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A multi-objective model for the green capacitated location-routing problem considering environmental impact

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ABSTRACT

The Capacitated Location-Routing Problem (CLRP) is a strategic-level problem involving the selection of one or many depots from a set of candidate locations and the planning of delivery routes from the selected depots to a set of customers. During the last few years, many logistics and operations research problems have been extended to include greenhouse effect issues and costs related to the environmental impact of industrial and transportation activities. In this paper a new mathematical model for the calculation of greenhouse gas emissions is developed and a new model for the CLRP considering fuel consumption minimization is proposed. This model, named Green CLRP (G-CLRP), is represented by a mixed integer linear problem, which is characterized by incorporating a set of new constraints focused on maintaining the problem connectivity requirements. The model proposed is formulated as a bi-objective problem, considering the minimization of operational costs and the minimization of environmental effects. A sensitivity analysis in instances of different sizes is done to show that the proposed objective functions are indeed conflicting goals. The proposed mathematical model is solved with the classical epsilon constraint technique. The results clearly show that the proposed model is able to generate a set of tradeoff solutions leading to interesting conclusions about the operational costs and the environmental impact. This set of solutions is useful in the decision process because several planning alternatives can be considered at strategic level.

1. Introduction

In the last decade, consumers, businesses and governments have increased their attention to the environment. Society in general is becoming increasingly aware and concerned of the environmental impact of human activities and the indiscriminate use of natural resources. Companies are understanding and recognizing the need to assess and reduce the environmental impact of their products and services (Daniel, Diakoulaki, & Pappis, 1997; Frota Neto, Walther, Bloemhof, van Nunen, & Spengler, 2009). In this context, the transportation industry has a significant effect on the planet, because of the large quantity of fuel used in its regular operation and the environmental consequences and greenhouse effects of fuel consumption and pollution. As a consequence, Green Logistics and Green Transportation have emerged in all levels of supply chain management (Lin, Choy, Ho, Chung, & Lam, 2014), with growing value to researchers and organizations, motivated by the fact that current logistics centered on economic costs without accounting for the negative impacts on the environment is not sustainable in the long term (Lin et al., 2014).

Approximately 10% of the gross domestic product is devoted to supply chain related activities (Simchi-Levi, Kaminsky, & Simchi-Levi, 1999). Any effort in the optimal management of the supply chain is of great impact on the finances of the organization. The Capacitated Location Routing Problem (CLRP) is an important problem in the strategic level of the supply chain management, dealing with decisions of logistics operations, such as: (i) location of factories, warehouses or distribution centers, known as facilities or depots; (ii) allocation of customers to each service area; and (iii) transportation plans connecting customers, raw materials, manufacturing plants and warehouses. Therefore, the CLRP aims at approaching location and routing decisions together as an integrated problem.

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During the last few years, many logistics and operations research problems have been extended to include environmental issues and costs related to the environmental impact of industrial and transportation activities (Bektas & Laporte, 2011; Demir, Bektaş, & Laporte, 2014; Erdogan & Miller-Hooks, 2012; Lin et al., 2014). In this paper we propose a new mathematical model for the CLRP, named Green CLRP (G-CLRP), considering fuel consumption minimization. Briefly, the problem can be stated as follows. Given a set of depots I and customers J, the goal of the CLRP is to find the optimal selection of depots and the routes that connect them to the customers. Each facility has a setup or opening cost O_i. Associated with each edge $(i,j) \in V$ there is a traveling cost c_{ij}. Each customer $j \in J$ has a demand d_j which must be fulfilled by a single vehicle. A set K of identical vehicles with capacity Q is available. Each vehicle, when used by a facility $i \in I$, incurs a depot dependent fixed cost F_i and performs a single route. In the usual CLRP, one objective function is considered in the model: to minimize total operational cost, which includes setup cost of facilities, cost of use of vehicles and cost for transit between a pair of nodes. In the G-CLRP, in addition to the operational costs, a second objective function is included, which considers pollutant emissions generated due to fuel consumption in the routes performed. Given the inherent difficulty of aggregating these objectives into a global criterion, we formulate the problem as a bi-objective one. The Pareto-optimal solutions for the problem can be found and analyzed*a posteriori*by decision-makers or stakeholders. This model corresponds to a mixed integer linear problem formulation and was implemented in AMPL (Fourer, Gay, & Kernighan, 2002) and solved with CPLEX 12.5 (called with the optimality gap option equal to 0%).

The main contributions of this paper are:

- A new mathematical model for the computation of fuel consumption and total emissions is developed based on the forces acting on each vehicle during its operation.
- The proposed G-CLRP extends the CLRP, by considering the environmental impact in terms of fuel consumption minimization.
- The proposed model in this paper corresponds to a mixed integer linear formulation, which is characterized by incorporating a radial constraint that makes it possible to eliminate subtour constraints.
- This paper presents a contribution to the discussion of green VRP, by considering the integrated location of multiple depots and routing of multiple vehicles.

2. Overview and approaches for the CLRP

The CLRP is a special case of the Location Routing Problem (LRP), therefore any methodology proposed for the LRP can be extended to the CLRP, for this one needs to consider facilities and vehicles with limited capacity and customers with deterministic demand. The CLRP is considered an NP-hard problem, due to the combination of the Capacitated VRP (CVRP) and the Capacitated Facility Location problem (CFLP) (Contardo, Cordeau, & Gendron, 2013).

LRP have many applications in different economic fronts, such as: localization of central office and routing of army classified documents (Chan & Baker, 2005), distribution of documents to cities (Lin & Kwok, 2006), military logistics planning and operation (Burks, Moore, Barnes, & Bell, 2010), installation of waste incineration plants and routing and collection of garbage (Lopes, Barreto, Ferreira, & Santos, 2008), timber supply chain (Marinakis & Marinaki, 2008), supermarket chains distribution (Ambrosino, Sciomachen, & Scutell, 2009), vehicle parts distribution (Schittekat & Sorensen, 2009), mail distribution (Cetiner, Sepil, & Sural, 2010) and planning assignments in special examinations (Ahn, Weck, Geng, & Klabjan, 2012).

LRP have been solved using heuristics and metaheuristics, mathematical programming, and hybrid techniques including *matheuristics*.[1] Berger, Coullard, and Daskin (2007) solved the LRP with standard vehicles and facilities with unlimited capacity, considering the maximum length of each route, using a Branch-and-Price algorithm. Akca, Berger, and Ralphs (2009) described a Branch-and-Price algorithm based on the set partitioning formulation, discussing exact and heuristic variants of this algorithm. Belenguer, Benavent, Prins, Prodhon, and Calvo (2011) used a formulation of two indices with two types of binary variables, one of them is associated with the arcs and the other variable indicates whether or not the arc was used twice, because they are considered unique customer routes. Baldacci and Hadjiconstantinou (2004) proposed a new integer programming formulation for the CVRP based on a two-commodity network flow approach and a new Branch-and-Cut exact algorithm for the optimal solution. Contardo, Cordeau, and Gendron (2011), Contardo et al. (2013), based on the formulation in Belenguer et al. (2011), presented new three-index flow formulations and three-index two-commodity flow formulation. The results show that the first formulation type is more efficient than the second one. Contardo, Cordeau, and Gendron (2013) proposed a methodology for the CLRP as formulated in Akca et al. (2009), Baldacci and Hadjiconstantinou (2004), where new procedures of inequalities and separations for the flow formulations of the CLRP are presented. The results outperform those of Belenguer et al. (2011), improving the bounds found in the literature, solving to optimality some previously unsolved instances, and improving the upper bounds on some other instances.

In the case of Heuristics, on one hand iterative methods solve both sub-problems simultaneously, feeding back responses obtained from each sub-problem (Salhi & Rand, 1989). Hierarchical methods consider the main problem of locating depots and then the routing problem is solved as a subordinate issue (Albareda-Sambola, Díaz, & Fernández, 2005). Methods based on grouping of clients or clusters were proposed by Barreto, Ferreira, Paixao, and Santos (2007).

Metaheuristics have also been proposed for the LRP. In Prins, Prodhon, and Calvo (2006), a new metaheuristic to solve the LRP with capacitated routes and depots is proposed. The method consists of a GRASP, based on an extended and randomized version of Clarke and Wright algorithm, and a post-optimization using path relinking technique. In Prins, Prodhon, and Calvo (2006), a genetic algorithm with management of the population is proposed, denominated Memetic Algorithm with Population Management. The initial population is characterized by a small number of individuals initially generated with the Randomized Extended Clarke and Wright Algorithm (RECWA) and the method of randomized nearest neighbor; both are improved by a local search, and tournament selection is performed. Duhamel, Lacomme, Prins, and Prodhon (2010) proposed an approach called Evolutionary Local Search (GRASP ELS). The initial solutions are constructed using RECWA and are improved using the Local Search as it is proposed in Prins et al. (2006). The solution found is transformed into a giant tour. The result obtained by the giant tour becomes a solution to the LRP, using the division method inspired by Prins et al. (2006). Finally, the solution of the CLRP is improved again by using Local Search. The methodology is tested on several instances, improving some responses achieved by Prins et al. (2006, 2006).

Matheuristics are hybrid strategies that combine elements of heuristic techniques, metaheuristic techniques and mathematical programming techniques. In general, these hybrid strategies

[1] Combination of mathematical programming and heuristics.