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A carbon-sensitive two-echelon-inventory supply chain model with stochastic demand

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ABSTRACT

Rising environmental awareness is a critical factor that sets new standards and defines new practices around the world, impacting all industries and fields, including supply chain management. While traditional supply chains are designed and operated in a way that minimizes costs and increases profitability, this is no longer sufficient. Supply chain design is becoming more and more concerned with meeting the target of substantially reduced emissions, in addition to constantly evolving by integrating decisions across different levels in order to further minimize costs. In light of this, the current paper addresses the joint location-inventory problem and extends it to account for the reduction of carbon emissions. The problem consists of one plant, multiple distributors and multiple retailers, with products flowing from a plant to DCs and from there to retailers. To better reflect real-life circumstances, we also account for uncertainty by including a new variable that represents the probability of different demand scenarios.

1. Introduction

In a competitive market, companies eagerly try to reduce costs in order to ensure higher profits. Therefore, if the supply chain for a certain company adds more cost than value to the product, then the company will face an issue in expanding or even surviving in the market (Diabat, in press). On the other hand, a well-designed supply chain can cut costs and boost the company's growth. Demand is another critical issue that arises when supply chain management is discussed (Diabat, 2014). Unplanned surges in demand can impose pressure on the chain and may create delays that usually result in higher costs and lower customer satisfaction (Diabat et al., 2015b). On the other hand, if demand turns out to be lower than expected, the company will face unnecessary costs of inventory stored at distribution centers (DCs). If the commodity is perishable, the company will face a higher cost of losing inventory with time (Le et al., 2013; Diabat et al., in press). Therefore, demand adds uncertainty that can have a critical effect on supply chain design.

Environmental impact is another essential consideration in the design of contemporary supply chains. Current global efforts and to minimize environmental impact have encouraged companies to change their practices in order to increase efficiency and to reduce the harmful impact of their activities (Diabat and Al-Salem, 2015), including the adoption of renewable energy sources (Abdallah et al., 2013), recycling and waste management as well as reverse logistics (Alshamsi and Diabat, 2015). Most importantly, due to international frameworks, including the Kyoto Protocol, a target has been set with respect to the reduction of emissions. As global markets are evidently moving towards a unified plan to reduce GHG emissions, industries have started taking steps to meet the environmental challenges for two fundamental reasons. First, as consumers become more aware of the environmental impact of different industries, companies are increasingly obliged to adhere to international laws as part of their social responsibility. Second, carbon emissions' trading has created a new cost mechanism that can severely affect the growth of certain industries if it is not addressed properly.

This provides the motivation for the current work, in which we incorporate the environmental aspect to a joint location inventory model. Furthermore, we also address the uncertainty of demand, which is another critical consideration in a supply chain, as mentioned earlier. In terms of the solution technique, we choose to solve our model using General Algebraic Modeling System (GAMS).

The paper is organized as follows. Section 2 includes literature review, while Section 3 presents the problem definition and the model description. Sections 4 and 5 present the experimental design and the computational results. Finally, concluding remarks are given in Section 6.

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2. Literature review

There is a vast number of papers that address the joint location inventory problem. Furthermore, a number of important works deal with integrating stochasticity of demand in such problems, while several others deal with the improvement of the supply chain's environmental impact. In this section we will explore these works and describe our own contribution of tackling both aspects simultaneously.

In their early work, Daskin and Owen (2003) provided a qualitative discussion of different approaches to solve supply chain models. These approaches are static or dynamic, deterministic or stochastic and scenario planning. The study concluded that stochastic programming will experience advances that can provide better solutions and business decisions. Comparing different approaches, Zheng (1992) discussed the difference between an optimal solution under a deterministic EOQ policy and a stochastic model. His research indicates that at large quantities, the difference between deterministic and stochastic models is small and does not exceed one eighth.

Regarding the types of decisions to be made in a supply chain, they can be distinguished into: strategic, tactical, and operational. The strategic factors include investment decisions, such as location and number of distribution centers (DCs). The tactical factors depend on short term and long term goals, such as inventory policies. Operational factors deal with everyday decisions, such as how full each truck is. An early study conducted by Daskin et al. (2002) looked at the supply chain of blood banks in Chicago and resulted in a nonlinear integer programming that includes the strategic and tactical decisions. A more recent notable work on the integrated location and inventory problem is found in (Diabat et al., 2015a), where the authors develop an efficient Lagrangian relaxation technique to solve the non-linear mixed integer formulation, which aims to make location, order assignment and inventory decisions simultaneously. On another note, the work found in (Diabat and Theodorou, 2015) implements piecewise linearization to bring the integrated problem to a form solvable with the use of commercial software. The great advantage of this work is due to the fact that extensions of the problem can be accounted for and the problem will remain solvable with the use of commercial software.

In terms of green supply chains, they can be achieved through two approaches: either by creating a supply chain that incorporates environmental considerations, or by incorporating reverse logistics, such as recycling. In Sheu et al. (2005) studied the design of supply chains incorporating reverse logistics. Their research focused on logistical flow and a reverse used-products logistics chain within a green supply chain. The model aimed to maximize the profit of the logistical flow, taking into account both the manufacturing supply flow and the reverse supply chain in light of environmental considerations such as recycling fees and subsidies. Yang et al. (2009) extended on Sheu's et al. model by formulating a five-level supply chain, consisting of suppliers, manufacturers, retailers, consumers, and recovery centers. The extended model could be used as an effective tool to study the balance between environmental impact and total cost of the supply chain.

In the context of the carbon emission and credit approach, Hugo and Pistikopoulos (2005) investigated the integration of environmental considerations into supply chain management. They formulated a mixed integer linear programming model which combined classical supply chain costs with life cycle assessment (LCA) based on an impact assessment method known as Eco-Indicator 99. The results indicate that significant reductions in operational costs do not necessarily imply a drastic increase in environmental impact and vice versa.

Ramudhin et al. (2008) formulated a mixed integer programming that takes into account carbon trading in addition to supply chain costs. The authors noted that although the model included only carbon emissions, other GHG emissions could be included using carbon conversion factors. Therefore, it could give decision makers and investors a comprehensive understanding of the tradeoffs between operational costs and environmental impact. In a similar approach, Diabat and Simchi-Levi (2009) formulated a mixed-integer programming that optimized conventional supply chain costs in addition to including a constraint on carbon emissions. In this model, the supply chain has a carbon emissions cap as a constraint, meaning that the network design cannot be expanded beyond a certain size.

In our work, we add both extensions to the original model: the stochastic effect of demand and the environmental consideration of minimizing emissions. The presented model is solved using GAMS. In Wang et al. (2011), programmed a GA to solve an allocation problem of a two-echelon supply chain with stochastic demand by maximizing profit. They concluded that GAs can yield near optimal answers even with stochastic demand. Diabat et al. (2009) also explored solving another facility location problem using genetic algorithms. They studied the capacitated location problem with risk pooling (CLMRP), which included one plant and multi DCs and retailers facing stochastic demand. The GA successfully solves the non-linear integer programming to near optimum and with less CPU usage. Similar work was conducted by Jawahar and Balaji (2009). In this paper, we model the problem in a way that is solvable using GAMS and no need to develop any heuristics to solve it.

3. Problem formulation

The proposed model minimizes the cost of a supply chain considering stochastic demand and environmental impact. This model is the result of two extensions added to an existing model formulated by Diabat et al. (2013). The original model is based on the Economic Order Quantity (EOQ) policy and investigates the strategic and tactical decisions previewed as the number of DCs and inventories that are managed. The same model concept is investigated in Daskin et al. (2002), Daskin and Owen (2003), and Diabat et al. (2009). The five major cost components considered in the objective function are as follows:

i. DC fixed-location cost: the cost to establish and operate a distribution center;
ii. DC-retailer unit-shipping cost: the cost to ship one unit of a commodity from a DC to a retailer;
iii. Plant fixed-location cost: the cost associated with establishing and operating a plant;
iv. Plant-DC unit-shipping cost: the cost to ship one unit of a commodity from a plant to a DC; and
v. Carbon emission cost: the cost of emitting carbon dioxide above the allowed cap.

The first proposed extension ($\sum_{n \in N} q_n$) introduces new variables that will take into account scenarios of demand probabilities. However, it is important to note that the number of DCs is a strategic decision that will be made first regardless of the demand scenarios, whereas retailers assignment and inventory levels will be chosen according to the scenarios. Then, in order to include the additional extension of environmental considerations, another term that calculates the cost of emissions according to a certain cap is added. The terms added to the objective function for each extension are presented below. Note that the constraints of the original model remain unaffected: