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A new inventory model for cold items that considers costs and emissions

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ABSTRACT

A new inventory model that considers both cost and emission functions is proposed for environments where temperature-controlled items need to be stored at a certain, non-ambient temperature and to do so modular temperature-control units are used. Transportation unit capacity and storage unit capacity are considered, which results in non-linear, non-continuous cost and emissions functions. A set of exact algorithms are developed to find the optimal order quantity based on cost and emission function minimization, and the mathematical proof of the optimality of the solutions are presented. Using a variety of parameter ratios, a set of experiments are run to show the effectiveness of the proposed model compared to the current models in the literature and to provide managerial insights into the cold item inventory problem. Optimum order quantity for cost function optimization and emission function optimization are compared against each other and the tradeoff between the functions is analyzed to provide insights.

1. Introduction

According to a study by the University of Michigan[1], the top two contributors to the Green House Gas (GHG) emissions are the electric and transportation sectors. In the electric sector, refrigerants are the second highest contributor. In the transportation sector, small and heavy duty trucks together form more than 50% of the GHG emissions. Thus, policies that attempt to reduce emissions from transportation or refrigerant utilization have the potential to make an impact in the reduction of GHG emissions.

The handling, holding and transportation of temperature-sensitive products along a supply chain is known as the cold supply chain. Cold chain items are items that are required to be maintained in a specific temperature range. Examples of cold chain items are deep freeze items (−28 to −30 ºC) such as seafood, frozen items (−16 to −20 ºC) such as meat, chill items (2 to 4 ºC) such as fruit, vegetables and fresh meat, and pharmaceutical items (2 to 8 ºC), such as medications and vaccines (Routledge, n.d.).

Numerous recent studies have focused on the emissions resulting from the cold supply chain (Calanche et al., 2013; Dekker et al., 2012; James and James, 2010; Wang et al., 2013). These studies consider the emissions from refrigerated trucks and transporters, cold warehouses, packaging and other components in the supply chain.

1.1. Problem statement

This paper examines an inventory model for cold items that considers temperature-controlled unit capacities associated with holding and transporting the cold items in a supply chain. In addition, both the cost and emission functions for such an environment are analyzed.

We model the environment where temperature-controlled items need to be stored at a certain, non-ambient temperature and to do so modular temperature-control units are used. Modular temperature-controlled units are found in industrial applications in the form of segmented industrial freezers, multiple walk-in coolers, or temperature-controlled rooms that are partitioned in the warehouse[2]. Given the significant costs and emissions associated with creating a temperature-controlled environment, many distribution centers operate using segmented or modular temperature-controlled units rather than a single temperature-controlled unit for the entire holding area. The power required for cooling is directly proportional to the size of the freezer, therefore, rather than refrigerating the whole area, instead, a number of temperature-controlled units inside the larger warehouse

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[1] http://css.snre.umich.edu/css_doc/CSS09-05.pdf

[2] http://www.innovativecold.com/press_042010.htmhttp://www.srcrefrigeration.com/http://us.sanyo.com/dynamic/product/Downloads/MPR-514_MPR-1014_MPR- 11DH_Brochure_v1_LOW-49425968.pdf

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are used to keep the items cold. The advantage of such a design is that individual temperature-controlled units can be turned off to save cost and energy when they are not needed. Only when one unit reaches its capacity will the next unit be "turned on." As a result, there is a fixed (setup) cost for holding a group of items, which results in a step function to represent the fixed cost of turning on temperature-controlled units, in addition to the variable cost of holding items based of the number of units held in inventory. Consequently, a linear holding cost and emission function is not applicable to model this environment.

The purpose of this paper is three-fold: (1) derive the mathematical structure and model the holding and transportation costs and emission functions in the described cold chain environment, (2) propose an exact solution procedure to solve the mathematical models, and (3) analyze the tradeoffs involved in making inventory decisions based on minimizing emissions versus minimizing cost in the described cold chain environment.

The remainder of this paper is organized as follows. Section 2 surveys the literature on inventory models that consider cost and sustainability factors. Section 3 introduces and discusses the different components of the problem, which are the holding and transportation cost and emission functions, and derives the Cold Items Cost and Emission Minimization (CICEM) mathematical model. Section 4 presents the solution approaches for the developed models, and Section 5 presents our numerical examples. Section 6 provides a summary of our research and Section 7 offers suggestions for extending this research.

2. Literature review

The inventory management problem is a well-defined, well-studied problem in the literature and interested readers are referred to the following review papers (Bijvank and Vis, 2011; Karaesmen et al., 2011; Khan et al., 2011; Li, 2010; Paterson et al., 2011; Qin et al., 2011). The Economic Order Quantity (EOQ) was first presented by Harris (1913) and is the foundation for developing several research contributions in the field of inventory management.

The inventory problem has been studied considering other objective functions, in addition to, or instead of, the cost function (Franca et al., 2010; Rezaei and Davoodi, 2011; Tsai and Yeh, 2008; Rosič and Jammernegg, 2013). However, only recently has emission been considered in addition to the cost for the inventory problem. Cano-Ruiz and McRae (1998) illustrate that considering the environmental function as an objective function can lead to better solutions, rather than considering an environmental constraint to be satisfied.

Benjaafar et al. (2013) study the lot sizing problem considering the inventory policies' impact on the carbon footprint. They study a single firm with carbon footprint caps with the objective to minimize the summation of the fixed and variable ordering costs, holding costs and backordering costs. They consider a linear function of the order quantity for the carbon footprint constraint. The authors model four environments: (1) cap on the carbon footprint, (2) carbon tax model, (3) cap-and-trade policy on carbon footprint, and (4) carbon offset model.

Chen et al. (2013) propose a carbon-constrained EOQ model that considers a carbon footprint and model it as a constraint for the EOQ model. They derive the optimal order quantity with regard to a cost objective function and consider the emission function as a constraint. They explore the impacts of considering emissions as a constraint on the optimal order quantity for different scenarios and find that the solution is more sensitive to the changes in the emission function (constraint) than to the cost function (objective function). They also study the facility location problem with a constraint on the emission and find similar results.

Song and Leng (2012) study four carbon policies proposed by the Congressional Budget Office in a single period production planning problem to find the optimal production quantity. The problem has the same structure as the newsvendor problem, in addition to having a constraint on the emission. The four policies considered are carbon cap, carbon tax, cap-and-trade and carbon offset.

Absi et al. (2013) analyze a multi-period lot sizing problem considering deterministic demand with inventory holding costs and fixed and variable production and transportation costs. They model the emission function as a constraint and define four different scenarios: (1) Periodic carbon emission constraint, (2) cumulative carbon emission constraint, (3) global carbon emission constraint, and (4) rolling carbon emission constraint.

In all the above mentioned works, the emission function is considered as a constraint, and the cap for the associated emission is assumed to be given by a regulation. In contrast, Bouchery et al. (2012) consider emission factors in the objective function of an inventory model. To the best of our knowledge, this is the only work that considers the emission function of holding inventory as an objective function for the EOQ problem, which is optimized, along with the cost function. The authors identify a set of efficient frontier solutions with the goal of minimizing the cost and emission functions. They use a posteriori analysis method to help the decision maker choose among the provided solutions by using past knowledge that reveals the decision maker's utility functions. In another study, Bonney and Jaber (2011) examine some possible environmental consequences of common activities and suggest that an environmental aspect of all functions within the product life cycle including inventory planning and control should be considered. A simplified model is proposed to demonstrate how one could determine inventory parameters in an environmental context. In this model, the emission and costs associated with transportation are represented in the objective function.

In addition to the inventory problem, the emission function has begun to be considered in other parts of the supply chain, including the transportation section. There are several research papers that are interested in minimizing the emission of transportation (Bastani et al., 2012; Grahn et al., 2009; Ross Morrow et al., 2010; Safaei Mohamadabadi et al., 2009; Zahabi et al., 2012).

Concerning the transportation and emissions problems in a supply chain, Ülkü (2012) studies transportation from the perspectives of economics and the environment. His mathematical model includes the emission of packaging, the effects of load weight and traffic on fuel consumption (and hence, emission) of delivery vehicles. Ji et al. (2014) also consider transportation emission and recommend larger order sizes to reduce the cost and emission of packaging, but do not propose any formulation. Pan et al. (2013) propose mathematical models to study the environmental impact of pooling of supply chains. They use data from two French retail companies and calculate the emission using their developed optimization models for two rail and road transportation modes. The authors conclude that supply network pooling is an efficient approach in reducing CO_2 emissions.

Table 1 characterizes each study by the problem of interest, as well as by how the authors model holding and transportation costs and emissions. Also, the studies are characterized by if the studies consider segmentation of the holding area or transportation unit capacity. As illustrated by Table 1, none of the studies consider the segmentation of the holding area. Also, none of the studies consider transportation unit capacity and quantity-dependent transportation cost with emission functions that incorporate the relationship between load weight and the fuel consumption in their inventory models. In addition, in all the works but one by Bouchery et al. (2012), the holding emission