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Design of forward supply chains: Impact of a carbon emissions-sensitive demand

Imen Nouira [a], Ramzi Hammami [a,*], Yannick Frein [b], Cecilia Temponi [c]

[a] ESC Rennes School of Business School, 2 rue Robert d'Arbrissel CS 76522, 35065 Rennes, France
[b] Laboratoire G-SCOP, Grenoble INP, UJF, CNRS, 46 Avenue Felix Viallet, 38031 Grenoble, France
[c] McCoy College of Business, Texas State University, San Marcos, TX 78666, USA

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ABSTRACT

We explore the impacts of a carbon emissions-sensitive demand on decisions relative to the design of forward supply chains (facility location, supplier selection, production technology selection and transportation mode selection). We investigate the design of a forward SC where a set of input items (components) are purchased from a network of external suppliers and used to manufacture a finished product in one or multiple production facilities to fulfill the demand of one or multiple customers. The demand for the final product is an endogenous variable sensitive to carbon emissions per unit and it is also assumed to increase with a decrease in the per unit carbon emissions of the product. We consider the case of a single customer and extend the model to multiple customers. Based on numerical experiments conducted on a case study from the textile industry, we use the models to provide a series of insights that might be instrumental to firms and policy makers. For instance, results indicate that customers' environmental awareness may encourage companies to bring the area of production close to the area of consumption and to select local suppliers. It might even be optimal to dedicate a production facility to each customer in spite of the incurred additional costs. However, if the customers are very demanding (in terms of reducing carbon emissions) then the best strategy can be to design a supply chain with relatively high emissions level because satisfying customer requirements may be very expensive in this case. Furthermore, if the customers are willing to pay a higher price for the product then this can lead to reducing per unit emissions. Our results augment the research to the fields of design of forward and greener supply chains by modeling and experimenting an endogenous demand sensitive to carbon emissions.

1. Introduction

External pressures such as government regulations, non-government organization requirements, and other external circumstances have made sustainability an important component for todays' corporations. In addition, an increasing number of consumers are becoming interested in the environmental impact of products (Altmann, 2015; Young et al., 2010; Mahenc, 2008; Rao, 2002; Chen, 2001). In particular, customers are increasingly concerned by the carbon footprint, identified by many researchers as one of the most important ways to evaluate the environmental impact of a product (Hammami et al., 2015; Benjaafar et al., 2013; Bjorklund et al., 2012; Dekker et al., 2012). According to the European Commission surveys (2008,2009), 83% of Europeans are very much attuned to environmental impacts, mainly the carbon footprint, when buying products. Today, there is a broad consensus that demand for many products is becoming sensitive to their carbon emissions level, as highlighted by Krass et al. (2013), Tang and Zhou (2012), Letmathe and Balakrishnan (2005), and Letmathe and Balakrishnan (2005).

Responding to the environmental concerns raised by the firms' customers, firms worldwide are taking initiatives to reduce the carbon emissions associated with their products and are using this criterion as a marketing tool to retain and increase their customer base. For instance, various firms are starting to attach carbon footprint labels to their products and to position these products as greener alternatives (Benjaafar et al., 2013). Two leading retailers in Europe, Tesco in the UK and Casino in France, have already embarked on aggressive labeling efforts (Benjaafar et al., 2013).

The amount of carbon emissions associated with a product depends on many decisions, some of which are not related to the design of the product itself but rather to the design of the product's supply chain (SC). For instance, the location of production facilities and the selection of raw materials suppliers impact the total distance traveled by a final product and its components and,

* Corresponding author. Tel.: +33 2 99 54 63 63.
E-mail address: hammami.ramzi@gmail.com (R. Hammami).

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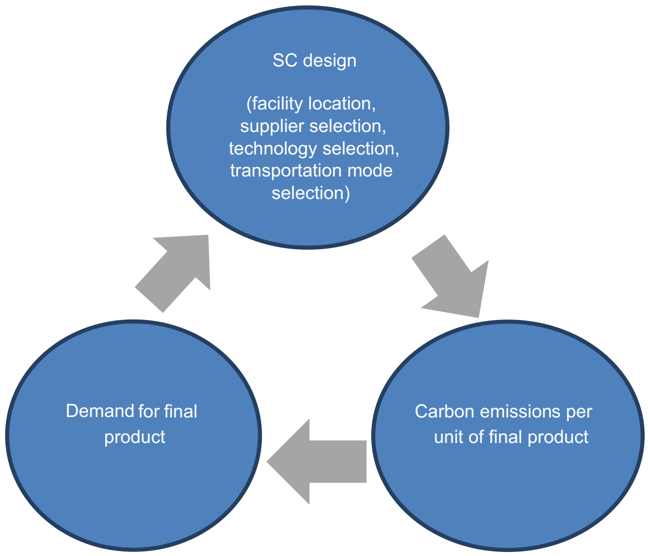

Fig. 1. Supply chain design with integration of carbon emissions-sensitive demand.

consequently, affect the carbon emissions generated during transportation. The selection of transportation modes and production technologies are other examples of SC decisions affecting carbon emissions. The level of carbon emissions is then impacted by SC design decisions. Thus, the demand of a product depends on its associated carbon emissions level, which depends on SC decisions.

We suggest that SC design models (in particular, optimization-based models) should evolve to capture customers' environmental preferences. The approach ought to consider the relation between SC design decisions, carbon emissions, and customer demand as presented in Fig. 1. Thus, demand should no longer be considered as an exogenous input parameter, as in most published SC design models, but rather be modeled as an endogenous decision variable sensitive to carbon emissions and, consequently, to SC design decisions.

In spite of the growing body of literature on green supply chain management (GSCM), recent research lacks quantitative models on forward SC design integrating environmental considerations (Tang and Zhou, 2012; Dekker et al., 2012). In addition, the quantitative models of GSCM focus mostly on the impacts of regulations, while largely ignoring market forces (Tang and Zhou, 2012). In particular, there is a lack of models capturing consumers' response to, and interest in, the environmental impact of products. This observation is in line with the conclusions drawn by Altmann (2015), Nouira et al. (2014), Krass et al. (2013) and Hassini et al. (2012). The main objective of our work is to develop SC design models that include carbon emissions-sensitive demand. Our research provides two main contributions to the field of GSCM:

- First, we address the environmental issues in SC literature from a new perspective as we incorporate carbon emissions-sensitive demand in SC design optimization models. The demand is assumed to be a piecewise linear function of the per unit emissions of the final product, which depend on SC decisions pertaining to facility location, supplier selection, production technology selection, and transportation mode selection. Two different models are developed, one model presents the case of a single customer supplied by a single production facility. The second model includes multiple customers, each supplied by a single production facility. Extensions of the model such as the case of a customer supplied by different production facilities and the use of other demand functions are also discussed.
- Second, our models provide insights for firms and policy-makers alike in their strategic decision making. Customers' sensitivity to carbon emissions raises different research questions that have not been explored yet in the literature. Some of these research questions include: what is the impact of customers' sensitivity on SC decisions and firm's performance? Could the environmental awareness of customers act as a driver for a greener SC without the existence of environmental legislation? In the case of multiple customers, should firms supply each customer from a dedicated local facility (in order to decrease emissions and increase demand) or should they open a unique facility to supply all customer zones? Our models are instrumental to assist on most of these issues.

A literature review on the integration of environmental issues in SC optimization models is presented in Section 2. We address the main features and assumptions of our models in Section 3. Section 4 focuses on the formulation of our mathematical models. In Section 5, computational experiments are presented and insights from results are discussed. Conclusions and suggestions for future research directions are drawn in Section 6.

2. Literature review

Environmental issues have been considered in quantitative SC models from different perspectives. There is a large body of literature on the design and management of reverse logistics networks. However, there are relatively few works dedicated to the consideration of environmental issues in the design of a forward SC as highlighted by many authors (Comas Martí et al., 2015; Diabat and Al-Salem, 2015; Dekker et al., 2012; Tang and Zhou, 2012). In this section, we provide an overview of environmental concerns in forward SC design models. A wider scope is then considered by reviewing research that focus on decisions pertaining to manufacturing management and technology selection, transportation mode selection, and supplier selection. We also investigate the relation between environmental considerations and demand. The section is concluded with overall comments as they pertain to our proposed models.

2.1. Supply chain design and facility location

The location of production and distribution facilities determines the total distance covered by components, semi-finished products, and finished products as they travel between the different sites of a company and onward to customers. It also has an impact on the emission of pollutants and on the energy consumption in the different arcs of the SC. The following models are amongst the most current on SC design and facility location integrating environmental considerations.

Hugo and Pistikopoulos (2005) proposed a multi-objective optimization model for SC design and planning. They maximized the net present value and minimized the environmental impact. Their evaluation was based on the LCA method and took into account the stages of procurement, manufacturing and transportation in the SC. In the model, the main SC decisions impacting the environment were the location of manufacturing plants and the allocation of products to plants. Technology selection and its environmental impact were implicitly considered due to the association of plants and manufacturing technology.

Diabat and Simchi-Levi (2010) develop a MIP model for the design of a SC with three echelons (plants–warehouses–retailers). The main decision in the model was to determine which plants and distribution centers to open so that logistics costs were minimized and total carbon emissions did not overstep the