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Research Article

Mathematical Formulation and Comparison of Solution Approaches for the Vehicle Routing Problem with Access Time Windows

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The application of the principles of sustainability to the implementation of urban freight policies requires the estimation of all the costs and externalities involved. We focus here on the case of access time windows, which ban the access of freight vehicles to central urban areas in many European cities. Even though this measure seeks to reduce congestion and emissions in the most crowded periods of the day, it also imposes additional costs for carriers and results in higher emissions and energy consumption. We present here a mathematical model for the Vehicle Routing Problem with Access Time Windows, a variant of the VRP suitable for planning delivery routes in a city subject to this type of accessibility restriction. We use the model to find exact solutions to small problem instances based on a case study and then compare the performance over larger instances of a modified savings algorithm, a genetic algorithm, and a tabu search procedure, with the results showing no clear prevalence of any of them, but confirming the significance of those additional costs and externalities.

1. Introduction: The Controversial Side of Sustainability in Urban Freight Policies

The last-mile link of road-based freight transport is the cause of a number of social, environmental, and economic negative impacts in many cities around the world, including traffic congestion, air pollution, noise pollution, and safety-related problems such as traffic accidents [1]. Nevertheless, life and economic activity in urban areas depend increasingly on the provision of goods and services and the elimination of the waste products generated and thus depend on urban freight transport [2]. The subsequent impacts have grown significantly over the last decades in urban areas around the world, as a result of the growth in the demand of goods by consumers and businesses [3] and the exponential growth of urban population [4]. This is why sustainable city logistics is contemplated as the solution to the problems of urban centers, with the main objective of reducing the impacts of urban freight transport without jeopardizing the social and economic needs of cities [5, 6]. The initiatives implemented by policy makers often have sustainability in the broad sense

as their ultimate goal, seeking to improve the environment (air and noise quality), secure pedestrian spaces, and prevent congestion and accidents [7].

Immersed in this scenario, one of the main research areas for city logistics over the last few years [8–11] has been the assessment of the impacts of these policies on urban areas, including the identification of the perceptions and interests of the different stakeholder groups involved in urban freight transport (citizens, residents, shippers, merchants, carriers, local authorities, etc.). The heterogeneity of those interests makes coordination and consensus very complicated when addressing specific delivery-related problems, resulting in the typical scenario where stakeholders act independently, with carriers seeking to maximize their own economic benefit (or rather minimize their own operational costs) and local authorities incorporating policies that seek to achieve the maximum possible degree of sustainability in the overall system.

Following the report issued by the Brundtland Commission [12] on Environment and Development, the concept of sustainable development has attracted worldwide attention.
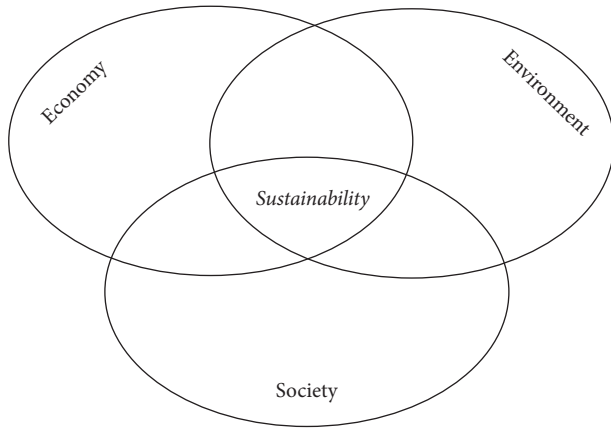
Figure 1: Representation of the three pillars of sustainability.

Sustainability has proved an enduring and compelling concept because it points in a clear and intuitive political direction and is also flexible enough to adapt to new challenges, be they technological, economic, or social. It is appealing to the general public and the scientific community in particular, as it implies a systemic view of the economy and ecology, and requires solutions that protect the interests of future generations. A deeper analysis of the sustainability concept emphasizes the fact that there coexist three different systems (see Figure 1), which can be described as environmental, economic, and social, interacting for mutual benefit or detriment within the different scenarios or activities carried out [13, 14]. This representation of the "three pillars of sustainability" includes the fact that the concept of sustainability itself is the result of interactions between three dimensions that overlap and which cannot be, or rather should not be, analyzed separately [15].

Returning to the concept of sustainability in the context of urban freight distribution, particularly in European cities, we have mentioned that local authorities and municipalities have this sustainability as the aiming point when implementing policies and measures. However, these measures usually address mainly two of the three pillars, the ones related to environmental and social sustainability. The focus on environmental sustainability seeks to reduce the emissions and pollution caused by vehicle traffic, increasing the air quality in cities with measures like the prioritization of the allocation of space to public transport or bicycle lanes. And social sustainability involves a set of purposes, such as increasing the accessibility of cities, reducing noise, increasing life quality, preserving historic centers (precisely the areas where the concentration of commercial and business premises is usually higher), and extending pedestrian areas while reducing the number of vehicles. These policies affecting urban freight transport fall mainly into six categories, defined by Stathopoulos et al. [11]:

(i) *Market-based policies* seek to modify the market prices of goods whose production and/or consumption generate negative external costs. Road pricing or the congestion ecotax is economically attractive measure and has a positive impact on traffic congestion in city centers. However, transport pricing policies require a prior understanding of the complementary, and often contradictory, roles of freight carriers and receivers.

(ii) *Land-use policies* have a major impact on freight movements within the city, as the concentration or dispersion of commercial activities has a significant effect on the streamlining of the supply, thus affecting both operators and residents.

(iii) *Infrastructural policies* are intended to promote the change of transport mode, seeking to alleviate the omnipresence of fossil-fueled, road-based transport of goods. One of the most common policies along this line is the introduction of urban distribution centers, pursuing the consolidation of freight, often with electric vehicles or bikes in charge of the final deliveries. Environmental and social sustainability guaranteed, the economic sustainability of these distribution centers depends on a delicate balance between private and public incentives, given that the expected reduction in mileage does not normally represent enough compensation for the loss of contact with customers suffered by carriers.

(iv) *Policies based on information* focus on the exchange of information between stakeholders, in order to support the planning and management of delivery routes for freight vehicles.

(v) *Management policies*, conducted by private and/or public stakeholders, are de-signed to promote some form of cooperation between carriers.

(vi) *Accessibility policies* refer to the rules and regulations applied by a control system or by local authorities. Access restrictions based on size, weight, or type of engine and access time windows are the most frequently used measures [16]. Their implementation in many European cities suggests that these accessibility regulations constitute one of the most effective ways to reduce emissions and congestion in the central areas of cities.

2. Routing for Urban Freight: Access Time Windows

In this paper, our focus is placed on this last category, particularly on the consideration of access time window policies. Widespread throughout Europe, they consist in the establishment of a period of time (between t_{CTW} and t_{OTW} in Figure 2) during which the access window is *closed* and access to a specified central area of the city is forbidden to freight delivery vehicles. This public policy, together with the restrictions imposed by the normal business hours of the receivers located inside that central area, whisks away a large part of the day, forcing carriers to adjust their routes and deliveries accordingly.

Sustainability is again the driving force behind these access time window restrictions. They free the city's central

FIGURE 2: Representation of an access time window policy along the time axis ($t = 0$ and T correspond to the start and end of the day, and t_{CTW} and t_{OTW} to the closing and opening times of the access time window, resp.).

area from the circulation of delivery vehicles during its most active part of the day, thus alleviating congestion and parking problems while avoiding high concentrations of pollutants in that sensitive area. However, while social sustainability seems to win here (since trucks are forced to use the street space only when citizen occupation is lower), some remarks are due with respect to the other two pillars in Figure 1. For instance, while this policy is likely to make the emissions caused by delivery vehicles lower *inside* the central area, the imposition of a new restriction on the planning of delivery routes will make them less efficient and longer, requiring more vehicles in the fleet, thus causing larger *overall* energy consumption and emissions. On the other hand, this also represents higher operational costs for carriers, which compromises the economic sustainability of the system.

However, the analysis and evaluation of access time window policies in European cities usually neglect these additional environmental and economic costs imposed onto the system, even though some research works have acknowledged their existence [8, 17]. Our work seeks to make a contribution towards the estimation of these costs, so that they can be incorporated to the analysis and evaluation of accessibility regulations, thus completing the sustainability scheme. Since both the environmental and economic costs are related to the configuration of delivery routes, we have developed a procedure to estimate to what extent access time windows affect carriers in their route planning process. We refer to this planning process, when subject to the time window regulations, as a Vehicle Routing Problem with Access Time Windows (VRPATW), which combines, within an operations research philosophy, the zonal and time factors affecting all the customers located inside the restricted central area of the city.

Cattaruzza et al. [18] provide a complete review of routing problems arising in city logistics, identifying four main challenges that capture the complexity of the urban environment: the consideration of time-dependent travel times [19, 20], multilevel distribution [21, 22], dynamic routing [23, 24], and multitrip routing [25]. Other recent VRP applications for urban freight include the formulation of an inverse vehicle routing approach to estimate urban delivery vehicle flows [26], or the consideration of travel times as random variables, thus formulating the routing approach in order to maximize the probability of serving customers within their assigned time windows [27].

This paper completes the work initiated in Muñuzuri et al. [17], where we presented the VRPATW as a new type of urban freight vehicle routing problem, essentially different from other city delivery approaches. Our objective here is to formulate a mathematical model for the VRPATW, to provide a benchmark for validating different solution procedures on
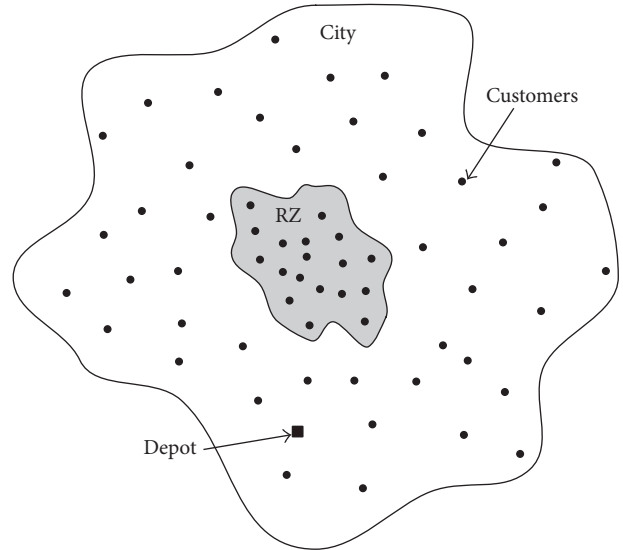

FIGURE 3: Schematic representation of a city with a restricted zone (RZ) subject to an access time window policy.

reduced-size problem instances. Also, for larger cases, we compare the performance of different solution techniques, based on heuristic and metaheuristic approaches. While the solution-building techniques are standard, the novelty of our approach is linked to the evaluation of the fitness function, which is described analytically by the formulation of the mathematical model.

3. Problem Description: The VRPATW Model

We consider a route optimization problem for a fleet of delivery vehicles in a city whose central area is subject to a time-related access restriction. We will refer to this central area as restricted zone (RZ). This RZ is under the influence of an access time window (TW) whereby access to the RZ is not allowed when the TW is closed. A time horizon corresponding to the time interval $[0, T]$ is thus defined, with all the resulting routes needing to be comprised inside, as well as two time instants, marking the start ($t_{CTW} \mid 0 < t_{CTW} < T$) and the end ($t_{OTW} \mid t_{CTW} < t_{OTW} < T$) of the closed-TW interval. The time window is then said to be open (OTW) when the time instant t is such that $t < t_{CTW}$ or $t_{OTW} < t$ and closed (CTW) when $t_{CTW} \leq t \leq t_{OTW}$. A series of customers with predefined demand are disseminated throughout the city, and we consider a single depot where all the delivery vehicles must start and end their respective routes. A fraction of the customers will be located within the RZ (in fact, the density of customers is likely to be higher inside the RZ than outside), and the delivery vehicles will therefore have to adjust their routes to the TW in order to comply with the access restriction regulations (see Figure 3). The modeling of the problem will thus have to pay special attention to the time factor, and all the costs involved in the modeling of the problem will be measured in time units.

We define the vehicle routing problem with access time windows (VRPATW) on a graph $G : [V, A]$, where V denotes
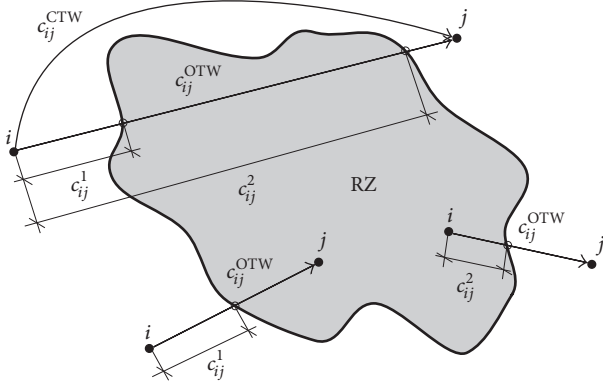
Figure 4: Cost structure of the links entering, leaving, and crossing the RZ.

the set of nodes and A the set of links. The representation of the depot uses two subsets of dummy nodes D and D', where $D = \{O_1, \dots, O_l\}$ denotes the subset of nodes where the delivery routes will start and $D' = \{O'_1, \dots, O'_l\}$ the subset where they will end, with $l > 0$ corresponding to the number of vehicles in the fleet, each vehicle having a fixed utilization cost C, the same for all the vehicles in the fleet. The set of nodes V is then defined as $V = D \cup D' \cup N$, where N is the subset of nodes with positive demand representing customer locations. Each node in the graph has a cost (measured in time units) $T_{D_i} > 0$, $\forall i \in V$, thus modeling the unloading or delivery time, which is equal to zero for the dummy nodes representing the depot ($T_{D_i} = 0 \ \forall i \in \{D, D'\}$). We also define two other subsets of nodes, Rz to include all the nodes located inside the RZ and $\overline{Rz}$ for all the nodes located outside the RZ, with $Rz \cup \overline{Rz} = V$. Given that the depot will typically be located outside the RZ, we define two additional subsets of nodes contained within $\overline{Rz}$, namely, $\overline{Rz}_o = \overline{Rz} \setminus D'$, including all the nodes from which a vehicle may start a displacement on a link towards another node, and $\overline{Rz}_d = \overline{Rz} \setminus D$, including all the nodes where the vehicle may end a displacement initiated in another node.

Each link $(i, j) \in A$ is subject to four types of displacement cost, again measured in time units (see Figure 4):

1. c_{ij}^{CTW} is the displacement cost from node i to node j while the access time window is closed.

2. c_{ij}^{OTW} is the displacement cost from node i to node j while the access time window is open.

3. c_{ij}^k with $k = \{1, 2\}$ is a cost related to the intersection of the route's path with the boundaries of the RZ, formulated as follows:

    1. $k = 1 \Rightarrow c_{ij}^1$ is the displacement cost between node i, located outside the RZ, when the route enters the RZ on its way towards node j, located inside. The parameter value $k = 1$ represents the fact that the route is "entering" the RZ.

    2. $k = 2 \Rightarrow c_{ij}^2$ is the displacement cost between node i, located inside the RZ, when the route

leaves the RZ on its way towards node j, located outside. The value $k = 2$ represents the fact that the route is "leaving" the RZ.

The last term considered in the model is the binary parameter $p_{ij} = \{0, 1\}$, which takes value 1 when the link crosses the RZ, that is, $p_{ij} = 1 \Leftrightarrow c_{ij}^1 \geq 0$ and $c_{ij}^2 \geq 0 \ \forall i \in \overline{Rz}_o$ and $\forall j \in \overline{Rz}_d$. The value of p_{ij} is 0 otherwise. Following all the above, the VRPATW can be represented by the following mathematical model:

$$\text{Minimize:} \quad \sum_{i=1}^{l} \left(s_{O'_i} - s_{O_i} \right) + C \sum_{i \in D} \sum_{j \in N} x_{ij} \tag{1}$$

$$\text{Subject to:} \quad \sum_{\substack{i \in D \cup N \\ i \neq j}} x_{ij} = 1, \quad \forall j \in D' \cup N \tag{2}$$

$$\sum_{\substack{j \in D' \cup N \\ i \neq j}} x_{ij} = 1, \quad \forall i \in D \cup N \tag{3}$$

$$
\begin{aligned}
s_i &+ T_{D_i} \\
&+ p_{ij} \left[c_{ij}^{\text{CTW}} \delta_{ij} + c_{ij}^{\text{OTW}} \left(1 - \delta_{ij} \right) \right] \\
&+ c_{ij}^{\text{OTW}} \left(1 - p_{ij} \right) - B \left(1 - x_{ij} \right) \leq s_j, \\
&\forall (i, j) \in \left(D \cup N, D' \cup N \right), \ i \neq j
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
s_i + T_{D_i} + c_{ij}^{\text{OTW}} &\geq s_j - B \left(1 - x_{ij} \right), \\
&\forall (i, j) \in (Rz, Rz), \ i \neq j
\end{aligned}
\tag{5}
$$

$$s_i \leq T, \quad \forall i \in D' \tag{6}$$

$$
\begin{aligned}
s_i &\leq t_{\text{CTW}} + B\alpha_{ij}^{k2}, \\
&\forall (i, j) \in \left(Rz, \overline{Rz}_d \right), \ k = 2, \ p_{ij} = 0, \ i \neq j
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
s_i &\geq t_{\text{OTW}} - B\alpha_{ij}^{k1}, \\
&\forall (i, j) \in \left(Rz, \overline{Rz}_d \right), \ k = 2, \ p_{ij} = 0, \ i \neq j
\end{aligned}
\tag{8}
$$

$$
\begin{aligned}
s_j &\leq t_{\text{CTW}} + B\alpha_{ij}^{k2} \\
&\forall (i, j) \in \left(\overline{Rz}_o, \overline{Rz}_d \right), \ k = \{1, 2\}, \ p_{ij} = 1, \ i \neq j
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
s_j &\geq t_{\text{OTW}} - B\alpha_{ij}^{k1} \\
&\forall (i, j) \in \left(\overline{Rz}_o, Rz \right), \ k = 1, \ p_{ij} = 0, \ i \neq j
\end{aligned}
\tag{10}
$$

$$s_i + T_{D_i} + c_{ij}^k = f_{ij}^k \tag{11}$$

$$
\begin{aligned}
f_{ij}^k &\leq t_{\text{CTW}} + B \left(1 - x_{ij} \right) + B\alpha_{ij}^{k2} \\
&\forall (i, j) \in \left(\overline{Rz}_o, \overline{Rz}_d \right), \ k = \{1, 2\}, \ p_{ij} = 1, \ i \neq j
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
f_{ij}^k &\geq t_{\text{OTW}} - B \left(1 - x_{ij} \right) - B\alpha_{ij}^{k1} \\
&\forall (i, j) \in \left(\overline{Rz}_o, Rz \right), \ k = 1, \ p_{ij} = 0, \ i \neq j
\end{aligned}
\tag{13}
$$

$$\alpha_{ij}^{k1} + \alpha_{ij}^{k2} \leq 1 + \delta_{ij} p_{ij}$$

$$\forall (i, j) \in \left(Rz, \overline{Rz_d} \right), \ k = 2, \ p_{ij} = 0, \ i \neq j \tag{14}$$

$$\alpha_{ij}^{k1}, \alpha_{ij}^{k2}, \delta_{ij}, x_{ij} \in \{0, 1\} \tag{15}$$

$$s_i, f_{ij}^{k} \geq 0. \tag{16}$$

Variable s_i represents the time instant when a delivery vehicle reaches node i, and x_{ij} is a binary decision variable that is set to 1 when a vehicle travels from node i to node j and to 0 otherwise. The objective function (1) seeks to minimize the overall route duration and the use of additional vehicles. The first term corresponds to the sum of the different route durations, and the second one penalizes the use of each vehicle with the fixed cost (measured in time units) $C \gg T$. The two first restrictions (2) and (3) are typical VRP formulations, forcing that exactly one vehicle enters and leaves each node. Restriction (4) forces that the instant of arrival to node i, plus the delivery time T_{D_i}, plus the corresponding travel cost (the binary parameter p_{ij} and the binary variable δ_{ij} lead to the addition, depending on the case, either of c_{ij}^{CTW} or of c_{ij}^{OTW}) is smaller or equal to the instant of arrival to the next node j in the route. The fixed value $B \gg T$ is used to impose the restriction only when node j follows node i in any one of the delivery routes. Restriction (5) complements the previous one, ensuring that the path followed between two nodes within Rz is as short as possible and uses the travel cost c_{ij}^{OTW} for its calculation. Restriction (6) ensures that all the routes end within the established time horizon. With respect to restrictions (7) and (8), they ensure that the arrival instant to a node $i \in Rz$, when the route is then bound for another node $j \notin Rz$, does not interfere with the TW. The auxiliary binary variables α_{ij}^{k2} and α_{ij}^{k1} control whether the displacement between nodes i and j interacts with the RZ or not. Restrictions (9) and (10) impose two different requirements. On one hand, the arrival instant to a node $j \in Rz$ when coming from another node $i \notin Rz$ must correspond to the OWT, and, on the other, when a route crosses the RZ travelling from node $i \notin Rz$ to node $j \notin Rz$, the access restriction during the TW must hold. Restriction (11) is included in the model for a better comprehension of the following restrictions and is used to define the f_{ij}^{k} variables, which represent the time instant when route k enters or leaves the RZ, should either case occur. Restrictions (12) and (13) guarantee that routes entering or leaving the RZ are compliant with the TW restriction and also allow the vehicle to wait just outside the boundaries of the RZ until the TW is open in order to continue its route. Finally, restriction (14) relates all the auxiliary binary variables with the binary parameter. If a route crosses the RZ and the TW closes sometime during that displacement, this restriction ensures that the vehicle is not inside the RZ during the CTW interval, forcing the time instant f_{ij}^{k} to be located outside that interval.

The first term of the objective function (see (1)) corresponds to the sum of route durations (arrival time minus departure time) for all the vehicles in the fleet. With respect to the second term, when a given vehicle leaves its origin node (contained in subset D), it can move towards another node in D' or in N. In the first case, the vehicle will follow a "virtual" route, which means it will not be used in practice, and the minimization of the objective function will cause its arrival time to be equal to its departure time. In the second case, the vehicle will follow a "real" route, visiting that customer in N and possibly other customers afterwards. By computing the sum of all the arcs leaving D nodes towards N nodes, we are computing the number of vehicles following "real" routes, that is, the number of vehicles being effectively used. This number is then multiplied by the fixed cost C to account for the fact that the solution should include the smallest possible number of "real" routes. Since the restrictions force that all the customer locations must be visited, the objective function will therefore determine the set of routes that (a) use the smallest possible number of vehicles and (b) are as short as possible.

4. Soft-Computing Solution Approaches

This section describes the heuristic and metaheuristic procedures implemented to solve large instances of the VRPATW, indispensable given the NP-hard nature of the problem. This includes, in the first place, a modification of the Clarke and Wright savings algorithm, followed by a genetic algorithm and a tabu search method. A description of each procedure will be provided under the following headings. It is worth noting that the three procedures use the same fitness function, corresponding to the objective function (1) of the mathematical model described in the previous section. The fitness function is evaluated following the procedure represented in Figure 5, which is thoroughly described in Muñuzuri et al. [17].

4.1. Modified Clarke and Wright Savings Procedure. In search for a fast heuristic method to solve the VRPATW, we adapted the classical Clarke and Wright savings algorithm (Clarke and Wright, 1964), originally applicable to the VRP. The modified procedure works generating two sorted lists of customer pairs. The first one (C&WList$_{\text{OTW}}$) is sorted in descending order of the potential saving attained in the overall route length when sequencing each customer pair during the open time window period. And the other one (C&WList$_{\text{CTW}}$) is sorted in the same fashion, but for the closed time window period. The algorithm starts by calculating the lists, generating an empty solution and inserting in it the first pair of customers from C&WList$_{\text{OTW}}$. The fitness function is then used to evaluate that partial solution, and the process continues with the sequential insertion of customers and evaluations until the solution is complete. The reevaluation of each partial solution after a new insertion is carried out in order to determine whether the next insertion will correspond to C&WList$_{\text{OTW}}$ or to C&WList$_{\text{CTW}}$. Once the solution is built using this greedy approach, further improvements are explored through the application of the local search operators 2-*opt*, 3-*opt*, *Or-opt*, and *Relocate* [28–30].
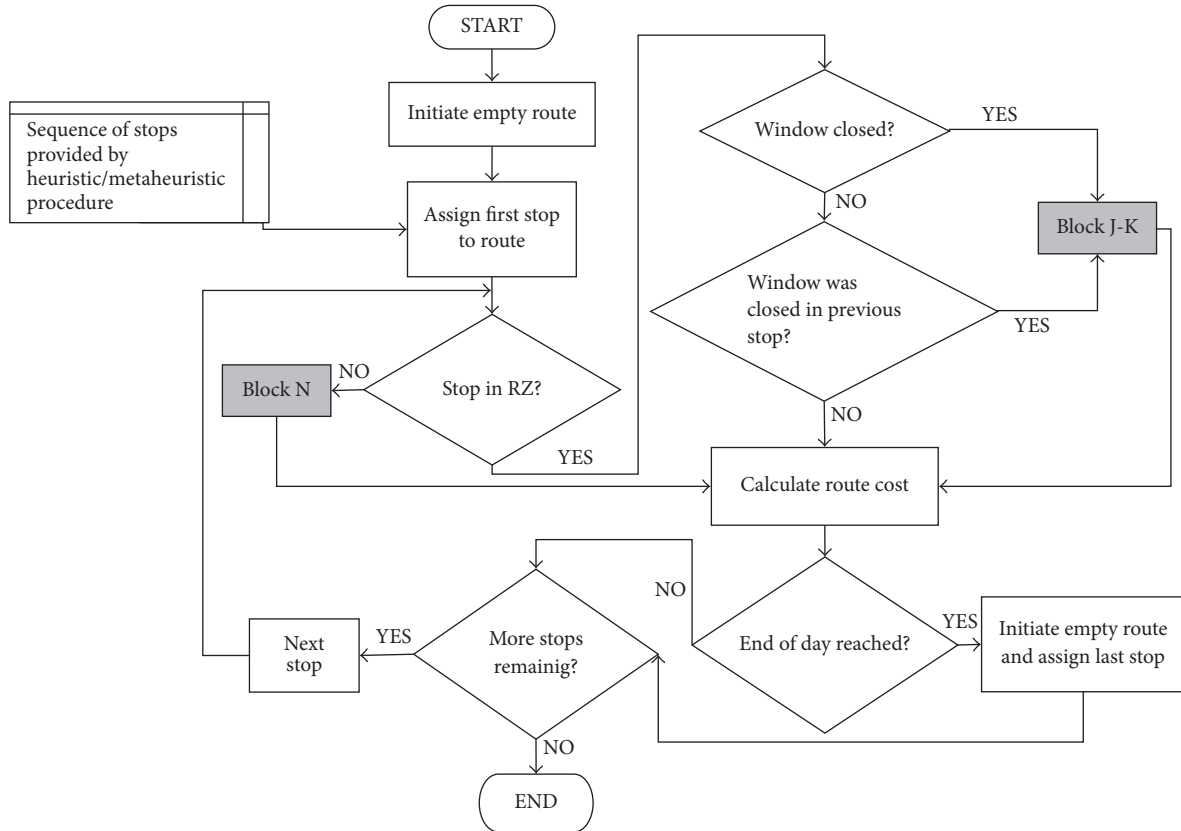
FIGURE 5: Schematic representation of the evaluation process for the fitness function used in the three soft-computing implementations.

4.2. Genetic Algorithm. The main features of this algorithm, similar to the one applied in Muñuzuri et al. [17], can be briefly described as follows:

(i) The initial population being generated randomly

(ii) Crossover: typical single-point crossover operator

(iii) Mutation: random selection and exchange of two stops in the sequence

(iv) Selection: following a roulette-based methodology

(v) Population restart: when the best fitness value being less than 5% below the average fitness value, keeping only the best individual in the population

(vi) The stopping criterion being only associated with the number of iterations

(vii) The process incorporating a local search routine at the end, seeking potential improvements that may have escaped the iterations of the genetic algorithm. This local search process again combines the *2-opt*, *Or-opt*, *3-opt*, and *Relocate* operators.

4.3. Tabu Search. Following its good performance when compared to other metaheuristics applied to the VRP, we tested a tabu search (TS) procedure to solve the VRPATW. These previous results [31, 32] prove the capabilities of this metaheuristic to solve all the VRP variants, obtaining good results in terms of solution quality and computational times.

Nevertheless, the VRPATW is different to other VRP categories in the sense that the same route segment may be extremely beneficial or costly, depending on its position within the overall route. It is therefore unclear whether the best metaheuristics for solving VRP instances will also perform best when applied to the VRPATW, which led us to undertake and test the implementation of this TS procedure.

Our TS algorithm follows a typical structure, with the initial solution determined using a greedy nearest-neighbor heuristic. The neighborhood space in the TS procedure was then defined as the exchange of positions of any two customers in the route. In each iteration, all the customers in the current solution (cs) are swapped pairwise, and the best new solution (bns) is stored. If this bns improves the best solution found so far (bs), then bs is updated. The tabu list (Tlist), following the neighborhood criterion defined, stores the customers that were swapped in the last iteration. The permanence of these movements in Tlist, or short-term memory, depends on the number of iterations T_{mx} completed since they entered the list.

As we mentioned before, the characteristics of the VRPATW may cause the swapping of two customers in the solution to result in significant alterations of the objective function *(fitness)*. These significant alterations will in general disturb the process of route length minimization, but they may also help to find unexpected improvements to the current solution. This is why we incorporated an aspiration

criterion to allow tabu swaps as long as they improve the overall best solution bs.

The long-term memory of the TS procedure uses a record of the frequency of occurrence of the different customer swaps (fTl). When the algorithm fails to find improvements to the solution during a fixed number of iterations (M_m), it moves towards alternative search paths, swapping the pairs of customers with lower involvement frequencies. This helps to diversify the search process. If this also fails, the secondary long-term memory process restarts the solution randomly, while keeping the best solution found so far bs. This restart is carried out a fixed number of times depending on the size of the problem (N_{lm}). Finally, the stopping criterion is simply related to the maximum number of iterations (It_m), and a local search procedure is also applied thereafter.

5. Results of the Application to a Case Study

We applied the above methodologies to different problem instances based on the same case study presented in Muñuzuri et al. [17]. It stems from the operation of a small-size carrier based in the Spanish city of Seville, currently subject to an access time window restriction, and assumes an average 20 km/h speed for the vehicles, a 20-minute unloading time at each customer, and a time horizon of 10 hours. The 60 problem instances tested were defined by the following parameter values:

(i) Number of customers (No. C): ranging from 10 to 150

(ii) Size of the restricted zone (RZ): 1.1, 1.6, and 2 km radius

(iii) Length of the closed time window period (CTW): 2, 4, and 6 hours.

The prior calibration of the genetic algorithm and the tabu search resulted in the following parameter values:

(i) For the genetic algorithm,

    (a) population size is 2 · number of customers;

    (b) maximum number of iterations is 6 · number of customers;

    (c) probability of mutation is 0.5.

(ii) For the tabu search,

    (a) maximum number of iterations is 150;

    (b) length of the tabu list is 5 for instances up to 25 customers and 7 for larger instances;

    (c) number of random restarts is 2 for instances up to 25 customers and 4 for larger instances;

    (d) maximum number of iterations the algorithm can run without improvement of the best solution found (which activates the random restart) is 10.

For each number of customers, we also tested the base scenario with no access time window restriction, since the comparison of the other solutions with this base scenario provides
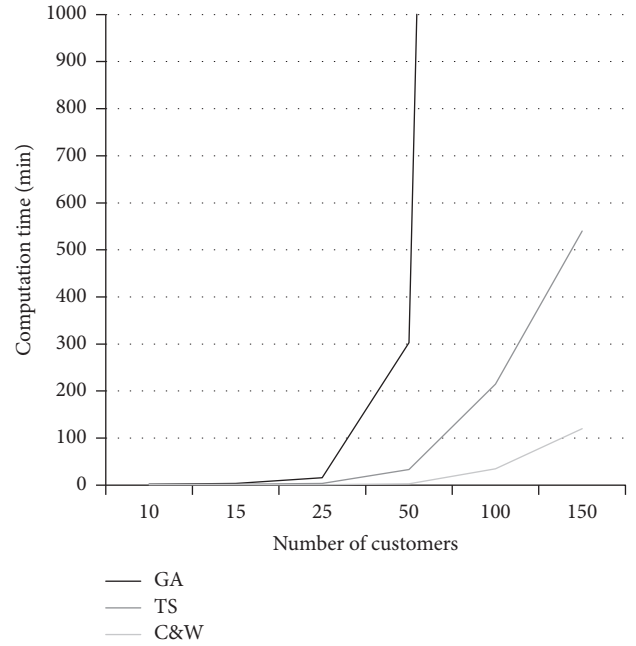

Figure 6: Computation times depending on the number of customers for the three soft-computing methods implemented.

the increases in route length generated by the regulation. We also solved the group of instances with 10 customers using the mathematical model and the Gurobi optimizer to obtain the exact optimal solution in around 2 hours using a 2.40 GHz CPU with 8 GB RAM. Larger instances could not be solved via the model in over a week, and we applied only the soft-computing methods. Figure 6 shows their computation times, with the GA requiring over 5 days for the largest problem instances, and Table 1 summarizes the description and the results obtained for each one of the 60 problem instances.

These results are not conclusive in terms of the best solution method, which goes alongside the results obtained by Figliozzi [33] for the time-dependent VRP, where no solution technique could be identified as prevalent. The genetic algorithm obtains slightly better results in most of the problem instances, but it also requires larger computational times. In any case, the increase in total route length with respect to the base scenario is clear and correlated with the size of the restricted zone and the duration of the time window restriction, in all the problem instances.

6. Conclusions

The implementation of urban freight policies aimed at increasing sustainability in the movement of freight in cities needs to take into account all the externalities and costs involved. In particular, access restriction policies usually result in longer and more inefficient routes, which in turn imply higher energy consumption and emissions and higher operational costs for carriers. Needless to say, this is so because freight needs to keep entering the city center and will keep doing it despite the regulatory barriers.

Within this scenario, operations research can help city planners to estimate the additional costs imposed on carriers

TABLE 1: Results obtained from the application of the different solution methodologies to 60 problem instances of the case study. For each case, the total route length (Fitness), measured in km, and the number of vehicles required (No. V) are shown.

Problem instance	No. C	RZ	CTW	GA + LocalS		TABU + LocalS		C & W		EXACT	
				Fitness	No. V	Fitness	No. V	Fitness	No. V	Fitness	No. V
1		0	0	112.02	1	112.02	1	112.02	1	112.02	1
2			2	112.02	1	112.31	1	112.31	1	112.02	1
3		1.1	4	112.31	1	112.59	1	113.35	1	112.31	1
4			6	113.92	1	114.68	1	114.95	1	113.92	1
5	10		2	112.02	1	112.02	1	112.02	1	112.02	1
6		1.6	4	112.71	1	112.59	1	113.84	1	112.59	1
7			6	142.74	1	142.82	1	142.74	2	142.74	1
8			2	112.02	1	112.02	1	112.02	1	112.02	1
9		2	4	123.84	1	123.07	1	123.07	1	122.90	1
10			6	171.16	2	171.18	1	190.72	2	171.16	2
11		0	0	140.91	1	141.51	1	141.51	1	-	-
12			2	141.51	1	141.60	1	141.90	1	-	-
13		1.1	4	141.09	1	142.16	1	143.21	1	-	-
14			6	145.30	1	145.62	1	145.38	1	-	-
15	15		2	141.51	1	142.81	1	145.38	1	-	-
16		1.6	4	143.23	1	144.26	1	160.59	2	-	-
17			6	178.28	2	191.10	2	194.50	2	-	-
18			2	140.91	1	141.09	1	142.84	1	-	-
19		2	4	146.60	1	146.60	1	161.69	2	-	-
20			6	285.30	2	286.31	2	288.83	2	-	-
21		0	0	258.41	2	259.22	2	262.43	2	-	-
22			2	261.13	2	260.24	2	266.93	2	-	-
23		1.1	4	262.43	2	261.09	2	267.20	2	-	-
24			6	262.11	2	271.47	2	270.22	2	-	-
25	25		2	262.27	2	261.40	2	261.76	2	-	-
26		1.6	4	264.09	2	262.30	2	269.33	2	-	-
27			6	296.74	2	279.92	3	291.02	3	-	-
28			2	262.34	2	267.23	2	266.13	2	-	-
29		2	4	265.75	2	264.37	2	263.53	2	-	-
30			6	349.20	3	348.61	3	355.37	3	-	-
31		0	0	431.88	3	437.66	3	440.17	3	-	-
32			2	436.19	3	439.33	3	441.17	3	-	-
33		1.1	4	440.11	3	443.67	3	440.00	3	-	-
34			6	456.31	3	460.35	4	466.03	4	-	-
35	50		2	434.24	3	450.76	3	458.13	4	-	-
36		1.6	4	455.52	4	442.82	3	441.76	3	-	-
37			6	493.28	4	487.21	4	505.97	4	-	-
38			2	434.92	3	460.91	4	441.56	3	-	-
39		2	4	462.90	4	447.95	3	456.84	4	-	-
40			6	582.30	4	582.54	4	529.31	5	-	-
41		0	0	815.26	6	815.86	6	824.80	6	-	-
42			2	816.61	7	819.85	6	831.22	6	-	-
43		1.1	4	829.60	5	822.49	6	826.20	6	-	-
44			6	880.40	6	819.31	6	825.63	6	-	-
45	100		2	818.87	7	819.31	6	830.43	6	-	-
46		1.6	4	825.67	5	820.91	6	846.21	6	-	-
47			6	867.60	7	883.49	7	871.02	6	-	-
48			2	848.01	6	836.33	6	835.89	6	-	-
49		2	4	837.73	6	826.64	6	829.88	6	-	-
50			6	849.74	7	898.83	7	904.07	7	-	-

Table 1: Continued.

Problem instance	No. C	RZ	CTW	GA + LocalS		TABU + LocalS		C & W		EXACT	
				Fitness	No. V	Fitness	No. V	Fitness	No. V	Fitness	No. V
51		0	0	1182.84	9	1178.55	8	1182.32	8	-	-
52			2	1205.06	8	1187.28	8	1201.28	8	-	-
53		1.1	4	1215.46	9	1195.82	8	1192.61	8	-	-
54			6	1194.15	8	1196.74	8	1205.90	9	-	-
55	150		2	1175.64	8	1187.14	8	1188.03	8	-	-
56		1.6	4	1200.33	9	1210.41	9	1212.68	9	-	-
57			6	1235.71	9	1242.38	9	1247.60	9	-	-
58			2	1218.46	9	1241.43	9	1233.53	9	-	-
59		2	4	1238.07	9	1270.76	9	1219.46	9	-	-
60			6	1247.47	9	1280.62	10	1302.50	10	-	-

and can also help those carriers to optimize their routes when they are affected by access time windows in a city. We have presented here the mathematical model for the vehicle routing problem with access time windows, which conceptualizes the problem and sets the basis for building solution techniques. The direct application of this mathematical model is nevertheless limited to small problem instances, so we have tested and compared three soft-computing methodologies, showing that the decision maker needs to choose between computational time and solution quality. Still, the application of these soft-computing methods to the smaller problem instances of our case study and the fact that they either find the optimal solution or reach a very close one confirm their soundness, and their subsequent application to larger problems provides a quantification of the extra costs imposed on carriers by access time window regulations.

Our work provides a framework for the evaluation of access time window implementations, and thus opens the door to further developments of this measure. For example, upon gaining better knowledge and understanding of those additional costs, carriers might be willing to pay in order to be allowed to deliver in the restricted zone outside the prespecified period, providing better service to their customers and reducing their costs at the same time.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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