



The distributionally robust newsvendor problem with dual sourcing under carbon tax and cap-and-trade regulations



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ABSTRACT

Both carbon tax and cap-and-trade regulations as carbon emissions reduction schemes are widely adopted and implemented in practice. Based on the dual sourcing newsvendor framework, this paper proposes two distributionally robust newsvendor models under those two carbon regulations. The optimal order quantity and carbon emissions of each model are derived by using a maximin expected profit method, and comparisons of the profits between the models with and without carbon emission regulations are provided. It is observed that the carbon tax regulation will lead to a lower profit while adjusting the value of carbon cap leads to comparable profits between the model under cap-and-trade regulation and that without carbon emission consideration. Finally, several numerical examples are presented to illustrate the analytical results and the models developed herein.

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1. Introduction

Reducing carbon dioxide (CO₂) and other greenhouse gas emissions has become a public consensus around the globe in recent years. There are many reports and scientific studies indicating that, if left unchecked, these gases will lead to major changes in the earth's climate system. Under growing public pressure, many national and international authorities have enacted legislations or designed mechanisms to curb these emissions. Cap-and-trade (also called emissions trading system) and carbon tax are widely adopted and implemented in practice. Under cap-and-trade regulation, a firm is allocated a predetermined amount of carbon emissions (a carbon cap) by a government agency. If the firm's actual amount of carbon emissions exceeds the carbon cap, it can buy carbon emission permits on a carbon trading market such as the European Emissions Trading System (EU ETS). If a firm's actual amount of carbon emissions is less than the cap, the firm can sell its surplus emission permits on the same market. Currently, there are more than 20 platforms for carbon trading in the world with the EU ETS being the largest. Under

carbon tax regulation, a firm is charged for its carbon emissions through taxes. According to a recent report by World Bank (2014), 14 countries have implemented carbon taxes. Because these two regulation schemes have different effects on operational decisions of a firm, many researchers, e.g., Avi-Yonah and Uhlmann (2009) and He, Wang, and Wang (2012), have studied this issue and compared the effects of cap-and-trade and carbon tax regulations.

Consequently, many manufacturing and service companies, as the primary sources of carbon emissions, have been searching for a more balanced strategy for maximum profits, better customer service and minimum carbon emission. Dual sourcing approach in supply chain management is one of the quick response systems and has been proposed to cope with uncertain market demand. From Warburton and Stratton (2005) and Rosič and Jammernegg (2013), dual sourcing means that in a supply chain system, a retailer has two supply sources. The first supplier is cost-efficient and has long replenishment lead time while the second one is more expensive but can deliver on short notice. Moreover, the first supplier can be an offshore supplier which is usually far away from the market. Products from the offshore supplier may lead to high carbon emissions due to transportation or less sophisticated production technology, or both. The second supplier can be an onshore supplier located close to the market and generates low carbon emissions, but charges higher price for the same product. In this system, the retailer first orders products from the offshore supplier

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to meet the demand. Once the demand exceeds the ordered quantity, the onshore supplier is used to satisfy the remaining demand timely. In addition, those two supply sources may also be a single supplier with two ordering possibilities. This system is quite popular in certain industries such as fashion apparel (Choi, 2013; Rosič & Jammernegg, 2013). On the other hand, market demand is volatile and its distributional information may not be always available (Kumar & Goswami, 2015). It is more challenging for the retailer to make the right decisions under different carbon regulations.

To address the dual sourcing decision problem under different carbon emission regulations, in this paper we consider a newsvendor problem with dual sourcing under carbon tax and cap-and-trade regulations. We propose two distributionally robust optimization models assuming that carbon emissions are associated with product ordering and storing. We also assume that the demand distribution information is limited to the mean and variance. To maximize the expected profit against the worst possible distribution of the demand, we use the maximin approach to solve the models developed in this paper. Finally, several numerical examples are presented to illustrate these models and the analytical results.

The main contributions of this paper are as follows. First, this paper incorporates carbon footprint into the newsvendor problem with dual sourcing and constructs two distributionally robust newsvendor models under carbon tax and cap-and-trade regulations. Second, this paper adopts a maximin method to obtain the optimal order quantity so that the effects of uncertain demand can be reduced. Specifically, under carbon tax regulation, we prove that zero order quantity from the offshore supplier can be profitable. Under cap-and-trade regulation, we consider that the emission permits buying and selling prices of the retailer can be different and develop closed form expressions of the optimal order quantity to provide in depth analysis on how uncertainty can affect the solutions of newsvendor problem. Finally, under the two carbon regulations, two newsvendor models with dual sourcing are analyzed and compared regarding ordering time and quantities from offshore and onshore sources. The developed models and analytical results from this research would be useful for authorities in setting up carbon cap limits or tax rates if real industry data are used.

The remainder of this paper is organized as follows. Section 2 reviews related literature. Section 3 describes the problem in more detail and introduces notations used in modeling the problem. In Section 4, we formulate two distributionally robust newsvendor models with dual sourcing under carbon tax and cap-and-trade regulations. We also solve the models to optimality and compare the profits from these two models with that without considering carbon emission. Section 5 presents numerical examples to illustrate the models and the analytical results. Conclusions are presented in Section 6.

2. Literature review

The classical newsvendor problem, also called the single-period stochastic inventory problem, has attracted considerable attention in the past decades and there exists a large body of literature. Here, we limit this review to the works closely related to the models and methods used in this paper.

2.1. The newsvendor problem with dual sourcing under carbon emission regulations

The newsvendor problems with different carbon emission regulations have been widely discussed in recent years due to growing

environmental considerations. Song and Leng (2012) considered a mandatory carbon emission capacity, a carbon emission tax and a cap-and-trade regulation system, and investigated the single-period newsvendor problem under each carbon emission regulation. Assuming that carbon emissions are generated from product ordering, they derived optimal order policy under each carbon emission regulation, and provided insightful analysis on the effect of each regulation on expected profits. Zhang and Xu (2013) considered a single-period and multi-item newsvendor problem with cap-and-trade regulation. They derived optimal order policy to maximize total expected profit and proposed a simple solution method with linear computational complexity. Manikas and Kroes (2015) considered a multi-period newsvendor problem under cap-and-trade regulation, and applied a forward buying algorithm to determine the number of time periods to buy permits, the current production level, and the required current and future emissions permits. In addition to the above mentioned work focusing on solving optimal order policy for individual firms, there are several papers addressing supply chain coordination problems under different carbon emission regulations based on newsvendor framework. Recent publications include Du, Ma, Fu, Zhu, and Zhang (2015), Du, Zhu, Liang, and Ma (2013), Dong, Shen, Chow, Yang, and Ng (2016), among others.

In a single source newsvendor problem, typically a retailer orders from a certain supply source and has a one-ordering policy to satisfy the uncertain market demand. In such systems, unsatisfied demand is usually lost and financial losses incur when demand exceeds the order quantity. The retailer may need an emergency supply source to satisfy the unforeseen demand. Newsvendor models with dual sourcing as an extension to the classical newsvendor model have been proposed and widely discussed in literature. Khouja (1996) considered a newsvendor problem with an emergency supply option assuming that a fixed fraction of the shortage can be satisfied by the second ordering after demand realization. Warburton and Stratton (2005) developed a dual sourcing newsvendor model with an onshore and an offshore supplier. In their model, the offshore supplier has a low-cost and long lead time while the onshore supplier has a high-cost and is located close to the market. The onshore supplier is a backup to fulfil the remaining demand. Oberlaender (2011) incorporated different risk preferences into a newsvendor model with dual sourcing, and derived optimal order quantity to maximize expected utility of profit. Pando, San-José, García-Laguna, and Sicilia (2013) derived a closed-form expression of optimal order quantity for newsvendor problem with dual sourcing. They assumed that a variable fraction of the shortage can be satisfied with emergency order from the second supplier. Choi (2013) considered a newsvendor model with dual sourcing and developed a quick response system under carbon tax regulation. Assuming that the second order is placed based on a forecast update, the author illustrated how the carbon tax regulation affects the optimal choice of sourcing decision. Considering environment impact of transport, Rosič and Jammernegg (2013) investigated the newsvendor problem with dual sourcing under carbon tax and cap-and-trade regulations. Assuming that carbon emissions are directly related to the offshore order quantity, they derived optimal order quantity and showed that dual sourcing can have less transport emissions comparing to a single offshore sourcing strategy. Arian and Jammernegg (2014) further considered a newsvendor problem with dual sourcing under carbon cap regulation. They derived the optimal production policy and obtained some managerial insights with a sensitivity analysis.

In the above-mentioned models, probability distributions of the market demand are assumed to be known. However, in solving real world problems, it is often difficult to completely characterize market demand, especially with limited historical data or less accurate forecast methods. In the following section, we will

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