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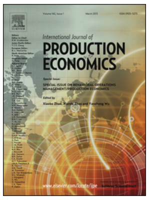

Carbon footprint and responsiveness trade-offs in supply chain network design

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ABSTRACT

Concern related to sustainability and greenhouse gases has grown among citizens as well as firms, which are increasingly committing to carbon emission reduction targets. However, firms' emissions come from direct and indirect sources, and from the different stages of their supply chain. Therefore, comprehensive supply chain approaches are essential to ensure the cost-effectiveness of carbon management strategies. These approaches should capture operational and environmental trade-offs arising from the interaction between different supply chain processes such as procurement, manufacturing, transport and inventory management. Considering all these processes, we propose a model for supply chain network design that takes demand uncertainty into account and includes decisions on supply chain responsiveness under different carbon policies: caps on supply chain carbon footprints, caps on market carbon footprints, and carbon taxes. Our model supports the analysis of the effect of different policies on costs and optimal network configuration and allows us to distinguish between different product types: functional or innovative products. With detailed numerical examples, we illustrate the type of analysis and managerial insights that can be derived with our model, which include the assessment of supply chains' potential for carbon abatement, the study of the effect of different carbon policies on supply chain costs and network design, the analysis of the impact of various product characteristics, the test of an alternative profit maximisation model, and the determination of the value of a supply chain carbon tax that should induce specific levels of carbon abatement.

1. Introduction

Consumers are increasingly seeking lower-carbon lifestyles. As recent Carbon Trust research reveals, 45% of UK shoppers – up from half that rate a year earlier – would be prepared to stop buying their favourite brands if the companies refused to commit to measuring their product carbon footprint (The Carbon Trust, 2011a). This consumer pressure explains the increasing resources that organisations are dedicating to carbon accounting, also called carbon footprinting, and, more generally, to carbon management.

Despite the limited reach of current carbon regulation, firms' commitment to meet voluntarily set environmental performance targets is becoming common practice (Comas Martí and Seifert, 2013). An indication of the adoption of such targets is that 59% of FTSE 100 companies have published targets on greenhouse gases, including carbon or energy reductions (The Carbon Trust, 2011b). Companies' greenhouse gas targets tend to focus on emissions related to their own operations, usually including direct emissions from owned or controlled sources and indirect emissions from the generation of purchased electricity or energy in general. However, companies' carbon accounting should include other indirect emissions that occur in a company's supply chain, e.g. caused by raw material and components suppliers, or by outsourced transport. In the future, it is expected that company carbon targets will develop to include such emissions, given the important opportunities they offer for emissions' abatement.

Since companies tend to rely on third-parties for their inbound and outbound logistics, transport emissions are rarely included in companies' carbon targets. In fact, the share of a product carbon footprint represented by transport emissions may significantly vary from one product to another depending, for instance, on the product's volume or weight, but more importantly on the employed mode of transport. In general, the trade-off in transport is that greater speed relates to greater emissions and greater costs (e.g. air freight compared to sea freight).

However, fast deliveries pay off for certain products; typically for those with high profit margins, with demand patterns that are

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difficult to predict and with high inventory costs (e.g. due to high obsolescence rates). According to the product characterisation proposed by Fisher (1997), these products are denoted innovative products, whereas those with low profit margins, low demand uncertainty and low inventory holding costs are denoted functional products. As Fisher (1997) explains, innovative products require responsive supply chains with short lead times in order to minimise stockouts, forced markdowns and obsolete inventory. Conversely, functional products require physically efficient supply chains primarily focused on cost, with less emphasis on lead time.

The level of responsiveness of a supply chain is not only determined by transport mode decisions, but also by other factors such as the location of its facilities. However, in facility location decisions, not only the nature of the product (innovative or functional) intervenes; manufacturing and raw material costs are also important factors (Krugman and Venables, 1995; Alonso-Villar, 2005). Especially for labour-intensive industries (e.g. apparel and electronics), manufacturing in low-wage countries can be very attractive despite them being far away from the markets where products are sold.

Therefore, we observe that there are opportunities for the companies wanting to reduce carbon emissions in looking beyond their own operations and consider indirect emissions from other processes in their supply chains such as transport emissions. However, we also observe that it is not easy for these companies to balance carbon considerations with supply chain responsiveness trade-offs and differences in manufacturing costs around the globe, as emissions and costs from different processes are interconnected. Moreover, as we explained, functional and innovative products have different requirements in terms of supply chain responsiveness. Thus, it is reasonable to think that the strategy to reduce the emissions closely depends on the product's characteristics: the emissions from a supply chain delivering a functional product and from a supply chain delivering an innovative product might be very different.

In this paper, we present a mathematical model to assist companies facing these joint environmental and operational trade-offs, and help them define carbon abatement strategies in a cost-effective manner. More precisely, we contribute to the literature with a supply chain network design model that simultaneously considers the emissions and costs related to both facility location and transport mode decisions, while taking into account the innovative or functional nature of products through the explicit consideration of demand uncertainty and inventory costs. We explicitly model differences across facility locations in terms of costs/emissions of raw materials or components, manufacturing technologies and labour.

The structure of this paper is as follows. In Section 2, we discuss the previous literature relevant to our research. In Section 3, we present our integer programming formulation of the problem considered. In Section 4, we present detailed numerical analyses to illustrate the relevance of the trade-offs captured by the model and the type of managerial insights that it allows to derive. In Section 5, we conclude and discuss future research opportunities.

2. Literature review

A key feature of the model presented in this paper is its comprehensiveness. The model aims to integrate carbon emission reduction policies in a supply chain network design framework that simultaneously captures facility location and transport mode decisions, which determine supply chain lead time and inventory levels. In the literature, we can find prior contributions covering one or more of these different aspects, although not all of them simultaneously. In this section, we go through prior research relevant to the trade-offs captured in our model.

First, we review contributions in the supply chain network design literature that do not include environmental aspects. We focus on the literature relevant to the trade-offs of interest, i.e. transport mode choice and supply chain responsiveness. Baumol and Vinod (1970) set the basis for transport mode choice models. This body of the literature explicitly takes into account demand uncertainty when studying the value of shorter lead times (Tyworth, 1991; Meixell and Norbis, 2008). As Blauwens et al. (2006) explain, the crux of the inventory theoretic approach lies in the fact that explicit attention is paid to all costs in the supply chain that are affected by the choice of transport mode. However, it is rare for supply chain network design models to jointly capture transport mode and facility location decisions. Wilhelm et al. (2005) present one such model, taking into account transport mode capacities and both fixed and variable costs. Carlsson and Ronnqvist (2005) also consider both types of decisions for a case study of a forestry company. However, these models assume deterministic demand, whereas ours takes into account demand uncertainty, which is highly relevant, as emphasised in the transport mode choice literature.

As noted earlier, demand uncertainty is particularly high for innovative products and lower for functional ones. As Fisher (1997) explains, demand uncertainty, holding costs and inventory costs are important factors to be considered when defining supply chain strategies. Langenberg et al. (2012) and Seifert and Langenberg (2011) provide quantitative support for Fisher's qualitative framework. They present supply chain network design models that explicitly capture supply chain lead time and responsiveness decisions, and take into account demand uncertainty. We extend this modelling approach by incorporating carbon footprints and carbon policies, by capturing transport mode decisions and also by explicitly modelling geographical differences in procurement costs.

We now review the operations management contributions that include carbon emissions and other environmental aspects. Environmental supply chain models (i.e. mathematical models that combine operational and environmental aspects) have been proposed to provide support in different decision-making settings (Dekker et al., 2012).

The selection of manufacturing technologies is one of the decisions that have been studied by these models. The models presented in Bloemhof-Ruwaard et al. (1996) and Hugo and Pistikopoulos (2005) assist in the selection among technologies with different costs and environmental impacts, the latter being captured with indicators based on life cycle assessment (LCA). Drake et al. (2010) focus on technology choices and capacity investments and study how these are affected by emissions regulation.

Inventory level decisions considering carbon emissions have been recently studied by several authors. Assuming deterministic demand, Benjaafar et al. (2013) analyse how simple operational models could be adapted to include carbon footprint parameters. Their goal in this study was to showcase the importance of developing such supply chain models to account for carbon emissions and evaluated the impact of carbon footprint policies. (Hua et al., 2011) investigate in detail how various carbon emission reduction policies impact inventory management decisions, using the classical EOQ model as a benchmark. Chen and Monahan (2010) add demand uncertainty to inventory models considering different environmental policies and introduce the term environmental safety stock. In our work, we include inventory decisions in a broader supply chain network design model, and we assume uncertain demand.

Transport mode selection models including carbon policies are presented by Hoen et al. (2014), aiming to study the impact of carbon emission regulation on the traditional trade-off between lead time and transport costs. Their models take into account product demand uncertainty and capture the effect of transport mode choices on lead time. However, they do not integrate location–allocation decisions, while our models do.