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Effects of emission reduction and partial demand information on operational decisions of a newsvendor problem

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ABSTRACT

This paper analyzes a newsvendor problem with partial demand information under two kinds of carbon emission regulations, in which only the mean and variance of the demand distribution are known. Under the carbon cap and cap-and-trade regulations, two distributionally robust models are formulated to determine the optimal order quantities to maximize the worst-case expected profits. We derive the closed-form expression of the optimal order quantity and show that the cap-and-trade regulation can lead to higher profit and lower carbon emissions. Numerical examples are provided to illustrate the theoretical results and develop the robustness of system parameters via the robust parameter design technique. The results indicate that compared with carbon emission parameters, the demand information parameters have more effect on the optimal worst-case expected profit and less effect on carbon emissions under carbon cap regulation. And the demand information parameters except for the variance of demand have more effect on both the optimal worst-case expected profit and carbon emissions under cap-and-trade regulation.

1. Introduction

Over the past few decades, global warming has received increasing attention. It is widely believed that the emissions of 'anthropogenic' greenhouse gases (GHG), among which carbon dioxide (CO_2) is the most important, largely contribute to global warming. The United Nations Framework Convention on Climate Change formulated the Kyoto Protocol (1997) to reach an international agreement on carbon emissions reduction targets with the aim of mitigating global warming. Many legislations and regulations, such as cap-and-trade and carbon cap regulations, have been enacted or implemented to curb carbon emissions. Under the cap-and-trade regulation, a central authority (usually a government body) sets a carbon emission cap for a firm, if a firm's total carbon emission amount exceeds the carbon cap, the firm may buy carbon emission permits on the carbon trading market, conversely, the firm can sell any surplus permits (Hua et al., 2011; Luo et al., 2016). A cap-and-trade regulation was implemented in Europe in 2005 under the European Union Emissions Trading Scheme (EU ETS), which is the world's largest carbon-trading scheme. Under the carbon cap regulation, a firm's total carbon emission amount must be less than or equal to the cap set by a central authority. The Chinese government has carried out a set of comprehensively strict measures, such as carbon cap regulation, to control carbon emissions and ensure clean air. For example, as a result of the carbon cap regulation proposed in the Asia-Pacific Economic Cooperation (APEC) meetings in Beijing in 2014, approximately 4000 factories were ordered to close or curb production, which eventually led to the emergence of the 'APEC blue' in December.

As the primary sources of carbon emissions, firms have to incorporate carbon emission reduction into their operational management. With carbon emission regulations, firms should redetermine their operational decisions to maximize profit and reduce carbon emissions. Many multinational companies, such as P&G, HP, Wal-Mart etc., attempted to achieve low-carbon and sustainable development in managing their supply chains. Reducing greenhouse gas emissions also makes these companies more competitive and gives them a better brand image. On the other hand, in practice, it is very difficult to forecast the full demand

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information because the market demand is often volatile and uncertain. Instead, only partial demand information, such as the mean and variance of the demand distribution, may be estimated accurately using historical data. For example, in the fashion industry, after the new product is launched, it is much easier to estimate the mean and variance of the demand than the demand distribution because few reliable historical data are available. Under this scenario, for a decision-maker, the following questions are important: (i) What are the impacts of carbon emission regulations and partial demand information on a firm's decisions? (ii) Which approach can guarantee that a firm's operational decisions are robust? (iii) Does a firm attain higher profit and lower carbon emissions?

Motivated by such practical challenges, in this paper, we incorporate carbon emissions into a newsvendor problem with partial demand information where only the mean and variance of the demand distribution are known. Given that carbon emissions are generated from ordering and storing process, we developed two distributionally robust models under carbon cap regulation and cap-and-trade regulation. The objectives of these two models are to determine the order quantity to maximize the worst-case expected profits. Using these two models, we analyze the effects of the carbon emission regulations on order decisions and further compare results under two different carbon emission regulations. More managemerial insights are provided in numerical examples via a robust sensitivity analysis.

The contributions of this paper in relation to the existing literature are threefold. First, two distributionally robust newsvendor models with the constraints of carbon cap and cap-and-trade regulations are developed, and the effects of emission reduction and partial demand information on operational decisions of the newsvendor problem are analyzed theoretically and computationally. Second, the performances of carbon cap regulation and cap-and-trade regulation are compared for the newsvendor problem with partial demand information, and the existence of a carbon emission regulation with higher profit and lower carbon emissions is provided. Finally, a robust sensitivity analysis on all system parameters is performed and the parameters that have greater effect on profit and carbon emissions are proposed.

This paper is organized as follows. In Section 2, we provide a literature review. Section 3 describes the problem in more detail and introduces the notations used to model the problem. In Section 4, we formulate two mathematical models for the distributionally robust newsvendor problems under carbon cap and cap-and-trade regulations. We also derive a closed-form optimal solution for each model and compare these two regulations. Section 5 presents numerical examples to illustrate the theoretical results and develop the analytical results of robustness. Conclusions are presented in Section 6.

2. Literature review

This paper focuses on operational decisions for a newsvendor problem with partial demand information under carbon emission regulations, which is closely related to a distributionally robust newsvendor problem and a newsvendor problem considering carbon emissions.

2.1. The distributionally robust newsvendor problem

The distributionally robust newsvendor problems related to our work in this paper have previously been widely studied in the literature. Scarf (1958) developed the first distributionally robust newsvendor model, assuming that the mean and variance of demand are known. He derived an analytical expression of the optimal order quantity to maximize the worst-case expected profit. Gallego and Moon (1993) provided a very compact proof of the optimality of the formula proposed by Scarf (1958) and discussed several extensions. This model was later extended by Moon and Choi (1995), Alfares and Elmorra (2005), Mostard et al. (2005), and Lee and Hsu (2011), who considered balking behavior, shortage cost penalty, resalable returns, and advertising expenditure, respectively. Recently, Kwon and Cheong (2014) considered the distributionally robust newsvendor problem with a free shipping option and derived the optimal order quantity to maximize the worst-case expected profit. Kamburowski (2014) used the maximin and maximax rules, which maximize the worst-case and the best-case expected profits, respectively, to analyze the distributionally robust newsvendor problem. He provided some new theoretical foundations for deriving optimal order quantities of the problem under the best-case and worst-case demand scenarios. Han et al. (2014) incorporated the risk attitude into the distributionally robust newsvendor problem and derived a closed-form order formula to maximize the worst-case expected profit versus risk trade-off (risk-averse) when the mean and standard deviation of the demand are known. They also used numerical results to illustrate the combined effect of considering risk aversion and ambiguity aversion in solving the considered problem. Pal et al. (2015) considered the distributionally robust newsvendor problem with customers' balking by assuming that the holding cost depends on the order quantity. They analyzed the optimal order quantity for maximizing the worst-case expected profit. Above-mentioned literature developed various types of distributionally robust newsvendor models and these models analyzed the optimal order quantity to maximize the worst-case expected profit of the firm. There are several literature using the minimax regret or maximum entropy approaches to analyze the optimal order quantity of the distributionally robust newsvendor problem, e.g., Yue et al. (2006), Perakis and Roels (2008), Jiang et al. (2011), Andersson et al. (2013), Zhu et al. (2013), Raza (2014), Kamburowski (2015), Raza et al. (2018).

The main characteristics of the models discussed above are that carbon emissions are not considered into the distributionally robust newsvendor problem and unconstrained optimization methods are used to solve the optimal order quantity of the firm. This paper considers that carbon emissions are generated from the ordering and storing process and develops two distributionally robust newsvendor models under carbon cap and cap-and-trade regulations. Using constrained and unconstrained optimization methods, we solve the optimal order quantities of the firm under carbon cap and cap-and-trade regulations, respectively. We also analyze the effects of carbon regulations on the optimal robust order decisions and compare carbon cap with cap-and-trade regulations when only the mean and variance of demand distribution are known.

2.2. The newsvendor problem considering carbon emissions

Newsvendor problems considering carbon emissions have been strongly emphasized in recent years due to society's growing environmental consciousness. Song and Leng (2012) investigated the effects of carbon regulations on the newsvendor problem by assuming that carbon emissions are generated from the production process. They formulated three models under the mandatory carbon emission capacity, carbon tax and cap-and-trade regulations and derived the optimal production quantity of under each regulation. Choi (2013) proposed a quick response system under carbon tax regulation for industrial practices in the fashion industry. Based on the newsvendor framework, they investigated the effects of carbon tax regulation on the optimal inventory policies for the single-ordering and the dual-ordering quick response systems.