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Cold supply chain design with environmental considerations: A simulation-optimization approach

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ABSTRACT

In response to strict regulations and increased environmental awareness, firms are striving to reduce the global warming impact of their operations. Cold supply chains have high levels of greenhouse gas emissions due to the high energy consumption and refrigerant gas leakages. We model the cold supply chain design problem as a mixed-integer concave minimization problem with dual objectives of minimizing the total cost - including capacity, transportation, and inventory costs - and the global warming impact. Demand is modeled as a general distribution, whereas inventory is managed using a known policy but without explicit formulas for the inventory cost and maximum level functions. We propose a novel hybrid simulation-optimization approach to solve the problem. Lagrangian decomposition is used to compose the model into an integer programming subproblem and sets of single variable concave minimization subproblems that are solved using simulation-optimization. We provide closed-form expressions for the Lagrangian multipliers so that the Lagrangian bound is obtained in a single iteration. Furthermore, since the solution of the integer subproblem is feasible to the original problem an upper bound is obtained immediately. To close the optimality gap, the Lagrangian approach is embedded in a branch-and-bound framework. The approach is verified through extensive numerical testing on two realistic case studies from different industries, and some managerial insights are drawn.

1. Introduction

Global warming has become a pressing issue in the last few decades, particularly with the plethora of recent scientific research providing strong evidence for its existence and showing its severe negative effects (Solomon et al., 2007). Currently, specialists concur that the radioactive forcing attributed to the anthropogenic greenhouse gas (GHG) emissions is the main cause of the global warming phenomenon (NRC, 2005). Thus, many endeavors have been made by governments, organizations and firms around the world to reduce the emissions of GHG.

In many industries, supply chain operations are a significant source of GHG emissions. It was estimated that more than three quarters of the GHG emissions associated with many industrial sectors are attributed to supply chain activities (Huang, Weber, & Matthews, 2009). Companies have devoted considerable attention to reduce the environmental footprint of their supply chains, aiming to achieve their sustainability commitments, mitigate risk on their brand value, and satisfy their environmentally-conscious customers (EPA, 2010). Nowadays, several global companies including IBM, Johnson&Johnson and PepsiCo require their suppliers to report or control their GHG emissions, whereas other companies are taking steps to control their supply chain emissions. For example, Wal-Mart has recently announced that it is on track to reduce GHG emissions from its supply chain by 18 million metric tons by 2015 (WALMART).

In cold supply chains, products must be stored and transported at low temperatures near or below the freezing mark. This necessitates the use of refrigerated warehouses and trucks that consume large quantities of energy for refrigeration. Higher energy consumption is associated with higher carbon dioxide (CO_2) emissions in power generation facilities. Furthermore, refrigeration systems utilize large quantities of HydroFluoroCarbon (HFC) gases that have high global warming potential (GWP) and very long lifetime in the atmosphere. Regular and catastrophic leakage of HFC gases from cold supply chain constitutes a significant component of their global warming impact. Therefore, these gases must be taken into account when determining the best design and operations of cold supply chains.

In this paper, we study the cold supply chain design problem and provide a mathematical model to represent its economic and environmental effects. The problem is formulated as a concave mixed-integer programming problem, where the objective is to minimize the expected total cost of the supply chain, including capacity,

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Nomenclature

a_j	Annual fixed cost for opening a warehouse
b_j	Annual fixed CO_2-equivalent emissions from a warehouse
c_{jkl}	Unit shipping cost from a plant to a warehouse
d_{il}	Expected annual product demand from a retailer
e_{jkl}	CO_2-equivalent emissions for shipping a product between a plant and a warehouse
eCO_{2jkl}	Average CO_2 emissions from shipping a product between a plant and a warehouse
$eHFC_{jkl}$	Average HFC gas leakage for shipping a product between a plant and a warehouse
$f_j(.)$	Volume-dependent capacity cost function
$g_j(.)$	Annual CO_2-equivalent emissions from a warehouse as a function of its volume
GWP_{HFC}	Global-warming potential of a HFC gas
N_l	Number of units shipped of a product
N_v	Number of shipments using a truck type
o_{ij}	Annual CO_2-equivalent emissions for serving a retailer from a warehouse
r_{ij}	Annual cost of serving a customer from a warehouse
$s_{jl}(.)$	Maximum inventory function
$t_{jl}(.)$	Inventory cost function
u_l	Product volume
U_v	Volumetric capacity of a truck type
x_{ij}	Binary decision variables for assigning retailers to warehouses
y_{jkl}	Number of products shipped from a plant to a warehouse
z_j	Binary decision variables for locating warehouses

transportation and inventory costs, in addition to costs associated with the global warming impact due to GHG emissions. We consider the environmental effects of both CO_2 emissions due to energy consumption and leakage of refrigerant gas in warehouses and vehicles.

To solve the model, we propose a novel Lagrangian approach embedded in a branch-and-bound framework. Unlike classical Lagrangian relaxation approaches that use iterative methods such as subgradient optimization or cutting plane methods, we are able to provide a closed-form expression for the best Lagrangian multipliers, so we get the Lagrangian bound in a single iteration. Since the solution of the main subproblem is feasible to the original problem, we also get an upper bound immediately. A branch-and-bound algorithm is used to close the optimality gap. The proposed approach requires the evaluation of the inventory cost and the maximum inventory level at the branching points. Since we address the case of general demand pattern and inventory policy where explicit formulas for the inventory functions are rarely available, we resort to a simulation-optimization algorithm to estimate these functions. Discrete-event simulation is embedded into a bisection search algorithm to find the best control parameters of the inventory system.

The rest of this paper is organized as follows: in the next section we review the recent literature in the area of environmentally-conscious supply chain design . Sections 3 and 4 discuss the economic and environmental aspects of cold supply chains. The mathematical formulation of the cold supply chain design problem is presented in Section 5. In Section 6, a solution method combining Lagrangian decomposition, branch-and-bound, and simulation-optimization is presented in detail. Numerical testing on two case studies from different industries are conducted and the results are presented in Section 7. Finally, conclusions are drawn in Section 8.

2. Literature review

Until the last decade, little attention was given to the environmental impact of supply chains. As noted by Current, Min, and Schilling (1990), only a few supply chain network design papers have included environmental metrics in their objective functions. Furthermore, these were *ad hoc* models designed for specific applications and not generic ones. However, with the escalating pressure from both governments and consumers to reduce the environmental footprint, the interest in designing green supply chains has risen sharply in the last decade. Several aspects of green supply chains were considered in the literature, including reverse supply chains, green manufacturing and remanufacturing, and environmentally-conscious lot-sizing.

Incorporating environmental aspects in supply chain design necessarily entails a trade-off between economic and environmental objectives. However, as shown by Benjaafar, and Daskin (2013), by making minor operational changes, it is possible to achieve vast reductions in the environmental footprint of supply chains without significantly increasing the cost. A variety of supply chain design models that incorporated GHG emission minimization as an objective have appeared recently in the literature, each was based on certain assumptions and has a specific focus. Ramudhin, Chaabane, Kharoune, and Paquet (2008) proposed a green supply chain design model that integrates carbon trading considerations but assumed that facility locations and sizes are known in advance. Conversely, Diabat and Simchi-Levi (2009) considered a similar carbon-capped supply chain design problem that treats the manufacturing and storage capacity of the manufacturers as variables, but does not account for the possibility of carbon trading. Harris, Mumford, and Naim (2009) considered a multi-objective variant of the traditional uncapacitated facility location problem with economic and environmental objectives and implemented an evolutionary algorithm to find a set of non-dominated solutions. Bin and Jun (2009) presented a nonlinear MIP model for a green supply chain design, showing the positive economic and environmental effects of implementing e-commerce on the supply chain operations. A more detailed and sophisticated multi-objective model that embeds life-cycle assessment (LCA) concepts within the supply chain design process is presented by Bojarski, Lainez, Espuña, and Puigjaner (2009). The strategic decisions addressed in the model are facility location, processing technology selection and production/distribution planning. Trade-offs between the total cost and the environment influence is thoroughly studied by Wang, Lai, and Shi (2011), who applied a normalized normal constraint method to find a set of evenly distributed Pareto optimal solutions and studied their sensitivity to the problem parameters. The closed-loop supply chain design framework proposed by Chaabane, Ramudhin, and Paquet (2012) combined multiple aspects from the previous references, including LCA and emission trading. Their MIP model takes into account the economic and environmental costs of manufacturing, distribution, warehousing and recycling activities. For a recent survey on location models within a supply chain environment, the reader is referred to Melo, Nickel, and da Gama (2009).

Within the current literature, three observations are worth mentioning. First, most of the models address the strategic location-allocation decisions in isolation from tactical ones such as inventory and routing decisions; Therefore they fail to exploit the significant potential savings in economic and environmental costs that can be achieved by considering the two levels of decisions simultaneously. Second, with very few exceptions (e.g., Elhedhli & Merrick, 2012), the literature has assumed that the environmental impact of the supply chain is linearly proportional to its scale. A more accurate and realistic approach is to consider economies of scale inherent in supply chain operations, leading to non-linear models. A final critique of the supply chain design models that consider emissions is that they have a narrow focus on CO_2 as the only GHG that deserves attention,