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Modeling a green inventory routing problem with a heterogeneous fleet

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A B S T R A C T

This paper introduces a green inventory routing problem with a heterogeneous fleet which extends the conventional inventory routing problem by considering environmental impacts and heterogeneous vehicles. A comprehensive objective is proposed, which minimizes the sum of inventory cost and routing cost, where the latter includes driver wage, vehicle fixed cost, fuel and emission costs, in which fuel consumption and emissions are determined by load, distance, speed and vehicle characteristics. We first construct a mixed-integer program, and then conduct numerical tests to quantify the benefits of using a comprehensive objective and heterogeneous vehicles. Managerial insights are also drawn from parameter analyses.

1. Introduction

Global warming is among the greatest challenges of this century, which is mainly caused by carbon dioxide (CO_2) emissions. To respond to this challenge, the United Nations, the European Union, and many countries have enacted legislations to control CO_2 emissions (Hua et al., 2011). Some companies, like IEKA, HP, IBM and GE, also begin to proactively implement 'green' initiatives, such as designing greener products or re-optimizing their supply chain networks (Wang et al., 2011).

Supply chain activities, such as production, transportation and inventory, all emit CO_2. However, transportation is the most visible sector of the supply chain which produces most of the CO_2 (Dekker et al., 2012). The Intergovernmental Panel on Climate Change (IPCC) reports that transportation represents 14% of the greenhouse gases (GHG) emissions by economic sectors in 2010 (Pachauri et al., 2014). Since CO_2 is the second-greatest contributor to the GHG emissions (the first one is water vapor), reducing emissions (for simplicity, in following sections, when we say "emissions", we specifically refer to "CO_2 emissions") by road freight transport will make a good environmental sense. To this end, some companies in Germany and in the United Kingdom have started to adopt more fuel efficient vehicles such as electric and hybrid vehicles (Browne et al., 2011; Taefi et al., 2013). On the other side, companies can also optimize their operational decisions to curb emissions. Benjaafar et al. (2013) suggest that sometimes the second method might provide a greater reduction in emissions with less cost than employing low-energy-consumption technologies.

Moreover, Xiao et al. (2012) state that it is the cost of fuel consumption not the travel distance which is the greater concern to transportation companies. Therefore, in recent years, many researchers begin to employ fuel consumption cost as variable transportation cost in their models, trying to simultaneously describe the cost configuration correctly and reduce

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CO_2 emissions. Up to now, there are several papers that tend to minimize fuel consumption (or CO_2 emissions), or use fuel cost to measure variable transportation cost in vehicle routing problem (VRP) (Suzuki, 2011; Xiao et al., 2012; Zhang et al., 2014; Fukasawa et al., 2015; Xiao and Konak, 2016). There are also researchers who combine environmental effects into supply chain network design (Wang et al., 2011; Elhedhli and Merrick, 2012; Martí et al., 2015; Zhalechian et al., 2016). However, studies considering environmental concern in inventory routing problem (IRP) are scare (Treitl et al., 2014; Malekly, 2015). Thus, to enrich the research in this direction, a new IRP variant, i.e., the green IRP with a heterogeneous fleet (GIRP-H), is proposed, where both fuel consumption and CO_2 emissions are considered.

Demir et al. (2011) have analyzed several models for estimating fuel consumption for road freight transportation. Their study indicates that fuel consumption is determined by a number of factors, such as distance, load, speed and vehicle characteristics. In this study, we compute fuel consumption based on a comprehensive model of Barth et al. (2005) and Barth and Boriboonsomsin (2009). This model has been adopted by Bektaş and Laporte (2011), Franceschetti et al. (2013) and Koç et al. (2014) in pollution-routing problem. Since fuel consumption is the direct cause of CO_2 emissions (Zhang et al., 2014; Cachon, 2014), we can directly transform the amount of fuel consumption, through multiplying by a coefficient, into that of CO_2 emissions.

The rest of this paper is organized as follows. Section 2 introduces related literatures and clarifies the contributions of this study. Section 3 describes our problem and constructs the mathematical model. In Section 4, we add some valid inequalities to strengthen the model and describe solution method. Computational tests and analyses are conducted in Section 5. Section 6 concludes this paper and suggests future research opportunities.

2. Literature review

The IRP is to determine simultaneously the optimal inventory strategy and vehicle scheduling, thereby minimizing the supply chain system's total (or average) cost. It is first introduced by Bell et al. (1983), since then the academic world has conducted extensive research on it. It can be classified according to following criteria: time horizon, demand pattern, supply chain topology, inventory strategy and vehicle fleet (Andersson et al., 2010). Based on different assumptions, some other kinds of IRP can also be defined, such as the IRP with a single product (Zhao et al., 2007) or with multiple products (Coelho and Laporte, 2013a). Interested readers are recommended to review papers by Moin and Salhi (2007), Andersson et al. (2010) and Coelho et al. (2013). In this section, we only present the studies in terms of time horizon, which is more closely related to our research.

In terms of time horizon, IRP can be divided into two categories: infinite time horizon IRP and finite time horizon IRP (sing period or multiple periods). The objective of infinite time horizon IRP is to minimize the system's average cost by determining optimal replenishment intervals, product quantities delivered and vehicle routes. For finite time horizon IRP, we need to determine the customer sets visited in each period and corresponding product quantities delivered, as well as vehicle routes, in order to minimize the system's total cost.

To solve infinite time horizon IRP efficiently, several policies are introduced, such as fixed-partition policies (FPP) and power-of-two (POT) policy. Under the FPP, retailers are partitioned into different regions. Each time if a retailer in a specific region is served, then the same vehicle must visit all other retailers in the same region (Anily and Federgruen, 1990, 1993; Anily and Bramel, 2004). Under the POT policy, retailers' replenishment intervals are limited to power-of-two multiples of a base planning period (Viswanathan and Mathur, 1997; Zhao et al., 2008).

For most companies, logistics planning requires some changes after running for a period of time due to variations in demands and production plans. In this circumstance, infinite time horizon IRP is not applicable. Therefore, recently many researchers begin to study finite time horizon IRP (Archetti et al., 2007; Moin et al., 2011; Coelho and Laporte, 2013a,b; Adulyasak et al., 2013; Desaulniers et al., 2015). In this study, a multi-period IRP considering environmental implications is investigated.

In traditional supply chain system, companies and researchers only care about profits, costs and service levels. However, with increasing environmental pressures, many begin to consider fuel consumption or CO_2 emissions in their problems. Although in recent years, a few scholars start to consider environmental issues in IRP, they usually simplify the calculation of fuel consumption or emissions, which is not accurate and realistic. For example, Alkawaleet et al. (2014) and Mirzapour Al-e-hashem and Rekik (2014) only consider travel distance in computing emissions. In our study, a comprehensive model is constructed, where fuel consumption and CO_2 emissions are influenced not only by distance, but also by load, speed and vehicle characteristics.

Another key aspect of our work is that a heterogeneous fleet is used, because in real-world distribution problems, deliveries are usually implemented by several types of vehicles (Hoff et al., 2010; Koç et al., 2014). There are two types of problems belonging to this category: the fleet size and mix VRP and the heterogeneous VRP. The distinction is that the former one usually assumes the number of vehicles to be unlimited; however, the latter often works with a limited fleet. Although a few papers that study green IRP calculate fuel consumption as we will do (Al Shamsi et al., 2014; Treitl et al., 2014; Malekly, 2015; Soysal et al., 2015, 2016), within our knowledge, the green IRP with a heterogeneous fleet has not yet been studied. Al Shamsi et al. (2014) and Malekly (2015) work with 1 vehicle, and the other three papers use a homogeneous fleet. We believe there is merit in investigating heterogeneous green IRP, because it is often difficult for a homogeneous fleet to simultaneously control costs and CO_2 emissions. For instance, as to light duty vehicles, although their fixed transportation cost is