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Estimating the extra costs imposed on delivery vehicles using access time windows in a city

Jesús Muñuzuri *, Rafael Grosso [1], Pablo Cortés [2], José Guadix [3]

University of Seville, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

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ABSTRACT

Analyses performed before introducing access time window policies in the center of European cities often do not evaluate the extra costs imposed on carriers from the additional number of vehicles required and increase in tour length. To facilitate this evaluation, we have developed a vehicle routing algorithm that considers the existence of access time windows and adapts tours to this restriction in the best possible manner. The procedure is based on a genetic algorithm, which we calibrate by analyzing several experiments in a test network. We then apply the algorithm to a real case study in the city of Seville, where local authorities are considering increases in the duration of the time window restriction and the size of the restricted area.

1. Introduction

Since the early 1990s, especially following the United Nations' introduction of Agenda 21, the efforts of local authorities for urban mobility have increasingly focused on sustainability (Hart, 1994), a trend that has further intensified after the Kyoto Protocol (Zegras, 2007). Energy conservation, environmental protection and reducing the need to invest in infrastructure through better planning mark the path of growth for most cities in the developed world. Urban transport policies promote using alternative transport modes by enhancing public transportation or bike lanes, and the regulations increase the pressure on private motor vehicles by restricting accessibility to the inner parts of the city, eliminating parking spaces and developing pedestrianization schemes (Anderson, Allen, & Browne, 2005).

Considering urban freight transport, and given the unfeasibility of modal shifts, local policies and regulations focus mainly on accessibility, restricting the movements of polluting or noisy vehicles or banning their access to central areas during certain time windows (Muñuzuri, Larrañeta, Onieva, & Cortés, 2005; Zunder & Ibáñez, 2004). Other previous works analyze the effect of time windows imposed by customers on urban freight deliveries (Ando & Taniguchi, 2006; Qureshi, Taniguchi, & Yamada, 2009), but our research focuses on these access time windows, which constitute a widespread policy in Europe, with most medium and large cities applying them under different configurations (Van Duin & Muñuzuri, 2006). They seek to eliminate delivery vehicles from the congested inner city areas, which are often attractive for tourists, shoppers and other visitors, during the middle of the day. These access policies also have a significant effect on freight delivery operations, as the density of commercial premises and freight deliveries is much higher in central areas. These time windows are also normally closed during daily business hours, the only time when retail freight receivers are accepting deliveries (Muñuzuri, Cortés, Guadix, & Onieva, 2012).

Local authorities introduced these access time window restrictions to respond to sustainability criteria, seeking to eliminate congestion and pollution from the central areas of cities during the most popular time of the day. However, the analyses related to these policies' introductions have failed to consider relevant input (Seasons, 2003), including the extra costs imposed on freight transport companies, forcing them to use an increasing number of extra vehicles and cover longer distances, depending on the size of the restricted area and time window duration. Sustainability is usually a combination of social, environmental and economic sustainability (Richardson, 2005), but while these access time window policies guarantee the social side of sustainability, thus benefitting residents and shoppers, this is not the case for the other two sides, at least for carriers and retailers involved in urban freight deliveries (Quak & De Koster, 2007).

We have taken this environmental and economic perspective in our analysis, seeking to estimate the additional costs imposed on carriers so that the corresponding cost-benefit analyses can

* Corresponding author. Tel.: +34 95 448 72 05; fax: +34 95 448 72 48.
E-mail addresses: munuzuri@esi.us.es (J. Muñuzuri), rgrosso@us.es (R. Grosso), pca@esi.us.es (P. Cortés), guadix@esi.us.es (J. Guadix).
[1] Tel.: +34 95 448 81 37.
[2] Tel.: +34 95 448 61 53; fax: +34 95 446 31 53.
[3] Tel.: +34 95 448 73 89; fax: +34 95 448 73 29.

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consider them (Vickerman, 2000) when introducing access time window policies. The objective is to determine to what extent access time windows affect local carrier routes and operations; this calls for formulating a specific routing problem that examines the resulting scenario. Despite constituting one of the most widespread topics in scientific literature, the list of vehicle routing problem types continues to increase, mainly due to the ever-increasing complexity of fleet management scenarios. The main concern of this paper lies in defining a complex transportation scenario, where route planning must consider the existence of access time windows to a specified area of a city.

This type of time window differs from those found in the Vehicle Routing Problem with Time Windows (VRPTW) approach in that the local authorities, not the customer, impose it. The time window is related to not only accessing the customer's premises but also the overall restricted area, forbidding delivery vehicles to cross or wait inside of it, even if no delivery operations are in progress. There is a relatively large area of the city subject to access restrictions under a predefined timetable, which transit operators must consider when planning their daily routes. We refer to this planning process as Vehicle Routing Problem with Access Time Windows (VRPATW), which combines the zonal and time factors to equally affect all customers established inside the restricted area.

Considered within the large VRP family (Laporte, 2009), operations research techniques have been increasingly applied to handle planning problems related to urban freight deliveries (Crainic, Ricciardi, & Storchi, 2004). Optimizing vehicle routing in cities, due to its specific characteristics, has usually been associated with the time-dependent vehicle routing problem (Donati, Montemanni, Casagrande, Rizzoli, & Gambardella, 2008; Malandraki & Daskin, 1992), real-time dynamic vehicle routing (Fleischmann, Gnutzmann, & Sandvoß, 2004; Gendreau, Guertin, Potvin, & Taillard, 1999) or a combination of both (Chen, Hsueh, & Chang, 2006). Also using a case-study analysis, Figliozzi (2010) assessed the influence of urban congestion on the cost of freight vehicle tours, but the research work most similar to ours can be found in two recent papers. Quak and De Koster (2009), on the one hand, analyze the influence of access time windows in a multi-town scenario using a standard VRPTW commercial software package; Conrad and Figliozzi (2010), on the other hand, estimate the effect of congestion on urban delivery route planning using a Time Dependent Vehicle Routing Problem (TDVRP) approach. We will compare our VRPATW procedure with these approaches (considering that access restrictions are equivalent to infinite congestion), showing that a specific development as described here is required when considering a single-town scenario with many customers.

For our solution approach, we have used a standard genetic algorithm to determine the effect of access time windows on fleet routing and scheduling. Though genetic algorithms remain among the best analytical tools to solve routing problems (Gendreau, Potvin, Bräysy, Hasle, & Løkketangen, 2008; Golden, Raghavan, & Wasil, 2008; Toth & Vigo, 2002), including the VRPTW (Caramia & Onori, 2008; Zhao, Wu, & Liu, 2008) and TDVRP (Duan, Yang, & Wang, 2010; Jung & Haghani, 2001), our objective here was not methodological but practical, using this algorithm simply as a tool to estimate the effects of the time window policies in cities. Algorithmically, we believe the main methodological contribution lies in computing the fitness function, designed specifically for the VRPATW characteristics.

The remaining of the paper is structured as follows. Section 2 describes the VRPATW and the different cases that may arise when evaluating a given route distribution. Section 3 describes the genetic algorithm and its applications to the VRATW, the VRPTW and TDVRP, which are then calibrated with the test problems in Section 4. Section 5 is devoted to applying these techniques to a real case study in Spain, which provides some conclusions and opportunities for further developments, discussed in Section 6.

2. Problem description

We consider our vehicle routing problem defined on a graph: $[N,L]$, where N is the set of nodes and L the set of links communicating them. N contains one node d with a positive supply level (depot), a subset C of nodes with a positive demand level (customers) and another subset $\overline{C}$ of nodes with zero levels of supply and demand, such that $N = (C \cup \overline{C}) \cup d$. A number V of vehicles (where V is a variable) travel through the graph visiting the different customers, with only one vehicle per customer. We do not consider capacity restrictions on vehicles, which is a realistic assumption for less-than-truckload urban freight deliveries, where vehicles are rarely full (Muñuzuri et al., 2005).

The problem is defined inside a predefined time horizon, corresponding to the day's working hours. The objective is to minimize the number of vehicles that must be used and the total travel distance for transporting goods from depot d to the nodes of C, crossing the necessary nodes of subset $\overline{C}$ along the way. This multiple objective is often found in VRP literature (Calvete, Galé, Oliveros, & Sánchez-Valverde, 2007). The objective function is thus: $nv\cdot(\sum_{i\in C}x_{0i} - 1) + \sum_{i,j\in C}x_{ij}\cdot d_{ij}$, where nv is a fixed cost for each additional vehicle (the first vehicle is not penalized) and x_{ij} equals 1 if a vehicle travels from node i to node j, and 0 otherwise.

We also define a set T of time costs associated with different links in the graph. These costs depend only on the transit of vehicles through links, and not on the amount of freight carried by those vehicles. In general, we incur cost t_{ij} when traveling from node i to node j. We also compute the unloading time at each customer as time cost h, incurred every time a vehicle visits a customer node contained in C. Within N, we also consider a subset RZ of nodes that correspond to the restricted zone and cannot be crossed or visited during a pre-specified closed time window period (CWT), which is obviously smaller than the overall time horizon. We finally assume that $C \cap RZ \neq \emptyset$ and $\overline{C} \cap RZ \neq \emptyset$.

The VRPATW thus differs from the classic VRPTW formulation in two main assumptions: (1) the time window is not assigned to customer nodes but to a whole RZ area of the network; and (2) in the VRPTW, time windows correspond to the time interval during which the corresponding customer can be visited, whereas the time window in the VRPATW corresponds to the time interval during which delivery vehicles are not allowed to drive or wait

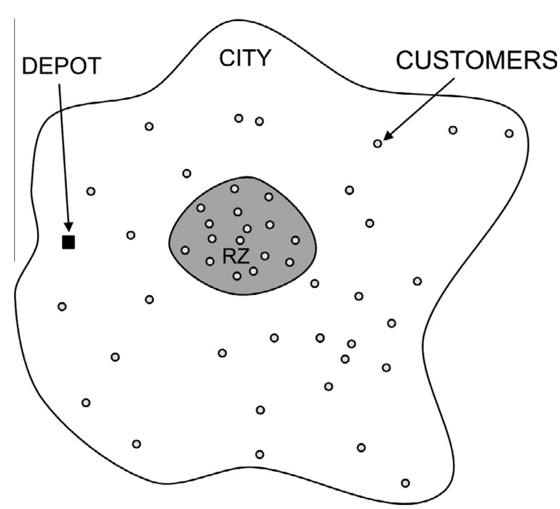

Fig. 1. Schematic representation of a city where a VRPATW applies.