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A carbon market sensitive optimization model for integrated forward–reverse logistics

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ABSTRACT

Globalized supply chains, volatile energy and material prices, increased carbon regulations and competitive marketing pressure for environmental sustainability are driving supply chain decision makers to reduce carbon emissions. Enterprises face the necessity and the challenge of implementing strategies to reduce their supply chain environmental impact in order to remain competitive. One of the most important strategic issues in this context is the configuration of the logistics network. The decision concerning the design of an optimal network of the supply chain plays a vital role in determining the total carbon footprint across the supply chain and also the total cost. Therefore, the logistics network should be designed in a way that it could reduce both the cost and the carbon footprint across the supply chain. In this context, this research proposes a quantitative optimization model for integrated forward–reverse logistics with carbon-footprint considerations, by integrating the carbon emission into a quantitative operational decision-making model with regard to facility layout decisions. The proposed research incorporates carbon emission parameters with various decision variables and modifies traditional integrated forward/reverse logistics model into decision-making quantitative operational model, minimizing both the total cost and the carbon footprint. The proposed model investigates the extent to which carbon reduction requirements can be addressed under a particular set of parameters such as customer demand, rate of return of products etc., by selecting proper policy as an alternative to the costly investment in carbon-reducing technologies. To solve the quantitative model, this research implements a modified and efficient forest data structure to derive the optimal network configuration, minimizing both the cost and the total carbon footprint of the network. A comparative analysis shows the outperformance of the proposed approach over the conventional Genetic Algorithm (GA) for large problem sizes.

1. Introduction

Reducing and mitigating carbon emission, the culprit of global warming and climate change, is an increasingly important concern for both industry and government (IPCC, 2007). In the UK, the government has targeted to reduce carbon emissions by 60% from 1990 levels by 2050 (Carbon Trust, 2006). The United Nations, the European Union, and many countries have enacted legislations or designed mechanisms such as carbon taxes, carbon offset, clean development, cap and trade, carbon caps and joint implementation to curb the total amount of carbon emissions. Firms worldwide, in response to such mechanisms and legislations or to concerns raised by their own customers, are undertaking initiatives to reduce their carbon footprints.

However, most of the carbon emission reduction initiatives have focused largely on replacing energy inefficient equipment and facilities, redesigning products and packaging, finding less polluting sources of energy and implementing energy-saving programmes. While such efforts are valuable, many firms tend to ignore a potentially more significant source of emissions, which is driven by business practices, operational policies, interaction, and coordination in a long and complex supply chain, where the flow of products to consumers engages multiple firms (NSF Symposium report, 2010). For example, determining the frequency of supply and deliveries could be as important in reducing carbon emissions as the energy efficiency of the vehicles used to make these deliveries. Similarly, several decisions that a firm makes regarding its facility location, supplier and transportation mode selection, etc., can significantly affect it's carbon footprint. In addition, in order to keep high service level, suppliers may require storing inventories in multiple locations that are close to

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their customers, increasing associated carbon footprint. It is therefore necessary to address the problem of carbon emissions reduction from supply chain and logistics perspective.

The Kyoto protocol introduced three major mechanisms for carbon emission reduction: namely carbon trading, clean development mechanism (CDM) and joint implementation (JI). The first mechanism serves as an economic incentive for companies to reduce carbon emissions. Governments set a specific limit of carbon emission for a particular company called carbon cap. If a company wishes to exceed the specified allowance, it will have to buy emission credits from companies that produce less GHGs or below their cap. The second and third mechanism allows countries to gain emission credits by financing emission reduction projects in developing countries and allows specified countries to carry out emission reduction projects in other countries to get emission credits. The carbon trading mechanism applies pressure on companies to reduce carbon emissions throughout their operations towards implementing more environmental friendly ways of conducting their business and to contribute to emission reduction projects worldwide. In addition, with the creation of the 'carbon market', competition amongst firms towards becoming 'greener' has become a major challenge.

Literature surveys conducted by Hua et al. (2011), Abdallah et al., (2010), Sundarkani et al. (2010), Benjaafar et al. (2013), and Cachon (2009) have identified a growing need for developing quantitative models and decision support systems for operations management, supply chain management, and logistics to address the issues associated with curbing carbon emissions. In addition, Diabat and Simchi-Levi (2009) highlight that integrating environmental issues into production, supply chains, and logistics is a complex process. However, with current financial incentives, branding benefits, governmental pressure, and the potential of creating a competitive edge, managers and practitioners have to move away from their current practices and identify ways to green their supply chains, a shift which is receiving increasing on-going research attention. In particular, there is a need for model-based research that extends and integrates current quantitative models which focus on minimizing cost and maximizing profit by including carbon-footprint criteria under different policy situations. These models could then be used to understand how carbon emissions parameters affect operational decisions. Such models can help policy makers to choose different policies related to reduction of carbon cap such as emission cap and trade, taxes on carbon emissions, etc. In addition, these models could also be used to understand how the specifics of these policies would affect the costs and carbon emissions of various firms.

Currently firms put more emphasis productivity and customer satisfaction, which leads firms to focus on their supply chain and integrated logistics (Pishvaee et al., 2009). An efficient and robust logistics network can contribute towards a competitive advantage for firms and helps them to cope with increasing environmental and competitive pressures. Pressed by legislation and environmental consciousness while balancing economic benefits, several leading companies including General Motors, Kodak and Xerox have succeeded by focusing on their reverse logistics and recovery activities. Logistics network and its configuration are very important strategic issues in supply chain management and have a significant impact on the total performance of the supply chain. Decisions such as determining the numbers, locations and capacities of facilities and the quantity of flow between them are dependent on the logistic network design. Reverse logistics is evolving and requires setting up additional appropriate logistics infrastructure for arising flows of used and recovered products. Physical location, facilities and transportation links need to be chosen to transfer forward products from manufacturers to customers and to convey returned products from their former users to manufacturers for the purpose of recovery or safe disposal. Configuration of reverse logistics network has a strong influence on the forward logistics network and vice-versa. Separating the design may lead to sub-optimality and therefore integration of design of forward and reverse logistics network is needed. Following the structure of integrated forward/reverse logistics model as presented in Pishvaee et al. (2009), this research uses an integrated forward/reverse logistics network as shown in Fig. 1.

The integrated logistics network shown above is a single product, multi-stage logistics network. It includes production, distribution, customer, collection, recovery and disposal centres. There are hybrid processing facilities such as distribution-cum-collection centre which is advantageous when compared to separate distribution or collection centre with regard to cost savings and carbon emission reduction. The main motivation behind this activity is sharing of material-handling equipment and infrastructure, prompting to use the above-mentioned integrated forward–reverse logistics network. New products are shipped from production-cum-recovery centre through distribution-cum-collection centre to customer zones while considering forward logistic. For reverse logistics, returned products are collected at distribution-cum-collection centre, then recoverable products are sent to production-cum-recovery centres and scrap products are sent to disposal centres. All these activities have significant impact on the carbon emission in the supply chain.

Aforementioned situation demands for the formulation of a comprehensive analytical model for systematically integrating forward and reverse logistics considering both the cost and the carbon emission criteria. Recognizing the inherent complexity of such integrated logistics network design problem, this paper extends the existing problem scenario, develops a mathematical model and proposes a solution methodology that can near-optimally minimize both the cost and the carbon emission considering various policies and criteria. We assume that some critical parameters such as demand and returned products are deterministic but customer demand, quantity and quality of returned product have high degree of uncertainty even in a short period of time. Depending on the degree of uncertainty, the level of carbon footprint can also vary. Benjaafar et al. (2013) showed that how important insights could be drawn by integrating carbon-emissions parameters into traditional and widely used lot-sizing models. This paper is a step forward contribution in this direction.

The decision regarding the design of an optimal network of the whole supply chain plays a major role in determining the total carbon footprint across the supply chain. This decision also involves a lot of investments. This research proposes an efficient quantitative optimization model for single period, single product integrated forward/reverse logistics network design, which takes into account both recovery and disposal activities. It further incorporates different carbon emission parameters into operational decision-making, which minimizes both total cost and total carbon footprint. This research further uses forest data structure algorithm proposed by Delbem et al. (2012) as a solution methodology to derive the optimal/suboptimal network configuration. Furthermore, we compare the results obtained using this solution methodology with the results obtained using Conventional Genetic Algorithm (CGA). A comparative study shows the outperformance of forest data structure algorithm for large sized problem with large number of operational nodes.

The remainder of the paper is organized as follows. Section 2 systematically reviews the state of the art literature to identify research gaps and makes a case for the presented research. Section 3 introduces and discusses the development of the proposed mathematical model of the problem under consideration with several defined policies and Section 4 discusses the proposed solution methodology namely forest data structure algorithm and its application. Section 5 presents data related to problems and computational experiments. Section 6 presents numerical results and comparative study of various policies. A comparison of the proposed approach