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Mitigation of greenhouse gas emissions in vehicle routing problems with backhauling

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ABSTRACT

In this paper, the decrease in the emission of greenhouse gases is evaluated using the vehicle routing problem with backhauls and time windows by considering the energy required for each route and estimating the load and distance between customers. Using a *scatter search*, problems from the literature with up to 100 randomly distributed customers were analyzed. Our results indicate that the distance traveled and the transportation costs increase as the required energy decreases, but the amount of fuel consumed also decreases; therefore, the emission of greenhouse gases also decreases. In some cases, the number of vehicles remains the same or increases because a better solution is achieved with shorter, better distributed routes. In addition, using a cooperative game approach, we found that different transportation companies operating jointly results in decreased emissions as well as operating costs.

1. Introduction

The negative impact of vehicular transportation on the environment is undeniable due to its effect on land usage, resource consumption, and damage to ecosystems and human health. In addition, according to the Intergovernmental Panel on Climate Change (IPCC), the emission of greenhouse gases (GHG) very likely have caused the observed increase in average global temperatures, a phenomenon known as Global Warming (IPCC, 2007). Freight transport generates 13% of the total amount of anthropogenic GHG at the global level (IPCC, 2007). Millions of tons of CO_2 are released into the environment annually (McKinnon, 2007), and this sector is undergoing continuous growth.

To plan their operations, freight transport companies must address an optimization problem that has been widely studied in the literature, known as the vehicle routing problem (VRP). The VRP determines a set of routes, each followed by one vehicle, to serve all of their clients; these routes start and end at a given depot and must satisfy a set of constraints. Complete descriptions of the VRP and the aforementioned variants are found in Toth and Vigo (2002) and Golden, Raghavan, and Wasil (2008). The most common variant of this problem is vehicle routing restricted by capacity (CVRP), in which the demands of each customer must be fulfilled without exceeding the vehicle's capacity. In practice, it is common for the clients to specify a time window in which they want to be visited. This gives rise to the VRP with time windows (VRPTW), which has been tackled with both heuristic and exact methods (Baldacci, Mingozzi, & Roberti, 2012; Yu, Yang, & Yao, 2011).

One of the VRPTW variants considers two types of customers, termed linehaul and backhaul (VRPBTW). The backhaul customers are served after all of the linehaul customers on the route have been visited. Ropke and Pisinger (2006) presented an extensive study of this problem and its variants. Freight transport planning with VRPBTW is highly applicable for decreasing the environmental impact of freight transport because this method involves two services that are commonly rendered separately along the same route, thereby increasing vehicle use. To consider environmental and energy aspects in route planning, existing mathematical models must be analyzed. Consequently, new computational approaches to practical solutions for these types of problems must be proposed.

The incorporation of themes such as the minimization of energy and CO_2 emissions in routing problems is a relatively recent topic addressed in the literature. Kara, Kara, and Yetis (2007) proposed a new objective function that considers minimization of the product between the load and the distance traveled by the vehicle in the CVRP, which they termed the Energy Minimizing Vehicle Routing Problem. The model was tested using two examples from the literature, and the solution differed from that of the classical VRP because the energy also depends on vehicle load. However, the load between two nodes is only one of the many variables that influence the energy required by a vehicle. Bektaş and Laporte (2011)

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reported on the different factors that affect energy requirements and the mathematical models that exist to predict fuel consumption and emissions. Load, distance, and speed must be considered to determine the required energy, and the driver, fuel, and environmental costs must also be considered to establish the objective function. They also presented results for three variants of the problem: minimization of distance, minimization of the distance–load product, and minimization of energy. The study of Xiao, Zhao, Kaku, and Xu (2012), developed an optimization model that added a new factor, named Fuel Consumption Rate (FCR), to consider the load dependence of fuel consumption. A Simulated Annealing algorithm with hybrid exchange it is used to minimize the fuel consumption to the classical CVRP and the results showed that the new model can reduce 5% on average of the fuel consumption considering 27 CVRP benchmark instances (from 50 up to 483 customers).

Although the above studies provide a basis for studying VRP problems, it is not clear whether an extension to VRPBTW can be made that will address minimization of the required energy based on load, speed, and distance.

Our objective in this paper is to propose a new vehicle routing variant that minimizes GHG emissions. The contributions of the present paper can be summarized as follows:

- Defining a new objective function that considers minimizing the required energy instead of the distance traveled in the VRPBTW, based on the model proposed by Bektaş and Laporte (2011) to mitigate GHG emissions.
- Demonstrating that consideration of both linehaul and backhaul customers in the planning of vehicle routes can decrease GHG emissions compared to independent planning for each type of customer.
- Solving the VRPBTW using examples from the literature for up to 100 customers.
- Applying the theory of cooperative games for the studied examples.

This paper is organized as follows: Section 2 presents both the formulation proposed for the VRPBTW and the method used. Section 3 describes the experimental results, which are further discussed in Section 4. Conclusions are presented in the last section.

2. Materials and methods

In the proposed solution of the VRPBTW, four elements were considered: determination of the energy requirement (to build the model's objective function), a mathematical formulation, the use of the Scatter Search (SS) metaheuristic, and use of the cooperative game approach (as an option to mitigate the increase in cost that the implementation proposes). These elements are detailed below.

2.1. Energy requirement

Let $G = (N,A)$ be a network with a set of nodes (customers) N and a set of arcs, $A = \{(i,j)|i,j \in N\}$. The set of nodes is separated into $N = \{\{0\},L,B\}$, where 0 is the depot, $L = \{1,\ldots,n\}$ is the set of linehaul customers, and $B = \{n+1,\ldots,n+m\}$ is the set of backhaul customers. Each node $i \in N$ is associated with a non-negative amount and of products to be delivered or picked up (if a linehaul, $b_i = 0$); a time window $[e_i,l_i]$ where e_i is the lower bound and l_i is the upper bound of the time window and at a service time s_i that represents the time for loading or unloading products. A symmetric travel time matrix $T = [t_{ij}]$ and a fleet of identical vehicles, $V = \{1,\ldots,v\}$, in which each vehicle k has a capacity q are available.

The energy required in each arc (i,j) of the transport network is estimated using Eq. (1), as proposed by Bektaş and Laporte (2011). In this equation P_{ij}, represents the total amount of energy required for arc (i,j); w is the empty vehicle weight in kg; f_{ij} is the load carried by the vehicle in kg; d_{ij} corresponds to the distance in meters; and v_{ij}^2 is the vehicle speed in the arc in m/s, α_{ij} is a specific constant of the arc, and β is a specific vehicle constant, which are given by Eqs. (2) and (3), respectively.

$$P_{ij} \approx \alpha_{ij}(w + f_{ij})d_{ij} + \beta v_{ij}^2 d_{ij} \tag{1}$$

$$\alpha_{ij} = a + g\sin\theta_{ij} + gC_r\cos\theta_{ij} \tag{2}$$

$$\beta = 0.5C_d A\rho \tag{3}$$

In Eqs. (2) and (3), a corresponds to the vehicle acceleration in m/s^2; g is the gravitational constant in m/s^2; θ_{ij} is the angle of arc (i,j); C_r is the coefficient of rolling resistance; C_d is the coefficient of drag; A is the vehicle frontal surface area in m^2; and ρ is the air density in kg/m^3.

2.2. Mathematical formulation

This study treats the VRPBTW in a different way from the traditional VRP; in addition to examining the costs of transportation (as a function of the distance traveled) and the types of customers (linehaul or backhaul), the VRPBTW considers the environmental impact in the search for a solution. The mathematical model used to represent this objective is derived from that used in Cho and Wang (2005) and includes the environmental impact factor proposed by Bektaş and Laporte (2011).

Let $x_{ijk} = 1$ if arc (i,j) is covered by vehicle k, or 0 otherwise. Let $u_{ik} = 1$ if the linehaul customer is served by vehicle k, or 0 otherwise. Let $v_{ik} = 1$ if the backhaul customer is served by vehicle k, or 0 otherwise; t_i is the time at which the service starts, and R is a very large value; f_{ijk} is the load transported by vehicle k over arc (i,j), so the proposed mathematical model is given in (4–18).

The new objective function for the VRPBTW, presented in Eq. (4), minimizes the amount of energy required by the route; in addition to the distance, this function considers the load transported on each arc of the trip and the vehicle speed, as detailed in Eqs. (2) and (3). Eqs. (5) and (6) express that each linehaul and backhaul customer must be served by exactly one vehicle. Eqs. (7) and (8) indicate that vehicle cannot exceed its capacity. Eqs. (9) and (10) are the flow conservation constraints. Eq. (11) represents the priority assigned to the linehaul customers over the backhaul for each vehicle k. Eqs. (12) and (13) correspond to the time window constraints. Eqs. (14)–(16) represent the flow balance, which models the flow as increasing (or decreasing) by the amount of individual customer demand, while the remaining equations define the decision variables.

$$\text{Min} \quad \sum_{i=0}^{n+m}\sum_{j=0}^{n+m}\sum_{k=1}^{v}[\alpha_{ij}d_{ij}(wx_{ijk} + f_{ijk}) + \beta v_{ij}^2 d_{ijk}] \tag{4}$$

$$\text{S.t.:} \quad \sum_{k=1}^{v} u_{ik} = 1 \quad i = 1,\ldots,n \tag{5}$$

$$\sum_{k=1}^{v} v_{ik} = 1 \quad i = n+1,\ldots,n+m \tag{6}$$

$$\sum_{i=1}^{n} a_i u_{ik} \leqslant q \quad k = 1,\ldots,v \tag{7}$$

$$\sum_{i=n+1}^{n+m} b_i v_{ik} \leqslant q \quad k = 1,\ldots,v \tag{8}$$