



Research on low-carbon strategies in supply chain with environmental regulations based on differential game

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ABSTRACT

With increasing carbon emissions and relatively unfavorable climate changes, all circles of society, including consumers, governments and enterprises, are paying more attention to low-carbon production. In this study, we consider a two-echelon supply chain consisting of one manufacturer and one supplier that try to increase sustainable profits by making efforts on CO₂ emission reduction in three progressive environment regulation situations using a Stackelberg differential game: (1) the market-based situation in which consumers' environmental awareness is mainly considered, (2) the government-based situation in which government intervention effect is mainly considered, and (3) the supply chain based situation in which the channel coordination effect is mainly considered. Dynamic expressions of the optimal sales price, emission reduction efforts and cost subsidy are derived from three situations with the goal of profit maximization. The results show that the emission reduction is largest with the highest efforts of the manufacturer and supplier in the supply chain based situation. The manufacturer makes increasing emission reduction efforts when consumers' environmental awareness, government intervention and channel coordination are introduced in sequence, and charges more money for low-carbon products according to the amount of emission reduction. The supplier makes more efforts only when channel coordination is introduced. Governmental regulation aimed at the final products and downstream enterprises cannot function effectively; a cost-sharing contract in the supply chain is needed to motivate the supplier to make greater emission reduction efforts. The simulations and sensitivity analyses are given to verify the effectiveness of the conclusions. Our study provides theoretical support for dynamic low-carbon production in the supply chain with environmental regulations from the market, government and operation.

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1. Introduction

Faced with the increasing trend of consumers' environmental awareness and a competitive business environment, enterprises are interested in improving economic and environmental performance for long-term sustainability. With increasing carbon emissions and relatively unfavorable climate changes, consumers are now paying more attention to environmental protection, especially in terms of CO₂ emission reduction and low-carbon products (Ghosh and Shah, 2015). In OECD countries, including China, more than 27% of consumers can be considered as "green consumers" for their strong environmental awareness (Zhang et al., 2015). Such

consumers' environmental awareness simulates the demand side to promote emission reduction in all of society. Increasing numbers of enterprises are emphasizing low-carbon production to maximize profits and prevent unfavorable climate change through emission reduction (Plambeck, 2012). At the same time, a competitive business environment leads to the closer cooperation of upstream and downstream enterprises. Channel coordination is imperative for improving the performance of the whole supply chain, and CO₂ emission reduction requires the cooperation of all partner enterprises (Panda et al., 2017). More than 1000 mainstream companies, including Wal-Mart, IKEA and IBM, now use the "low-carbon" label as a must in their supply chains, and they have implemented various preferential coordination policies to promote their upstream and downstream enterprises to work on low-carbon production together (Cohen and Vandenbergh, 2012).

Governments have also taken an active role in CO₂ emission reduction (Xie and Ma, 2016). In December 2015, representatives

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attending the 21st United Nations Framework Convention on Climate Change agreed to take much greater emission reduction efforts to reduce emissions to 40 gigatons before 2050. As the most powerful manufacturing country in the world, China has committed to greatly reducing emissions. About 45% of CO₂ emissions are produced through the manufacturing process (IPCC Report, 2014). The Chinese government thus implemented an industrial policy called “Made in China 2025” in 2015, to promote transformation and upgrading in manufacturing and to reduce CO₂ emissions in the manufacturing industry by 40% by 2025. Various industrial standards and goals for emission reduction have been carried out to regulate the behaviors of manufacturers since then. These administrative measures exert pulling power to motivate the supply chain to reduce its emissions (Wu et al., 2017). Simultaneously pushed by the market and pulled by policy, enterprises should be greatly motivated to reduce emissions. However, the effects of emission reduction in China in the last two years are not significant, with a 1.5% reduction in 2015 and only a 0.5% reduction in 2016 (Le Quéré et al., 2016). The target of a 40% reduction 10 years from now is far away.

To identify why there has not been a significant reduction effect since the implementation of “Made in China 2025” and to promote further emission reduction all around the world, many scholars dedicate to the study of low-carbon production. Most of them focus on macroscopic effects, such as market demand and government intervention, but neglect influences from the microscopic operation level, such as channel coordination (Zhang et al., 2015; Heydari et al., 2017b). To the best of the authors' knowledge, studies on emission reduction in the supply chain that incorporate macroscopic and microscopic factors in a comprehensive framework remain sparse. Furthermore, enterprises' emissions management is a long-term dynamic process, and the effects of emission reduction can be inter-temporal. Decisions on emission reduction in the prior period influence consumers' thinking and can affect relative decisions making in the next period. Hence, the dynamics of the emission reduction problem (which are underdeveloped in previous studies) should be taken into consideration (Benchekroun and Martín-Herrán, 2016). To extend the literature on emission reduction, we connect the effects of regulations from the macroscopic aspects (government intervention and market demand) and the microscopic aspect (the supply chain coordination) simultaneously, and we take the dynamics into consideration by using the differential game theory and Stackelberg game theory in our model. We investigate the following research questions: (1) What are the respective and superposed impacts of consumers' environmental awareness and government intervention on the emission reduction decisions of supply chain players? (2) How can a manufacturer motivate a supplier to optimize emission reduction from the whole-system viewpoint? What kind of coordination contract is needed for this purpose? (3) What are the equilibrium emission reduction, efforts, sales prices and cost subsidy when supply chain players take into account the future effect of their decisions on the dynamics of reference emission reduction in different situations? This paper analyzes the emission reduction decisions of a two-echelon supply chain composed of one manufacturer and one supplier in three decision situations: the market-based environmental regulation model (mainly considering the consumers' environmental awareness effect), the government-based environmental regulation model (mainly considering the government reward/penalty effect) and the supply chain based environmental regulation model (mainly considering the channel coordination effect). The problem of the investigated supply chain is to set the emission reduction efforts, cost subsidy and sales price for the product to maximize the overall profitability in the long run, in

which the sales price, emission reduction effort and cost subsidy are the decision variables under the authority of the manufacturer. The supplier only masters its own emission reduction effort. Both the manufacturer and the supplier are far-sighted: they seek profit maximization in the long run and consider the effects of the “reference emission reduction” (which is influenced by emission reductions during the previous period because of the time lag).

Considering that there is a consecutive relationship between emission reduction decisions in each period, this paper takes account of the time variation by using differential game models and addresses the above-mentioned issues by merging three research streams—consumers' environmental awareness, government intervention and channel coordination—in a dynamic way. Although several models have been developed in these disciplines, none explored the comprehensive effect of all the three factors in one framework or compared the differences considering the time lag effect. This study contributes to the literature in three main aspects. (1) It introduces the impact of time into the analysis framework and studies emission reduction strategies in the supply chain in a dynamic way. In our study, both the manufacturer and the supplier are far-sighted. When making emission reduction decisions in the current period, they take the further influence into consideration so that the decision-making progress is consecutive and iterative. (2) It constructs a comprehensive model including the macroscopic effects of consumers' environmental awareness and government intervention on the emission reduction. The macroscopic effects on emission reduction are divided into two parts in our study—the market and the government—and their respective and superposed impacts are analyzed. (3) It considers the microscopic factor at the operation level to further promote emission reduction. Channel coordination is put forward in our study to explore the profit allocation mechanism in the emission reduction problem, through which the gap between macroscopic and microscopic effects can be connected. The results show that the manufacturer makes increasing emission reduction efforts when consumers' environmental awareness, government intervention and channel coordination are introduced in sequence, and the manufacturer charges more money for low-carbon products according to the level of emission reduction. The supplier makes greater effort only when the channel coordination is introduced. However, governmental regulation aimed at the final products and downstream enterprises cannot function effectively, and a cost-sharing contract in the supply chain is needed to motivate the supplier to make greater emission reduction efforts. Our study explains why the “Made in China 2025” policy does not work well and puts forward solutions for the government. It also contributes to practice by advising managers on how to plan efficiently to reduce product-related emissions against the background of consumers' environmental awareness and government intervention.

This paper is arranged as follows. In Section 2, the relevant literature is reviewed. Section 3 presents the assumptions and notation. In Section 4, three differential game models are formulated according to the environmental regulation situation, i.e., market-based environmental regulation, government-based environmental regulation and supply chain based environmental regulation. Section 5 presents a comparison of the different situations. Simulations and sensitivity analysis are conducted in Section 6, and conclusions are presented in Section 7.

2. Literature review

This study is closely related to four main streams of literature: (1) consumers' environmental awareness, (2) government intervention, (3) supply chain coordination and (4) differential game

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