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Local search heuristics for sectoring routing in a household waste collection context

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ABSTRACT

This paper addresses the problem of residential waste collection, as a real life application of a sectoring-arc routing problem (SARP). Tactical decisions comprise the partition of the service territory into a number of sectors so that each sector can be covered by a set of vehicle trips. In addition, operational decisions involving the design of the vehicle trips that minimize total routing time are to be made. Apart from supporting good vehicle trips, sectors should also be planned such that the workload time imbalance as well as the number of connected components are minimized. These later try to promote service areas (sectors) geographically concentrated and grouped into delimited regions. We propose two local search methods: a hill climbing and a tabu search based heuristic. A constructive heuristic for obtaining an initial solution is also suggested. By means of a normalized weighted sum of criteria for evaluating solutions, the local search heuristics were tailored to improve the features of the initial solution. The algorithms are tested on random instances and also on real life based instances. The results show that the proposed local search methods are an efficient way of obtaining good quality solutions to implement in practice. Results also highlight that the proposed function for evaluating solutions during the search phase plays an essential role.

1. Introduction

Waste collection systems cover different types of waste, such as residential, commercial, recyclable or skip waste. Depending on the characteristics and location of the waste containers, vehicle trips are tackled via node or arc routing problems.

This paper addresses a residential waste collection problem, in which waste is collected along the streets by a fixed number of capacitated vehicles. Thus, a capacitated arc routing approach is considered. Moreover, depending on streets size and on traffic rules, some streets can only be serviced in one direction, whereas others demand collection on both sides and in both directions. Large one-way streets need to be represented by multiple segments, and consequently the street network is represented by a mixed multigraph.

This research was motivated by real life applications. Therefore, the design of vehicle trips is threefold. Firstly, it should minimize the total routing time, which represents the time required for the waste collection. Secondly, the street network must be partitioned into a given number of sub-regions (also called *sectors*, or *service areas*), which should be balanced and as connected as possible (i.e. with a small number of connected components). Thirdly, each sector must be serviced by a single capacitated vehicle that performs one or more trips within a limited workload time, due to labor regulations. The balance criterion is meant to reduce the differences among the work assigned to the vehicle crews. It should be noted that improving the connectivity and workload time balance of the sectors promotes solutions in which service areas are both geographically concentrated, grouped into delimited regions, and with similar services for different vehicles. Service connectivity and concentration enable not only specialization, but also the allocation of responsibilities to the vehicle crews.

Given that no bounds are known to limit neither the number of connected components nor the workload time imbalance, tackling together these two features gives rise to some challenging issues. For instance, if adding up a new task to a given sector is ruled by connectivity, it is enough to guarantee that the new task shares at least one node with those tasks already assigned to that sector. On

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the other hand, sectors can be built up simultaneously and ruled by the workload time if their balancing is required.

Note that these two rules can be incompatible if, e.g. the sector with the smallest workload time has no unassigned adjacent tasks (i.e. unassigned tasks linked with tasks in that sector). For that reason, and despite this research stems from the one presented in Mourão, Nunes, and Prins (2009), constructive heuristics such as the ones suggested in the aforementioned paper, even if adapted, lack to produce effective solutions for the problem under analysis.

Alternatively, we propose two local search algorithms, one of which is based on hill climbing, and the other is a tabu search, being the initial solution provided by an improved constructive method. To simultaneously deal with the three optimization criteria (total routing time, imbalance and connectivity within service areas) both local search algorithms make use of a weighted normalized function to evaluate solutions during the search process.

The problem under analysis can be modeled as a sectoring-arc routing problem (SARP) (Mourão et al., 2009) with additional features required for the solutions. This is a NP-hard problem since it combines a sectoring problem (also known as districting, district design, or territory design) with a mixed capacitated arc routing problem (MCARP), as the street network is a mixed one and vehicle capacities are limited. In fact, if only one sector is considered, it reduces to the MCARP that is itself a NP-hard problem since it extends the capacitated arc routing problem (CARP), introduced by Golden and Wong (1981) for undirected networks.

To the best of the authors' knowledge, the local search (LS) methods suggested in this paper have never been addressed to solve the SARP. For these LS methods we propose tailored moves that favor the connectivity of the service areas. Moreover, and following the literature on what concerns evaluation measures to similar problems, we also analyze the benefits of integrating different measures for evaluating solutions during the search process. The computational results show that the generated solutions are attractive from a practical point of view.

The remainder of this paper is organized as follows. In Section 2 we review the related literature and highlight the position of this research, and in Section 3 the problem is described. The local search solution methods are detailed in Section 4. Lastly, the computational results are summarized and analyzed in Section 5 before the conclusions, which are given in Section 6.

2. Literature review

The construction of trips has been widely addressed in the literature, most of which is devoted to node routing approaches, as may be confirmed in Golden, Raghavan, and Wasil (2008), and in Toth and Vigo (2014). Extensive surveys regarding arc routing can be found in Dror (2000), Perrier, Langevin, and Campbell (2006a), Perrier, Langevin, and Campbell (2006b), Wøhlk (2008), Corberán and Prins (2010), and Corberán and Laporte (2014).

The design of sectors has been considered for multiple purposes, such as political districting (Bação, Lobo, & Painho, 2005; Bozkaya, Erkut, & Laporte, 2003), commercial territory design (Jarrah & Bard, 2012; Ríos-Mercado & Fernández, 2009; Salazar-Aguilar, Ríos-Mercado, González-Velarde, & Molina, 2012), road maintenance (Muyldermans, Cattrysse, & Van Oudheusden, 2003; Perrier, Langevin, & Campbell, 2008), meter reading (Assis, Franca & Usberti, 2014), and also waste collection (Constantino, Gouveia, Mourão, & Nunes, 2015; Hanafi, Freville, & Vaca, 1999; Lin & Kao, 2008; Male & Liebman, 1978; Mourão et al., 2009; Teixeira, Antunes, & Sousa, 2004).

Some routing problems, as those related with road maintenance or waste collection, require not only the design of sectors, but also sectors with some specific features such as connectivity and balancing. Sectors balance is a feature which is required to obtain sectors similar in size or in the workload required.

Several balance measures have been proposed, such as the ones based on: (i) trips duration (Hanafi et al., 1999; Kim, Kim, & Sahoo, 2006; Mourão et al., 2009) or on their estimates (Gonzalez-Ramírez, Smith, Askin, Miranda, & Sánchez, 2011); (ii) the length of the links serviced (Perrier et al., 2008); (iii) the quantity serviced (Male & Liebman, 1978; Mourgaya & Vanderbeck, 2007; Salazar-Aguilar et al., 2012); (iv) a relationship between quantity and traveled distance (Lin & Kao, 2008; Teixeira et al., 2004), or; (v) on the number of customers (Salazar-Aguilar et al., 2012). Despite being different, all these measures are meant to evaluate the workload assigned to each sector. Therefore, sectors balance increases to some extent the chance of a fair distribution of workload amongst the different crew teams.

Sectors balance can be promoted through different ways, namely: (i) by constraints that impose upper bounds on cost (Haugland, Ho, & Laporte, 2007), on demand (Mourgaya & Vanderbeck, 2007), or on the length of each sector (Perrier et al., 2008); (ii) by tailored evaluation functions (Assis et al., 2014; Gonzalez-Ramírez et al., 2011; Hanafi et al., 1999; Lin & Kao, 2008; Ríos-Mercado & Fernández, 2009; Salazar-Aguilar et al., 2012), or; (iii) by the solution method as a whole (Kim et al., 2006; Male & Liebman, 1978; Mourão et al., 2009; Teixeira et al., 2004).

The balancing requirement is also referenced in the routing literature that solely discusses the construction of vehicle trips. For instance, both Jozefowiez, Semet, and Talbi (2009) and Oyola and Løkketangen (2014) address the capacitated vehicle routing problem with trip balancing. In this extension of the problem, two minimization objectives are tackled: the difference between the longest and the shortest trip length, and also the usual total length.

The connectivity within each sector is related to the contiguity of its demand units (i.e. units to be serviced and usually represented by nodes or links in a network), and therefore to the possibility of reaching each other within their service area. For this purpose, some authors suggest heuristics that consider specific rules to assign demand units to sectors, which additionally favor the concentration of each service area in a geographical subregion (Hanafi et al., 1999; Haugland et al., 2007; Mourão et al., 2009; Muyldermans et al., 2003). Additionally, Constantino et al. (2015) propose exact models and heuristics to attain the concentration as well as the connectivity of the service zones.

Other authors consider connectivity explicitly as a constraint, as is the case of the local search based methods of Ríos-Mercado and Fernández (2009) and Lei, Laporte, and Guo (2012). On the other hand, the heuristic solution methods proposed by Perrier et al. (2008) consist of solving mixed integer linear programming (MILP) models in which connectivity is explicitly imposed by linear constraints.

As previously mentioned, the SARP addressed in this paper is a problem which involves simultaneously tactical and operational decisions namely, sectors design and the planning of vehicle trips. The idea is to avoid successive sub-optimization by embedding operational activity measures, or their estimates, in strategic or tactical decisions (see e.g. Salhi & Rand, 1989; Simchi-Levi, 1992; Cattrysse, Van Oudheusden, & Lotan, 1997; Ghiani & Laporte, 2001). A survey on waste management systems mainly focused on strategic and tactical issues is due to Ghiani, Laganà, Manni, Musmanno, and Vigo (2014).

A few studies combine the design of service areas with the definition of trips, as is the case of Teixeira et al. (2004), Kim et al. (2006), or Ramos and Oliveira (2011) for node routing applications, and Male and Liebman (1978), Mourão et al. (2009), or Constantino et al. (2015) for the arc routing case.

The heuristic solution approach of Teixeira et al. (2004) for a recyclable waste collection case study is a constructive three phase