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A competitive multiperiod supply chain network model with freight carriers and green technology investment option

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ABSTRACT

This paper presents a multiperiod supply chain with freight carriers network model. In this model manufacturers, retailers, and carriers maximize the net present value (NPV) of their investments in ecologically friendly technology. Future production, inventory, transaction, and transportation costs savings are used to help fund investments. The environmental impact of production, inventory, transportation, and consumption of products in the supply chain network are all integrated. The tradeoff between the initial technology investment and its ecological footprint effect is considered for the supply chain planning period. We provide variational inequality formulations of the equilibrium conditions and then propose the modified projection method, along with conditions for convergence. Numerical examples are examined with an analysis of the effects of ecologically friendly technology investments on supply chain network production, transportation, and sales.

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1. Introduction

Consumer, regulatory, community, competitive, and media pressures have caused firms to raise their environmental awareness and improve their ecological footprint. Firms and their stakeholders have come to realize that the major way to reduce their environmental burdens is through their supply chain networks (Bloemhof-Ruwaard, Beek, Hordijk, & Van Wassenhove, 1995; Hill, 1997; Nagurney & Toyasaki, 2005; Toyasaki, Daniele, & Wakolbinger, 2014). Recently and practically, Walmart plans not only to decrease its own CO_2 emission but also decrease emissions in its extended supply chain. They have encouraged and supported their suppliers's efforts to reduce emissions by focusing on clean energy efforts in agriculture, waste, packaging, deforestation, and product use and design (SCDigest Editorial Staff, 2017). As a result, many organizations have embraced ambitious green practices and programs. One of the major environmental burdens is the focus on global climate change and, thus, their carbon footprints.

Supply chain activities and practices represent the greatest opportunity for carbon footprint reduction (Fahimnia, Tang, Davarzani, & Sarkis, 2015; Wiedmann & Minx, 2008). For example, in 2015 Siemens announced that it would spend nearly $110 million to lower the company's emissions. Siemens plans to slash its carbon emissions in half by 2020 and to become carbon neutral by 2030. The company insisted that the investment would eventually pay off through savings of between $20 million and $30 million annually. At the same time, Dell announced that it uses packaging material made of wheat straw and suggested that this new material uses 40% less energy to produce, 90% less water, and costs less to make than traditional packaging (Fehrenbacher, 2015). Hence, to reduce their ecological and carbon footprints firms may need to invest in technology while capitalizing on savings achieved through process improvement and the use of environmentally friendly materials.

Wiedmann and Minx (2008) defined carbon footprinting as a methodology that estimates the total greenhouse gas emissions in carbon equivalent units across a product's lifecycle, including raw material procurement, manufacturing, packaging, logistics, recycling, and waste disposal. The literature and research on carbon emissions management within the supply chain has been growing. Techniques for accounting and measurement of supply chain carbon footprints in itself is an area of research (Sundarakani, De Souza, Goh, & Shun, 2008). Calculations have also considered specific stages of the supply chain, bounding the accounting, such as energy and carbon emissions associated with the transportation links and warehousing activities (Cholette & Venkat, 2009; Sarkar, Ganguly, Sarkar, & Pareek, 2016). IBM provided a carbon heat map to illustrate the degree of

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carbon impact on the operations of a typical supply chain. Butner, Geuder, and Hittner (2008) presented a case study of carbon footprint estimation in the supply chain of a leading importer of bananas in the USA. Accenture (2010) argued that shippers and buyers can reduce not only the transport emissions of their product but also the whole lifecycle carbon impact of products through alternative sourcing and production processes.

Nevertheless, most of the literature on sustainable supply chain management has focused on environmental decision making and closed-loop supply chains as in recycling and remanufacturing (Bhattacharjee & Cruz, 2015; Wakolbinger, Toyasaki, Nowak, & Nagurney, 2014). The literature on managing carbon and ecological footprints in supply chains is only starting to ascend.

To further extend the research and provide additional insights for policy makers and managers from both economic and environmental perspectives, a supply chain network game theoretic model is introduced in this paper. The model considers the environmental impact of production, inventory, transportation, and consumption of products in the supply chain network, and the tradeoff between the initial investment in technology and its ecological footprint effect in the supply chain over a longitudinal planning horizon. NPV is one of the core economic performance evaluation criteria in financial decision making, and has been widely adopted in supply chain management (cf. Dhavale & Sarkis, 2015; Liu & Cruz, 2012; Sun & Queyranne, 2002; Yang, Ronald, & Chu, 2005). However, this is the first time that NPV is used to analyze the tradeoff between investment in carbon footprint reduction and cost savings in a multiperiod competitive supply chain network with multiple interacting decision makers.

Moreover, the formulation discussed here provides purposeful and detailed representation of each of the key categories of decision makers who influence the demand and supply of products considering both economic and environmental issues. The specific focus of this study is on ecologically and economically balancing and optimizing production flow and its movement across a dynamic multilayered supply chain, when the SC partners are dealing with technology investment strategy and its future effect on production, inventory, shipment, and customers' demand.

Mainly, this paper extends the literature as follow:

- We explicitly model competition among manufacturing firms, retail stores, and freight carriers in terms products and inventory quantities, product shipping costs, and energy rating levels using initial technology investments. This multi-faceted inclusion of competition from price, quantity, and energy rating level dimensions leads to results that can be used to assess the trade-offs between initial investment and future costs and meeting demands at each supply chain echelon.
- This study is the first that models integrating oligopolistic competition among manufacturers, retail stores, and freight carriers using shipping price, product flow, and environmentally sensitive demand functions with nonlinear cost functions.
- Explicit integration of environmental preferences of retailers and manufacturers in selecting their manufacturers and carriers, to help form a green supply chain network and address global environmental issues is something that other models have not addressed.
- Consumer awareness of green technology and foot print outcomes in spatial price equilibrium conditions are modeled using customers' demand functions that consider not only the price of product at retail stores but also the retailer energy ratings.

In introducing this work and study, this paper is organized into a number of sections. In Section 2, an overview of the literature is presented to provide support for and positioning of research. In Section 3, the multiperiod competitive supply chain network model is introduced. We derive the supply chain network governing equilibrium conditions and provide the variational inequality formulations in the Appendix. Also, qualitative studies and computational procedure that yields closed form expressions, at each iteration, for the variables are given in the Appendix. In Section 4, we present our numerical examples. We conclude and provide managerial insights in Section 5 and then summarize our paper in Section 6.

2. Background

The research on modeling supply chain decision making and management from operational, tactical, and strategic business, environmental, and social perspectives has seen substantial growth in recent years (Brandenburg, Govindan, Sarkis, & Seuring, 2014; Ding, Liu, & Zheng, 2016; Fahimnia et al., 2015; Ouardighi, Sim, & Kim, 2016; Zhu & He, 2017).

Researchers have investigated environmental decision making in supply chain management processes and associated optimization from a number of dimensions. Usually, economic decisions have played a significant role. For example, Nagurney, Liu, and Woolley (2007) and Cruz (2008) developed supply chain models which included the maximization of revenue and the minimization of environmental emissions. Frota Neto, Bloemhof-Ruwaard, van Nunen, and van Heck (2008) designed an evaluation of sustainable logistics networks where activities affecting the environment and cost efficiency are considered.

There may be tactical and strategic supply chain network design problems such as joint transportation planning and warehousing decisions (Mallidis, Dekker, & Vlachos, 2012) that have been considered for supply chain carbon emissions planning. The decisions have also been mapped into multiple optimization objectives, usually with some form of tradeoffs. For example, bi-objective models integrating the broader strategic supply chain configuration planning decisions that sought maximization of NPV and minimization of environmental impact have been outlined in the Guillen-Gosalbez and Grossmann (2009) study.

Some have utilized regulatory policies related to internalizing externalities such as including emission taxes in a competitive supply chain network model consisting of firms competing in an oligopolistic manner (Nagurney, Yu, & Floden, 2013). Taxing is one way of integrating external economic costs into the supply chain. Another approach is the market mechanism related to trading of emissions, carbon or other wastes emission. For example cap-and-trade market mechanisms have been an effective method of internalizing externalities and have been modeled by varying emission caps to determine supply chain economic performance and integrating environmental issues into supply chain decisions (Cruz & Liu, 2011; Dhavale & Sarkis, 2015; Diabat & Simchi-Levi, 2009; Zakeri, Dehghanian, Fahimnia, & Sarkis, 2015).

Alternatively, some models have explicitly and uniquely focused on environmental objectives. One such model focused on transportation depots and operations emissions reduction under an explicit and singular environmental objective function is Harris, Mumford, and Naim (2014). Yet, competitive modeling can extend beyond just alternative designs in the supply chain. For example, a competitive supply chain network model for fashion that incorporates marketing and reputational efforts can also be a way to design supply chains. One such model for eco-labeling in the fashion industry and their supply chains introduced by Nagurney, Yu, and Floden (2015b), in which, profit-maximizing behavior of the fashion firms which incur eco-labeling costs with information associated with the carbon footprints of their supply chains was revealed to the consumers. These consumers show their preferences for the branded products of the fashion firms through their demand price functions, which include the carbon emissions information.