Unveiling Key Parameters: Time Windows and Travel Times in Capacitated Waste Collection

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Abstract. Numerous studies in waste management propose solutions to the Waste Collection Problem, often focusing on constraints such as time windows and truck capacity. Travel times between points play a vital role in optimizing waste collection. However, the methods for determining them are frequently omitted. Another parameter that has a great influence on waste collection is the time window. Here, the impact of time windows and travel times on the capacitated waste collection problem with time windows solution was assessed for collecting three waste types. Surprisingly, travel times were found to have minimal influence on route optimization, while time windows significantly affected the algorithm's ability to identify the most efficient collection route. Addressing these considerations is crucial for practical application and improving the performance of waste collection algorithms in real-world contexts.

Keywords: Vehile Routing Problem · Metaheuristics · Recycling

1 Introduction

The 21st century is known as the information era, with significant developments and changes in how citizens consume goods worldwide [12]. Physical borders nowadays are being overcome by digitalization and globalization, with people

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having access to international markets and consuming more as a consequence of the great number of options and strong merchandising [18]. For instance, waste generation is one main sector impacted by increased consumption of goods [2]. High-income countries have some technologies to deal with their waste generation impacts, but low and middle-income countries are currently facing serious waste management problems [22]. The impact of the bad waste management system on human health and the environment is often neglected by authorities, leading to severe sanitation problems in developing countries [21]. In this scenario, sustainability has become paramount to guaranteeing a safe environment for future generations [19].

In our modern society, "sustainability" has become a word often heard in political speeches, companies praising their production system as sustainable, and other situations [11]. With such mention, the word starts losing its real impact in our lives, becoming so usual to be heard that it is neglected. Even in the literature, one can find a diverse number of studies evaluating the sustainability of a determined system. Still, the real definition of sustainability is neither presented nor differs according to the motivation. With this in mind, Moore *et al.* have published a study devoted to analyzing the real meaning of sustainability to guide future studies [9]. The authors analyzed 209 articles mentioning sustainability and enumerated the key concepts of sustainability "(i) after a defined period of time, (ii) a program, clinical intervention, and/or implementation strategies continue to be delivered and/or (iii) individual behavior change (*i.e.*, clinician, patient) is maintained; (iv) the program and individual behavior change may evolve or adapt while (v) continuing to produce benefits for individuals/systems". In other words, sustainability involves a concept that is not only based on respecting the economic, social and environmental pillars. It also involves an evolution of the initial proposal to follow and adapt according to the needs.

Sustainable solutions to waste management problems must consider future developments and ensure the initial proposed efficiency will keep the expected level. Several opportunities exist to explore optimization strategies in the municipal solid waste management system. The system is complex and divided into several steps, from discarding the waste on fixed dumpsters or household bins (depending on the system) to the final disposal [17]. In this system, waste collection is a task that consumes a considerable amount of resources and has a great impact on cities. Delayed garbage collection can cause health problems for humans by attracting wildlife, which in turn can spread diseases [16]. In most cases, the waste collection is carried out with pre-scheduled routes and collection days defined without optimization or even leaving the driver's decision [13]. The low amount of resources invested in this sector makes it difficult for the agencies in charge to improve the operations, leading to inefficiency in fuel expenses and increased operational costs. For instance, the collection cost can consume up to 60% of the company's budget [17]. In this regard, the sector could benefit from information and communication technologies to find feasible and cost-effective alternatives to improve their overall operation.

One of the possible alternatives to improve the waste collection operation is using algorithms to help decision-makers decide on the route to perform the waste collection [8]. The algorithm usually solves a problem modeled to represent the waste collection scenario. Several formulations have already been reported in the literature, most considering the waste collection problem as a vehicle routing problem with specific constraints related to the waste collection operation [8]. At first, the formulations were considering only distances to be optimized. However, increasing the formulation's similarity with real life has motivated researchers to include other objectives in their problems, such as environmental ones [1]. Despite the interesting solutions developed and presented in the literature, most studies are focused on modeling capacity as a constraint, ignoring other possible considerations in their formulation. For instance, time windows are extremely important when searching for optimization possibilities in route planning. When the authors consider time windows, it is unclear if travel times were calculated considering trucks traveling rather than regular cars. Additionally, time windows chosen to perform the task are not feasible (*i.e.* no lunch break or rest times).

In this context, the present paper is devoted to solving the Capacitated Waste Collection Problem with Time Windows (CWCPTW) using the finest metaheuristic algorithm available in Google OR-Tools, Guided Local Search (GLS) [14]. The solution was explored considering the simultaneous collection of the three waste types for the selective collection in Bragança, located in the northeast region of Portugal (paper, glass, and plastic waste). The influence of time windows and travel times were explored in the algorithm's performance to solve the problem. To do so, two time windows were selected: one considering only commercial hours and another considering commercial hours with lunch and rest breaks. Travel times were tested as obtained from Google Maps API and adjusted to the truck's travel times based on the literature [10]. The rest of the paper is organized to present the related literature in Sect. 2, the methodology used to carry out the work in Sect. 3, the results and discussion in Sect. 4, and the conclusion and future work in Sect. 5.

2 Literature Review

The nomenclature "waste collection problem" is not yet used in most papers dealing with the application of vehicle routing problems for waste collection. For this reason, to gather the most relevant literature for this study, papers with the keywords "vehicle routing problem", "waste," "time windows," and "capacity" were searched in the Web of Science search engine. The 135 papers found in this thematic were used to evaluate the current literature and developments and identify possible innovative research paths. The word cloud with the most used keywords amongst the published studies is shown in Fig. 1.

The word cloud is a fast way to analyze the field, observing the most common approaches to solve the waste collection problem under the desired constraints. For instance, several keywords refer to a specific algorithm or a class of algorithm, such as "genetic algorithm", "heuristic", and "metaheuristic". The next sections will briefly review the most recent formulations and algorithms.



Fig. 1. Word cloud of most relevant keywords amongst published studies. The size is proportional to the word count.

In general, Vehicle Routing Problems (VRP) are a family of problems devoted to finding the best solution to various logistic situations involving the assembly of delivery routes for trucks to serve all the customers with a given demand. In this family, capacity constraints are the most traditional, with the formulation of the Capacitated Vehicle Routing Problems well studied in the literature for a wide range of applications. Another constraint that is rather important to evaluate the viability of the solution in real scenarios is the time window. This constraint is often combined with capacity constraints to increase the complexity of the problem, arising the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW). The VRP has already been explored for several real-life applications [15]; however, due to the great development of these problems in the waste collection strategy, a new variant of VRP, the Waste Collection Problems (WCP), arose in the literature. These problems are similar to the VRP family. Still, the variants have other considerations and concerns intrinsic to the waste collection task, such as right-turn constraints, obnoxious effects, multi-compartment trucks, residential waste, fixed station waste, and more- [8].

Similar to the VRP, in most WCP, the vehicles have a limited and fixed capacity and can be rather homogeneous or heterogeneous. Considering the different needs according to the collected waste type, the fleets are heterogeneous in most cases. The same objective of distance shortening is the objective in these problems, leading to the reduction of costs and emission of gases. Also, most studies explore the possibility of using the smallest number of vehicles to perform the waste collection task [6]. The main difference between VRP and WCP relies on the possibility of visiting the central depot multiple times on the latter due to the specificity of the waste collection task. The truck will only return to the central depot to park if the customers are all served or if some constraint would be violated by continuing the collection (*e.g.* time windows). The algorithms class used to solve these problems can range from linear programming to evolutionary algorithms [3,20]. The literature has reached the consensus that exploring exact solutions is not feasible due to the extremely high execution time faced in those

cases since the problem is classified as NP-hard, meaning the problem potentially takes exponential time to solve and has no known polynomial-time solution. In recent years, metaheuristic algorithms have effectively found acceptable solutions to WCP within a feasible execution time.

The formulations created in the waste collection problem are diverse and can include not only the waste collection but also the waste transference from one point to another (*i.e.*, taking the waste from the central depot to interested stakeholders). There is also several studies devoted to exploring the transportation of specific waste types. Zhang *et al.* [24], for example, studied the development of a search algorithm, Variable Neighborhood Search in that case, to solve the multi-cycle medical waste recycling problem. The authors explained that medical waste recycling is traditionally performed by collecting the waste at determined sites and returning it to the recycling site, which involves two main decision variables. The first is the service time in medical facilities, which will depend on the number of clients and the time windows available. The second important decision is to assign the vehicles to the routes for medical waste collection within a service time cycle. The authors classified medical facilities with coefficients 1 and 2 to optimize these tasks. Suppose the institution requires daily visits due to large medical waste production. In that case, the frequency is considered to be 2 as coefficient. In contrast, if the institution does not produce a large amount of medical waste, the frequency is 1, and collection can be performed any day of the cycle. In this scenario, the vehicle leaves the central depot to collect medical waste from the medical institutions and travels back to the central depot. The route is planned to collect all institutions with frequency 2 and the possible ones with frequency 1 if time windows are respected. The Variable Neighborhood Search algorithm proposed by the authors to solve the medical waste problem consists of two stages. The first stage involves building the initial solution using the Clarke-Wright algorithm. The second stage will improve the initial solution based on the variable neighborhood search algorithm combined with the simulated annealing algorithm. Combining two search strategies to improve the initial solution is the main feature of this paper, taking advantage of different search mechanisms to build a robust and optimized solution.

Another example of formulation for waste collection, including time windows, was presented by Zhang *et al.* [23]. In this paper, the authors have created a formulation called Collection Vehicle Routing Problem of the Garbage Facilities. The initial formulation is than transformed to another one, the Vehicle Routing Problem with Simultaneous Pickup and Delivery and Time Windows. Transforming the problem from the initial formulation to the last one was adopted as a strategy to decrease the computational complexity and find a feasible solution to the problem. The initial formulation includes a problem in which the garbage facility serves as the collection point, with sufficient empty containers. The waste collection trucks will collect the waste from residential areas and take it to the garbage facility. Once the containers in the garbage facility are loaded, the trucks can take them to the transfer station and return the empty containers to the garbage facility. The vehicles should return to the garbage facility and exchange

the empty container for a fully loaded one. Once the working day finishes, the vehicles must return to the yard (parking station). To transform the problem and decrease its computational complexity, the authors used dummy customers, such as those performed in other works dealing with VRP variant solutions [5]. Two dummy customer types are used: the first represents garbage facilities with different time windows and pickup tasks. The second is the dummy customer representing the transfer station, with time windows and delivery tasks. The strategy used by the authors converts the multiple trips for delivery and pickup into a circular path starting from the yard and eventually returning to it. The authors solved the problem using a parallel simulated annealing algorithm developed using mixed integer programming formulation.

There are more studies reported in the literature with different approaches to finding the optimal path to perform the waste collection task using time windows as a constraint. In most cases, the authors devote a significant amount of effort to increase the complexity of the problem but do not evaluate the feasibility of their solution based on realistic time windows or algorithm execution times. Time windows are created to improve the system's efficiency in finding optimal and cheapest paths, sometimes not considering the driver's needs to rest, considering only lunch breaks. Sometimes, the authors only validate their algorithm using datasets, not real locations, or even consider Euclidean distances between points to optimize routes. Furthermore, in most cases, there is little information on how the authors calculate the travel times between points, which is also crucial considering the time window constraint.

3 Methodology

This paper aims to evaluate the solution to the CWCPTW using GLS, the finest metaheuristic algorithm available in Google OR-Tools. The system studied here comprises 50 sets of 3 dumpsters each, used for the selective waste collection in the city of Bragança, located in the northeast region of Portugal. Dumpster locations were provided by the company in charge of MSWMS, Resíduos do Nordeste (see www.residuosdonordeste.pt). The route optimization was performed considering the daily waste level inside dumpsters and the number of trucks available to collect each waste type (provided by the company). The waste generation was modeled considering the approximate population density around the dumpster location, which is reported to influence waste generation significantly [4]. The time windows necessary to perform the waste collection task in this scenario were defined based on the working hours in Portugal (9 a.m. to 7 p.m.), considering lunch breaks as well (12 p.m. to 2 p.m.) and also resting hours (5 p.m. to 6 p.m.). Experiments with route optimization were also performed using a time window that consider only the working hours, with no lunch breaks or rest times. The service time in each dumpster was considered 3 min, based on information provided by the company. The routes were planned for the simultaneous collection of the three waste types. It is important to highlight that a determined truck will only collect one type of waste. The general representation of the work performed is illustrated in Fig. 2.

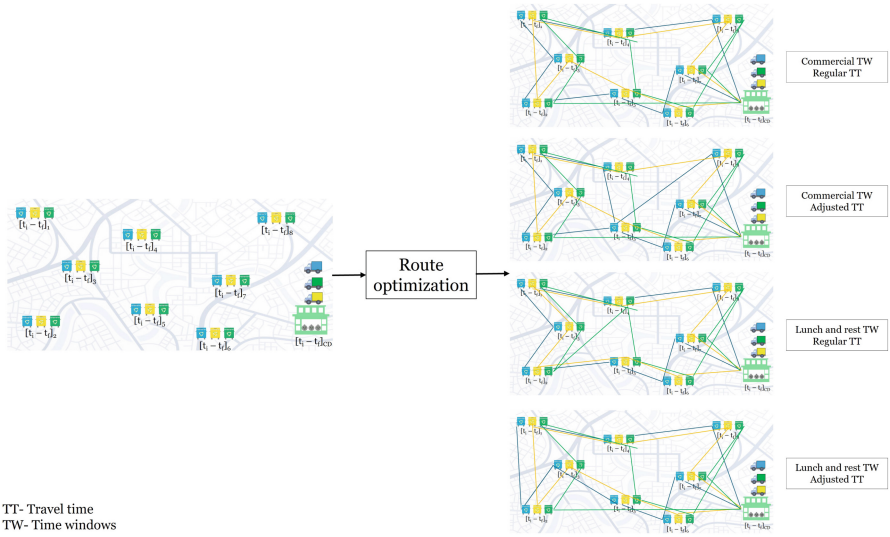

Fig. 2. Representation of the study performed. TW = Time Windows; TT = Travel Times.

3.1 Mathematical Formulation of the CWCPTW

The formulation for the CWCPTW is based on the traditional and recognized Capacitated Vehicle Routing Problem with Time Windows, which is a combinatorial optimization problem used to model several real-life situations in which a set of trucks needs to be used to serve customers for delivery or pick-up purposes. The problem can be summarized as finding the shortest path to serve a determined set of customers under two main constraints: the capacity of trucks and the time windows. The customers' demands are known, and all of them have a time window to be visited. The customers must be visited once by exactly one truck, and vehicles have a maximum capacity that cannot be exceeded.

The mathematical representation of the Capacitated Waste Collection Problem with Time Windows (CWCPTW) revolves around a complete graph, where V signifies the fleet of homogeneous waste collection vehicles with indices $1, 2, \ldots, k$, and C denotes the set of waste collection points. The graph comprises $n+1$ vertices, wherein vertex 0 represents the central waste disposal facility where trucks depart and arrive, and the waste collection points are labeled as $1, 2, 3, \ldots, n$. The CWCPTW entails various objectives, including the minimization of total travel time, the reduction in the number of waste collection vehicles employed, and the overall travel distance.

All edges originate and terminate at vertex 0, the central disposal facility. Each edge $(i, j) \in C_0$, in which $C_0 = C \in \{0\}$, is linked with a cost c_{ij} and a time duration t_{ij}, which may encompass the time spent on waste collection at point i, with the condition that $i \neq j$. The waste collection vehicles are constrained by a maximum capacity Q, and the waste collection points have associated waste

amounts d_i. These points must be visited within specified time windows $[a_i, b_i]$, where the vehicle must arrive at a waste collection point before b_i and after a_i. In cases where the latter condition is met, the vehicle must wait until a_i to execute the waste collection. The central disposal facility also imposes a time window $[a_0, b_0]$, mandating that waste collection vehicles do not depart before a_0 or arrive after b_0.

The parameters Q, a_i, b_i, d_i, c_{ij} are all non-negative integers, while the parameter t_{ij} is assumed to be a positive integer. It is further assumed that both c_{ij} and t_{ij} adhere to the triangular inequality. The formulation introduces two sets of decision variables, namely x_{ijk} and y_{ik}. For each arc (i, j), where $i \neq 0, j \neq 0, i \neq j$, and for each waste collection vehicle k, x_{ijk} is defined as 1 if the arc (i, j) is traversed by vehicle k in the optimal solution, and 0 otherwise. The additional decision variable, y_{ik}, pertains to each vehicle k and each waste collection point i, representing the time the waste collection vehicle k initiates the waste collection service at point i. If vehicle k does not commence service at waste collection point i, the decision variable y_{ijk} holds no significance. Assuming $x_ijk = 0$ for all waste collection vehicles, it is posited that $y_{ik} = 0$ for all k. The overarching objective of the problem is to design a set of routes, one for each waste collection vehicle, ensuring that each waste collection point is visited exactly once. All routes must commence and conclude at the central disposal facility (vertex 0), while adhering to specified time windows and capacity constraints. The formal mathematical formulation, drawing inspiration from the literature on the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW) [7], is detailed as follows:

$$\text{Minimize} \sum_{k \in V} \sum_{i \in C_0} \sum_{j \in C_0} c_{ij} x_{ijk} \tag{1}$$

Subject to:

$$\sum_{i \in C_0} d_i \sum_{j \in C_0} x_{ijk} \leq Q, \forall k \in V \tag{2}$$

$$\sum_{k \in V} \sum_{j \in C_0} x_{ijk} = 1, \forall i \in C_0 \tag{3}$$

$$\sum_{j \in C} x_{0jk} = 1, \forall k \in V \tag{4}$$

$$\sum_{i \in C} x_{i0k} = 1, \forall k \in V \tag{5}$$

$$\sum_{i \in C} x_{ihk} - \sum_{j \in C} x_{hjk} = 0, \forall h \in C, \forall k \in V \tag{6}$$

$$a_i \leq y_{ik} \leq b_j, \forall i \in C_0, \forall k \in V \tag{7}$$

$$y_{ik} + t_{ij} - Q(1 - x_{ijk}) \leq y_{jk}, \forall i, j \in C_0, \forall k \in V \tag{8}$$

$$x_{ijk} \in \{0, 1\}, \forall i, j \in C_0, \forall k \in V \tag{9}$$

The constraint {2} states that waste collection vehicles cannot carry more waste load than their capacity, and constraint {3} guarantees that each waste collection point is visited exactly once. The next three constraints {4}, {5}, and {6} are related to the continuity of the route, ensuring that each vehicle leaves the central disposal facility, and leaves again after performing the waste collection service at a determined point, and arrives back at the central disposal facility. Constraint {7} ensures that time windows are respected, and constraint {8} states that a waste collection vehicle traversing from i to j cannot arrive at j before $y_{ijk} + t_{ij}$. Finally, constraints {9} are the integrality constraints for the decision variable x_{ijk}.

3.2 Waste Generation Model

The study does not focus on waste generation model validation. However, it requires the model to generate waste daily to assess its ability to find the shortest path for waste collection. Three types of waste generation-plastic, paper, and glass-were simulated in this study. Previous research indicates that demographic density around dumpsters affects waste generation levels in a Portuguese city. As described in prior work, waste level fluctuations for different waste types were calculated based on demographic factors derived from satellite images of dumpster surroundings [17]. The parameter ranges from 0 to 1, with low population density areas having values near 0 and high-density areas having higher values. It is calculated by dividing the area with construction sites by the area of a circle with a 300 m radius around the dumpster. The dumpsters set is denoted as $\{A\}$, and days set is $\{B\}$. Waste level ($L^T_{e,f}$, percentage) and volumetric amount (V^T) for waste type T in dumpster e on day f can be calculated using this equation:

$$L^T_{e,f} = d_e \cdot C_T \cdot \sigma \ + L^T_{e,f-1} \wedge V^T_{e,f} = L^T_{e,f} \cdot \frac{V_D}{100} \tag{10}$$

In which L^T is the waste level of waste type T on day f for dumpster e. The demographic factor for dumpster e is introduced in the equation as d_e, and C_T is a constant that represents the influence of demographic factor on waste type T generation. The parameter σ introduced waste levels' stochasticity and oscillated between $[1, 20]$. The waste level in the first day was determined using a normal distribution function that returns random values on the range defined as $[0, 70]$. The volumetric waste level for waste type T, V^T was determined by multiplying the waste level L^T by the total dumpster volume, V_D. The model presented here allows determining waste levels for all waste types studied: paper (waste type PA), plastic (waste type PL), and glass (waste type G). The dumpster locations are illustrated in Fig. 3 and were provided by the company in charge of the municipal solid waste management in the region studied.

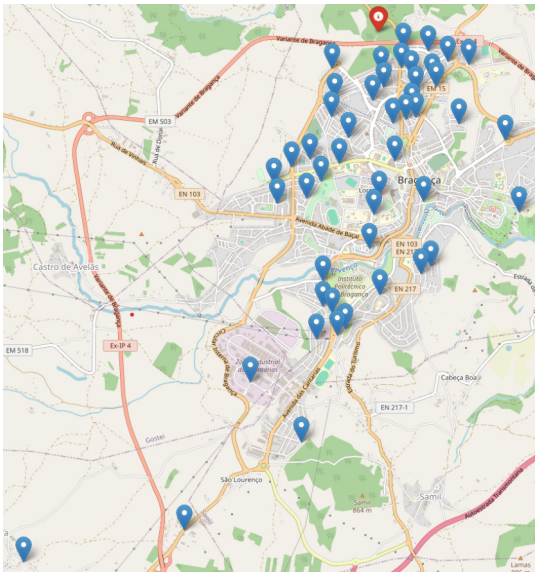

Fig. 3. Locations with three dumpsters (glass, paper, and plastic waste). The red location is the central depot. (Color figure online)

4 Results and Discussion

In this section, the results obtained for waste collection route optimization achieved using the Guided Local Search algorithm available in OR-Tools will be presented and discussed. The study was performed for 30 days, and the trucks used for the collection of the different waste types all have the same capacity ($Q = 16\,\mathrm{m}^3$). Following a similar dumpster/truck ratio as the real scenario, 3 trucks ($k = 3$) were considered per waste type for route optimization. The maximum capacity of waste that can be stored inside dumpsters is $TV = 2.5\,\mathrm{m}^3$.

The models used to simulate waste generation per type considered one parameter that has proven influence in waste generation, the demographic factor. There are different influences in waste generation per type using this parameter. The coefficients used to determine waste levels through days were $Cb = 9.52$, $Cy = 23.1$, and $Cg = 4.74$ for paper waste (blue dumpsters, Cb), plastic waste (yellow dumpsters, Cy), and plastic waste (green dumpsters, Cg), based on the literature [4].

The selection of dumpsters for collection on day i was performed based on the percentage level, using 90% as the threshold. The waste level used as a threshold here was proven to be the most effective according to previous waste collection studies. The problem was solved using the travel times gathered using Google Maps API, and a comparison was performed with a more realistic travel time obtained based on the paper published by Srinivas *et al.* [10], which presents a correlation between regular car and truck travel times.

4.1 Numerical Results

Four sets of results will be presented and compared in this section: one obtained with time windows in commercial hours only (9 a.m. to 7 p.m.) using regular travel times and truck-adjusted travel times, and another using more applicable time windows (9 a.m. to 12 p.m., 2 p.m. to 5 p.m., and 6 p.m. to 7 p.m.) in both travel time situations. The first time window is one example of what is often considered in most works exploring waste collection using time windows, and the second would be a more realistic time window that considers lunch breaks and rest times during the afternoon. The results obtained for the total time to perform the waste collection in the different scenarios studied are exhibited in Fig. 4.

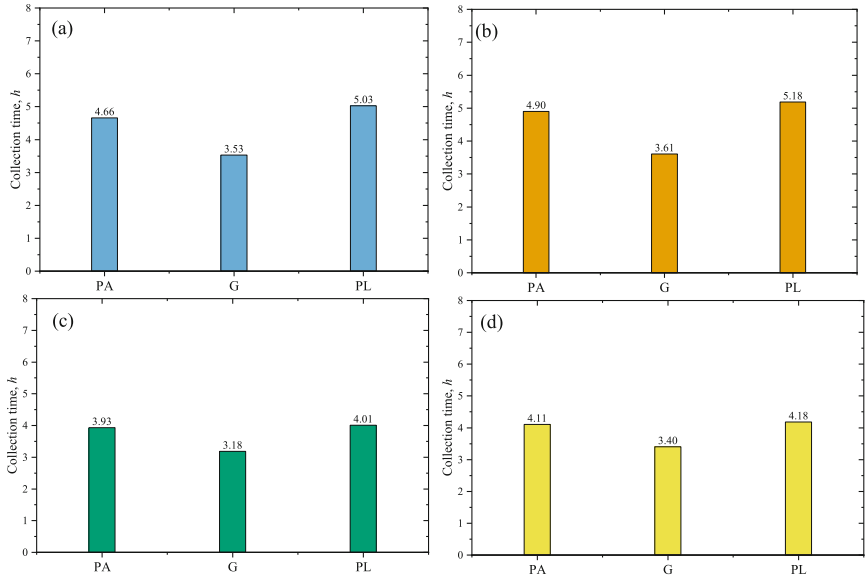

Fig. 4. Average daily time spent in collection task considering (a) working hours time windows and regular travel times, (b) working hours time windows and adapted travel time, (c) lunch break and rest hours time windows and regular travel times, and (d) lunch break and rest hours time windows and adapted travel times.

The results demonstrate that these parameters significantly influence hours spent during waste collection tasks. Comparing scenarios represented in Fig. 4a 4b reveals that regular travel times return smaller averages for daily waste collection tasks, which was expected considering that the adjusted travel times are more representative for trucks that are not as fast as cars. Nonetheless, the algorithm could still perform the route optimization using a more realistic travel time for the trucks, which is an important demonstration of the applicability in real scenarios. The time increase observed for all waste types was not the same,

which is a consequence of the difference in decision-making regarding the routes, once the algorithm had to follow different paths to respect all time windows.

Interestingly, the more realistic time windows scenario results reported in Fig. 4a and 4b returned average daily hours spent in waste collection tasks smaller than results obtained in wider time windows (0.75, 0.28, and 1.2 less time for paper, plastic, and glass waste collection in average). In other words, the algorithm's performance was improved by increasing the problem's difficulty, obliging the algorithm to improve route planning to respect all time windows. There is no report in the literature regarding the algorithm's performance in solving the waste collection problem using different time windows. The distance traveled also presented differences in the waste collection scenarios, and the average distance traveled per collection day is shown in Fig. 5.

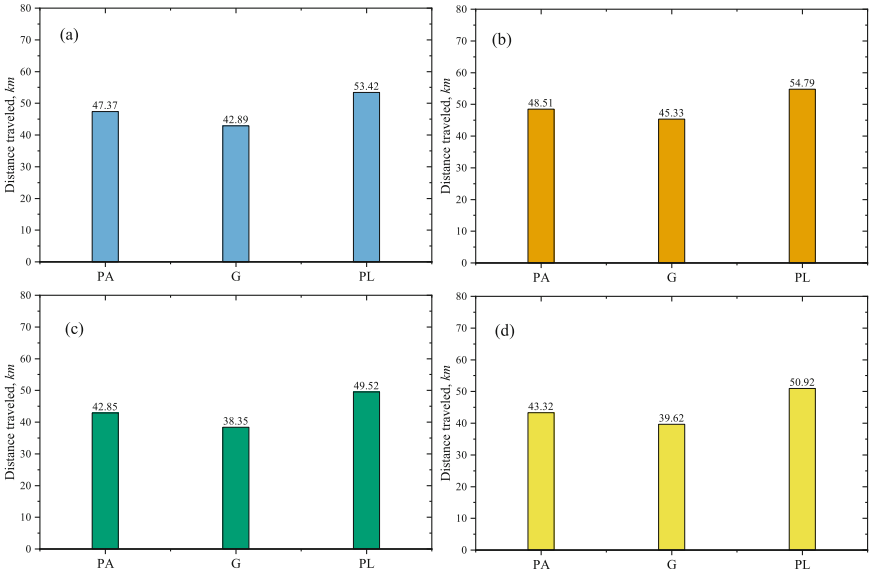

Fig. 5. Average daily distance traveled in collection task considering (a) working hours time windows and regular travel times, (b) working hours time windows and adapted travel time, (c) lunch break and rest hours time windows and regular travel times, and (d) lunch break and rest hours time windows and adapted travel times.

The results obtained for the average distance traveled in the different scenarios revealed a similar tendency as observed in the average daily time spent on waste collection tasks. Considering as the only difference the adjusted *vs* regular travel time, the difference was not so significant (*cf.* Fig. 5a *vs* 5b and Fig. 5c *vs* 5d). Comparing the different time windows and the same travel time (*cf.* Fig. 5a *vs* 5c and Fig. 5b *vs* 5d) revealed that the time windows are mainly influencing route planning. Specifically, the differences in distance traveled reached 4.9, 5.1, and 3.9 km for paper, plastic and glass waste collection on average. In

this case, the most restricted time windows resulted in better route planning using the GLS metaheuristic.

5 Conclusions and Future Work

In this paper, the influence of travel time and time windows on solving the CWCPTW using the GLS metaheuristic available in OR tools was assessed. The parameters evaluated are extremely important to validate the viability of implementing the solution in real scenarios. In most cases, the travel times used to solve the problems are acquired from external sources, and these sources often provide car travel times. Planning a truck route using the car's travel times might end up in future problems since the vehicles take considerably different times to travel the same route. Another important parameter is the time window to perform the waste collection task, often considered commercial hours. Here, a more realistic time window considering lunch and rest breaks was considered.

The scenarios were chosen to isolate the influence of one parameter and explore the algorithm's behavior upon changing the other parameter, keeping all the other parameters the same (*e.g.* number of trucks and demands). GLS algorithm revealed a small influence of travel times to solve this particular problem but a considerable influence of the time windows used. Interestingly, the most realistic and applicable time windows returned smaller average distance traveled to collect the waste and shorter times for all waste types studied.

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