost for backlogging products are also considered. Therefore, to answer these questions, we formulate problems as a dynamic programming model and derive its properties to show the preservation of convexity of objective function after minimization. On the basis of structural properties of the model and the constraint of carbon tax, the optimal order quantity is derived to minimize the expected total discounted cost for the manufacturer. Then, the effective range of the carbon tax is proposed to assist the government to setup a reasonable carbon tax. As the manufacturer could purchase raw materials from multiple suppliers to satisfy its demand, in this paper, we further established a supplier evaluation procedure to select appropriate suppliers based on the optimal order quantity.

The remainder of this paper is organized as follows. In Section 2, the related literature is provided from three streams including green supply chain management, inventory control with emissions constraints, and green supplier selection. In Section 3, the model setting and its formulation are introduced in detail. In Section 4, the structural properties of the model are analyzed. Then, the optimal ordering quantity and the effective boundary of carbon tax are characterized. In addition, a supplier selection procedure is proposed to select appropriate suppliers to satisfy the random market demand for the manufacturer. A numerical example using the data from the metal industry is presented. In Section 5, the possible extensions of our model are discussed. Section 6 concludes the paper. All the proofs are provided in the Appendix.

2. Literature review

This section reviews some related papers from three streams including green supply chain management (GSCM), inventory control with emissions constraints, and green supplier selection. In addition, the differences between this paper and other representative papers are pointed out.

The first stream, GSCM, is the motivation of this paper. In reality, the motivation for the introduction of GSCM could be ethical and commercial reasons [28]. Starting from the viewpoint of supply chain management (SCM), Seuring and Müller [26] suggested that sustainable SCM could not only affect management of material, information, and capital flows, but could also achieve the goals of the triple bottom line (environmental, social, and economic). Gavronski et al. [11] proposed that GSCM was the complex mechanisms. These mechanisms can be implemented at the corporate and plant level to assess or improve the environmental performance of a supplier base. Sarkis et al. [25] defined GSCM as integrating environmental concerns into the inter-organizational practices of SCM, for instance, reverse logistics. Given the characteristics of GSCM, Kim and Rhee [18] integrated four aspects which included green purchasing, green manufacturing/materials management, green distribution/marketing, and reverse logistics into GSCM. Similarly, Srivastava [27] put forward a more detailed framework which also integrated environmental criteria, including product design, material sourcing and selection, manufacturing processes, delivery of final products to consumers, and the end-of-life management of the product, into SCM. Recently, Barari et al. [3] discussed GSCM from the viewpoint of economy and ecology. They also suggested that making profits and achieving an ecological balance were the objectives of GSCM. Around the same time, Zhu and Sarkis et al. [32] described GSCM from another viewpoint. They pointed that GSCM can be defined as “an emergent environmentally sustainable organizational technological innovation”. Recently, Tseng et al. [29] proposed a similar concept about GSCM with the triple bottom line, from different aspects, they stated that ethics was also important through the whole supply chain. The aforementioned papers described the different characteristics of GSCM, but, they did not focus on a specific industry. Establishing appropriate regulations for a certain industry is desperately needed. For the manufacturing industry, developing sustainable operations can be improved from two aspects including the procurement of environmental raw materials and the optimization of manufacturing processes.

The second stream is inventory control with emission regulations. As pioneers, Hua et al. [15] studied the economic order quantity (EOQ) model under the mechanism of emissions trading. In their model, a key factor, transfer quantity of carbon emission, was integrated into the traditional EOQ model. In addition, the amount of emissions incurred by transportation and holding processes was described by linear relations with the order size. Based on the basic model, the optimal order quantity, the emission price, and the quotas of carbon emission are derived. Jaber Mohamad et al. [16] focused on the GHG emissions from the viewpoint of manufacturing processes. They developed a mathematical programming model with a constant demand, and the objective function of the model consists of the supply chain cost, the emission cost, and the penalty cost for exceeding the allowed limit. The emissions load was expressed as a convex function of the production rate or equipment speed. The cost functions of buyers were derived from the basic EOQ model. Absi et al. [1] developed a polynomial dynamic programming model to analyze the lot-sizing problems with environmental constraints and a deterministic demand. Four types of constraints including periodic carbon emission constraint, cumulative carbon emission constraint, global carbon emission constraint, and rolling carbon emission constrain were analyzed in their model. Choi [8] studied supplier selection under the carbon taxation scheme. The carbon emission cost function is mainly related to the distance between suppliers and buyers. The optimal order quantity was derived from the basic newsvendor model while considering the carbon tax. Emission cost was formulated as a monotonic increasing function with respect to the transportation distance. In addition, some possible extensions of the model were analyzed by Choi [8] under the buyback contract. Chen et al. [7] studied a carbon-constrained EOQ model, which is described by using a mathematical programming model. The objective function is composed of the traditional cost including setup cost, holding cost, and purchasing cost. However, the emissions were constrained by the carbon cap. Based on the optimal order quantities of the EOQ model and carbon-constrained EOQ model, the carbon prices were further analyzed under different carbon rules. Konur et al. [19] developed a similar model based on the basic EOQ model. In addition, they compared two transportation scenarios, less-than-truckload (LTL) and trucked (TL), under the influence of different carbon emission regulations. They analyzed the optimal transportation mode under each regulation. However, in our paper, we focus on the emissions incurred from the operations process in the manufacturing industry. The expected emission cost is derived based on a production process with exponential production time. In addition, the total discounted cost was developed with the random demand.

The third stream is green supplier selection. In SCM, evaluation and selection of appropriate suppliers is a significant issue which has attracted many researchers since the 1950s. With respect to green supplier selection, Noci [24] is a pioneer who proposed a green supplier ranking system to evaluate the environmental performance of suppliers. Lu et al. [23] integrated the analytic hierarchy process (AHP) and a fuzzy method to select green suppliers. Similarly, Lee et al. [22] applied fuzzy AHP to select green suppliers for the high-tech industry. In the light of the interrelationships among different criteria, Hsu and Hu [14] adopted an effective method, analytic network process (ANP) to evaluate green suppliers instead of AHP. Kuo et al. [21] built an integrated model which considered artificial neural networks (ANN), ANP, and data envelopment analysis (DEA) for green supplier selection. In a case

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