TRUCK SCHEDULING FOR WASTE COLLECTION IN PORTO ALEGRE

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RESUMO
Este artigo aborda o problema do escalonamento de caminhões no contexto da coleta de lixo sólido em Porto Alegre. O problema consiste em definir bons escalonamentos diários, dado um conjunto previamente determinado de viagens de coleta, no qual os veículos coletam lixo sólido em rotas fixas e esvaziam suas cargas em uma das usinas de reciclagem em operação no sistema. O principal objetivo é minimizar os custos totais envolvidos, simultaneamente obtendo uma utilização balanceada das usinas de reciclagem. O problema foi modelado como um problema de escalonamento de veículos com uma estrutura especial, e emprega uma variação do algoritmo leilão para resolvê-lo. Um método dinâmico de penalidades é adicionado ao algoritmo leilão para obter uma designação balanceada de viagens de coletas às usinas de reciclagem. Experimentos computacionais foram conduzidos com dados fornecidos pela empresa responsável pela coleta. Os resultados evidenciam que nosso método simultaneamente reduz os custos totais e obtém um balanceamento da quantidade de lixo descarregada em cada usina de reciclagem.

Palavras-chaves: escalonamento de veículos, gestão do lixo, algoritmo leilão, logística e transporte

ABSTRACT
This paper considers a truck scheduling problem in the context of solid waste collection in Porto Alegre, Brazil. The problem consists of designing "good" daily truck schedules over a set of previously defined collection trips, on which the trucks collect the solid waste in fixed routes and empty the loads in one of the several operational recycling facilities in the system. The main objective is to minimize the total costs involved, including traveled distance and fixed truck costs, as well as to obtain balanced assignments of solid waste into the recycling facilities, due to the social benefit of the solid waste program. We model this problem as a vehicle scheduling problem (VSP) with a special structure, and employ a variation of the auction algorithm to solve it. A dynamic penalty method is embedded into the auction algorithm to achieve balanced assignments of collection trips to recycling facilities. Finally, computational experiments are conducted on real data. The results show that our approach simultaneously reduces total costs and balances the solid waste assignments to recycling facilities.

Keywords: vehicle scheduling, waste management, auction algorithm, logistics and transportation
1. Introduction

Over the last few decades local authorities have devoted increasing attention to solid waste management due to its impact on the public concern for the environment. The quantity of solid waste produced in the world is so huge that landfills are no longer sufficient to contain them. Recycling seems to be the most effective option for the disposal of solid waste: glass, paper, aluminium, and organic matter can be successfully recycled in different ways. However, recycling requires the solid waste to be separated, collected and transported. Economic evaluation of a solid waste system takes into account three main types of cost: collection, transportation, and disposal (Angelelli and Speranza, 2002). As a result, the community has to pay the cost for any effort involving the solid waste processing. The recycling facilities are usually at a certain distance from the collection areas, which makes the transportation costs be a major concern in the evaluation of a solid waste system. The main purpose of this paper is to suggest a methodology for allocating trucks to the existing collecting sites in a Brazilian city, Porto Alegre, with the purpose to minimizing the total operating and fixed trucks costs.

Solid waste collection is one of the most costly services provided by a city to its residents (Bhat, 1996). Specifically, for Porto Alegre, 20% of the total budget of the Department of Urban Sanitation (known as DMLU, from the Portuguese “Departamento Municipal de Limpeza Urbana”) is spent in the solid waste management program, in which 70-75% of budget is spent in the waste collection and transportation. DMLU has a total annual budget of over US$ 20 million and employs 3500 workers. It carries out several services, including beaches sanitation, public toilets maintenance, garbage and solid waste collection, transportation, and disposal.

Concerning solid waste collection, at the beginning of each day, each truck is provided a schedule, that is, each truck crew is directed to collect and transport solid waste for a fixed amount of time before going to the recycling facilities. In the current schedule, each truck starts from the depot and collects waste for the time period between 1 to 3 hours in the morning. The length of time period depends on the collection region. Then, the truck empties its load at a recycling facility and returns to the depot. If this truck can reach the starting point of next trip before its starting time, it will serve the new trip and finally return to the depot. With at most 3 hours of collecting time, the trucks do not have the capacity constraint, which also makes the crew members perform the schedule easily. Nevertheless, this policy demands a large number of trucks and crew, resulting in increment of the costs for truck maintenance and crew salaries. More efficient schedules, on which some trucks can conduct the collections more than twice a day, may decrease the total costs involved in the system.

However, even if a schedule obtains the good operating and fixed truck costs, it cannot be employed unless the balanced assignment of solid waste into the recycling facilities is attained. A schedule is avoided if the trucks unload the solid waste only in several facilities and leave other facilities empty. Therefore, our objective in this case study is to investigate a good scheduling pattern that has good operating cost, fixed truck cost as well as balanced trip assignments to each recycling facility.

We model the problem as an instance of the single-depot vehicle scheduling problem (SDVSP), a classical optimization problem (Baita et al., 2000) in which additional restrictions were added to achieve a trip assignment balance among the recycling facilities in the system. The SDVSP can be defined as the problem of assigning vehicles to a set of predetermined trips with prescribed starting and ending times while minimizing the total capital and travel costs, and satisfying the following constraints: (i) every trip has to be assigned to exactly one vehicle; (ii) each vehicle performs a feasible sequence of trips; and (iii) only one depot exists in the system. The output of our model is an implementable schedule that provides a daily work assignment for each truck. We demonstrate that our approach decreases the total costs, which are composed of the fixed and operating costs, and obtains more balanced schedules in terms of the use of the recycling facility capacities.

The rest of the paper is organized as follows. Section 2 briefly reviews the existing work on waste collection problem as well as the algorithms for the SDVSP. In section 3, the
description of the solid waste system in Porto Alegre is provided. Section 4 presents our model and heuristic algorithm to solve the problem. In section 5, computational experiments, comparing our heuristic approach and the manual planning employed in DMLU, are presented. Finally, summary of the results and areas of future research are discussed in section 6.

2. Literature Review

Some studies have been conducted on the literature to describe the application of Operations Research/Management Science methods and techniques towards solid waste management. Recent review on waste management models can be found in Morrissey and Browne (2004). It is possible to categorize them based on the two key aspects of solid waste management (Bodin et al., 1989) as follows: (i) designing the efficient collection routes; and (ii) presenting the appropriate policies for the economic collecting.

The research works in the first category are focused on the design of efficient collection routes in order that the time providing the service is shorter and the covered regions are more compact (Bodin et al., 1989). Such works utilize some variations of the Chinese Postman Problem (Male and Liebman, 1978), set covering problem (Bautista and Pereira, 2005) or vehicle routing problem (VRP) (Tung, 2000) to define a travel sequences of streets that minimizes the total time. This task has already been carried out in Porto Alegre using a variant of the Chinese Postman Problem. As a consequence, our paper is not concerned with this aspect.

The research in the second category places emphasis upon designing appropriate policies for the efficient and economic collection. Kulcar (1996) adopts a two-phase optimization model to reduce the number of depots and receiving terminals as well as the transportation cost. Kirca and Erkip (1988) to determine the number of transfer stations needed and their location. Eisenstein and Iyer (1997) investigate a dynamic scheduling model based on a Markov decision process to reduce the truck capacity. Bodin et al (1989) develop a heuristic procedure to generate the daily collection routes for a truck based on the statistical load information and collection travel time. Bhat (1996) designs a simulation-optimization model to allocate trucks on disposal sites.

Our approach differs from existing works in a number of ways. First, we attempt to balance the solid waste delivered to each recycling facility. Second, our model takes into consideration not only the cost involved in truck transportation, but also with the fixed costs related to the number of trucks required. Finally, we propose an efficient heuristic procedure that can be used as a platform for the development of dynamic scheduling tools.

In order to achieve such features, a slightly modified SDVSP is selected to model the problem. Overview of algorithms and applications for the SDVSP and some of its extensions can be found in Freling et al. (2001). This problem has already been formulated as a linear assignment problem, a transportation problem, a minimum-cost flow problem, a quasi-assignment problem, and a matching problem in the literature. Currently, one of the best model and algorithm for SDVSP is the quasi-assignment and auction algorithm developed by Freling et al. (2001). Computational results show that this approach outperforms methods based on the minimum-cost flow and linear-assignment models.

3. Solid Waste Collection in Porto Alegre

The solid waste collection in Porto Alegre involves 150 neighborhoods, with a population of more than 1.3 million. More than 60 tons of solid waste are collected per day and distributed to 8 recycling facilities. The collection and distribution of the solid waste are carried out by DMLU. The recycling facilities are managed by cooperatives, where members are mostly poor and are not part of the mainstream economy. In these facilities, the solid waste is separated,
appraised, stored, and commercialized. The profit remains with the cooperatives, making it an important income source for more than 450 workers. As a consequence, the solid waste management program has balanced social and ecological benefits [http://www.lixo.com.br accessed 9 September 2004].

The collection is weekly performed on each street of the city from Monday through Saturday. The team of solid waste collection is composed of one driver and three garbage collectors, who are specially trained for handling this kind of waste. There are 24 specially designed trucks to support the collection. One of them is always used as a backup truck, in case a severe disruption occurs. Every day, trucks leave the depot at 8:00 am and start a collection route. The routes were defined by the DMLU managers based on the municipality neighborhood division. The idea is to conduct the collection of all streets within the same neighborhood. If a certain neighborhood is too large or has a dense population, the collection can be divided in more than one collection shift. The current routes, although not optimal in terms of operation costs, are well defined and known for the city residents. DMLU managers are not interested in changing the routes, since it will cause a major disturbance in the modus operandis of the system.

A requirement is that the solid waste should be on the street for a maximum of 30 minutes before its collection. Severe fines might be imposed on the residents who do not follow this rule. DMLU distributes informative leaflets giving the schedule of the collection trucks for each street. The main purpose is to protect the profits of the cooperatives that run the recycling facilities, since other independent companies may collect the waste before DMLU. When a truck completes its collection, it moves towards a recycling facility to unload the collected waste. The choice of which facility will be used by each truck is based on several criteria, such as distance from the collection ending point to the facilities, the current available capacity of the facilities and so forth. Since there are currently eight recycling facilities located in different places within the city limits, and the collection in a shift is conducted in distant neighborhoods simultaneously, DMLU managers have decided to send the trucks directly to the recycling facilities, instead of consolidating the cargo in a larger truck. When a truck arrives at the recycling facility, it is weighted and unloaded. After unloading, the truck returns to the depot. Then it continues to collect the garbage in another neighborhood if time is permitted. All trucks should go back to depot at 12:00 for lunch. The same routine is executed in the afternoon, starting at 14:00, and finishing at 18:00.

Although the system is effective, the transportation costs involved are extremely high. The city has not conducted systematic planning for allocating trucks. Consequently, managers in DMLU are concerned about the efficiency of the existing waste-flow methods. Furthermore, it is frequent to obtain poor schedules in terms of imbalanced trip assignments to recycling facilities where some recycling facilities may be allocated excessive collection trips, and other recycling facilities may be idle. Such schedules are rejected by the human schedulers when the social benefit of the solid waste program is considered. Basically, a good model needs to decrease the total costs consisting of fixed truck costs and travelled distance costs, and simultaneously create balanced allocations in terms of the use of capacity of recycling facilities. Since the starting and ending time of each collection trip are fixed, and the constraint of truck capacity does not exist, the problem can be modeled as a vehicle scheduling problem.

4. Model and Algorithm

In this section, we present a variant model of SDVSP that fits the solid waste collection problem in Porto Alegre. Based on this model, a heuristic algorithm, which is a variation of the auction algorithm (Bertsekas, 1992), is proposed to solve the problem. Before considering mathematical formulations, we introduce some definitions and notations related to VSP. Deadheading trip is movement of vehicles without transporting cargo. Trips $i$ and $j$ constitute compatible pair of trips if the same vehicle can reach the starting point of trip $j$ after it finishes trip $i$. Let $N = \{1, 2, K n\}$ be the set of trips, numbered according to increasing starting time, and
let \( E = \{(i, j) \mid i < j, i \text{ and } j \text{ are compatible pair of trips, } i, j \in N\} \) be the set of arcs corresponding to deadheading trips. The vehicle-scheduling network be \( G = (V, Z) \) with nodes \( V = N \cup \{(s, t)\} \) and arcs, where \( s \) and \( t \) denote the same depot in the network, with \( s \) simply meaning the depot as a starting point, and \( t \) as the terminating point. A path from \( s \) to \( t \) in the network represents a feasible vehicle schedule. The SDVSP can be formulated as a quasi-assignment problem as follows (Freling, 2001):

\[
\min \sum_{(i,j) \in Z} c_{ij} y_{ij}
\]

\[
st \quad \sum_{j \in \{t(i,j) \in Z\}} y_{ij} = 1 \quad \forall i \in N
\]

\[
st \quad \sum_{i \in \{i,j \in Z\}} y_{ij} = 1 \quad \forall j \in N
\]

\[
y_{ij} \in \{0, 1\} \quad \forall (i,j) \in Z
\]

where

\( c_{ij} = \text{cost of arc } (i, j) \in Z, \text{ generally defined as a combination of travel time along the arc and waiting time in the starting point of trip } j, \)

\( y_{ij} = \begin{cases} 
1 & \text{if a vehicle is assigned to trip } j \text{ directly after trip } i, \\
0 & \text{otherwise.}
\end{cases} \)

The constraints in the formulation assure that each trip is assigned to exactly one predecessor and one successor. We refer to Freling (1992) for a discussion about models and algorithms for the SDVSP.

Unfortunately, this formulation cannot be directly applied to this specific case study, due to two additional constraints (see previous section for details): (i) it is not allowed that a truck comes from the depot and directly goes to the recycling facility; and (ii) after finishing its collection trip, a truck has to go first to a recycling facility for unloading the garbage instead of going to the depot directly or serving a new trip. As a consequence, the solid waste collection should be treated as a SDVSP problem with some special structures and be solved using a specific algorithm.

4.1 Modeling the Problem

First, we need to construct a feasible network structure that simultaneously represents the problem. In this structure both the collection trips and recycling facilities are represented as nodes. For each collection trip, we created \( K \) associated dummy trips which represent \( K \) recycling facilities respectively. Figure 1 illustrates the network structure for this problem. The starting time of each recycling facility associated (RFA) trip is the ending time of the corresponding collection trip plus the travel time from the ending point of its collection trip to the recycling facility. The duration of each RFA trip is the unloading and service times at the facility. After determining the starting and ending times of each such RFA trip, we can construct the feasible network in such a way that a collection trip is connected to all recycling facilities through the RFA trips. There are no direct connections among collection trips, which meet the problem requirements. Since in vehicle scheduling problems, every trip needs to be covered, we introduce dummy arcs connecting the depot to all RFA nodes, and from these nodes to the depot (see Figure 2). As a consequence, several dummy vehicle assignments are carried out only to fulfill this VSP peculiarity. These dummy assignments, which have the format, “depot→RFA node→depot”, are easily discarded in the final solution.

For example, in Figure 2 trips 1, 2 and 3 have eight associated trips which represent the recycling facilities. \( r_{21} \) represents the recycling facility 1 for the collection trip 2. Vehicles from
the depot can go to trip 1, thus there exists an arc from depot to trip 1. After serving the trip 1, vehicle has to go to recycling facility to unload the waste.

Therefore, there are arcs from trip 1 to its associated dummy trips. It is not allowed for a vehicle to go back to depot directly unless the waste is unloaded in the recycling facility. Hence, this is no arc from trip 1 to depot. After unloading the waste in the recycling facility, the vehicle can go back to the depot or serve next compatible trips. So, there is an arc from the recycling facility to the depot, and there is also an arc from recycling facility to trip 3. There are no arcs from the recycling facilities for trip 1 ($r_{i1}, r_{i2}, ..., r_{iK}$) to trip 2 since they are not compatible trip pairs. Since every recycling facility is represented as a dummy trip, there are arcs from the depot to all dummy trips so that they can be covered.

Figure 1: An example of vehicle-schedule network for the case study

The new vehicle-schedule network is defined formally as follows. Let $T = \{1, 2, K, n\}$ be the set of waste collection trips, and let $R(i) = \{r_{i1}, r_{i2}, ..., r_{iK}\}$ be the RFA trips with collection trip $i$, where $K$ is the number of operational recycling facilities. These RFA trips represent the recycling facilities. The starting and ending time of each RFA trip is defined as the method discussed previously. Let $R = \bigcup_{i=1}^{n} R(i)$ be the set of all associated trips, and let $N = T \cup R$ be the set of whole collection and RFA trips. Let $E1 = \{(i, j) | i \in T, j \in R(i)\}$ be the set of arcs from the waste collection trip to the recycling facilities, and $E2 = \{(i, j) | i \in R, j \in T, i$ and $j$ are compatible pair of trips} be the set of arcs from the recycling facilities to the collection trips. The vehicle-schedule network is defined as $G = (V, Z)$ with nodes $V = N \cup \{s, t\}$ and arcs $Z = E1 \cup E2 \cup (s \times N) \cup (t \times N) \cup (s \times R) \cup (t \times R)$. Based on this network, the formulation of classical SDVSP discussed previously can be used to model the problem.

The solution of the model is a set of collection and RFA trips to each truck during each-day horizon. Whereas each collection trip is conducted only once everyday, each recycling facility can be visited more than once by trucks. Therefore, some recycling facilities might be visited repeatedly by the different vehicles and other recycling facilities may not be visited at all during the horizon. It turns out that some recycling facilities might be allocated excessive
collection trips, and other recycling facilities might be idle, which makes the human scheduler reject such schedule. A schedule, which presents simultaneously balanced capacity utilization of all recycling facilities and low operating and fixed costs, needs to be investigated. It should be noted that even with this special network structure, it is not guaranteed that the additional constraints (see section 3 for details) are satisfied if regular algorithms for the SDVSP are used. We combined this special network structure and a specific algorithm developed to satisfy the constraints in the problem. Next section describes our solution approach to achieve such appropriate schedules.

4.2 The Proposed Heuristic Method

Currently, one of the best model and algorithm for the SDVSP is the quasi-assignment and auction algorithm (Freling, 2001), respectively. The auction algorithm was originally proposed Bertsekas (1992) for the classical symmetric assignment problem. With the scaling technique, the complexity is $O(nm \log(nC))$, where $n$ is the number of elements to assign, $m$ is the number of possible assignments between pairs of elements, and $C$ is the maximum absolute benefit. In the classical symmetric assignment problem, we need to match $n$ persons and $n$ objects on an one-to-one basis. Let $a_{ij}$ be the benefit of matching person $i$ and object $j$. The objective function is to maximize the total benefit. In the auction algorithm, each object $j$ has a price $p_j$, and this price is updated upwards as persons bid for their best object, that is, the object for which the corresponding benefit minus the price is maximal. The auction algorithm is composed of two phases: bidding phase and assignment phase. In the bidding phase, every unassigned person looks for its “best” object; in the assignment phase, the object selects the person with the highest bid since it may receive more than one bid. Meanwhile, if some objects that have already been assigned to some persons in a preceding iteration are now assigned to new persons, the persons who lose their objects are inserted into an unassigned set. After all persons and objects are matched, the auction algorithm is terminated.

The combined forward and backward auction algorithm consists of forward and backward auction iterations, in a forward iteration the persons bid for the objects, while in a backward iteration objects bid for the persons. Freling et al. (2001) describes the auction algorithm as follows: The value of a bid of trip $i$ (or person $i$) for another trip $j$ (or object $j$), which is candidate for forward assignment, is denoted by $f_{ij} = a_{ij} - p_j$. The value of a bid of trip $i$ for the depot is denoted by $f_{it} = a_{it}$. Let $N$ be all trips and $A$ be all arcs in the feasible network, respectively. Introduce $p_{ij}$ to denote the price of object $j$ when backward auction is conducted.

**Auction-SDVSP: Algorithm for SDVSP**

**Step 1:** Perform the forward auction algorithm for each trip $i \in N$ (or person $i$) which is currently not assigned to a trip $j$ (or object $j$) or depot.

**Step 2:** Determine the trip or depot $j_t$ with the maximum bid value $\beta_t = \max \{f_{ij} | (i, j) \in A\}$. Determine also the second highest value $\gamma_t = \max \{f_{ij} | (i, j) \in A, j \neq j_t\}$. If trip $i$ (or person $i$) has only one arc $(i, j) \in A$, set $\gamma_t = -\infty$; if $j_t = t$, update the assignment and price $\pi_t = a_{it}$, then go to Step 4.

**Step 3:** Update the prices: $p_{ij} = p_{ij} + \beta_t - \gamma_t + \epsilon = a_{ij} + \gamma_t + \epsilon$, $(\epsilon$ was originally presented for avoiding cycling in the auction algorithm, and it has been proved that the auction algorithm can obtain the optimal solution if $\epsilon < 1/n$ ?), and $\pi_t = a_{it} - p_{it}$. Update the assignments. If trip $j_t$ is already backward assigned, then remove the previous assignment.

**Step 4:** Return to Step 1.
The reverse auction procedure is similar, with bids for candidates for forward assignments replaced by bids for candidates for backward assignments.

In order to restrict the number of trips assigned to each recycling facility, a modified auction algorithm, which dynamically adds penalties to some related arcs, is designed. Each time the number of trips serving a recycling facility exceeds a given limit, all remaining arcs connecting trips to this specific recycling facility are penalized, making them less attractive in the final solution. The penalties are dynamically imposed to an arc if the assignment phase finds that the recycling facility is overloaded of assigned trips. We have decided to use penalties instead of hard constraints in order to avoid infeasibility.

```
routine DynamicPenalty:
begin
  for each recycling facility r
  begin
    Determine the numbers of trips assigned to it
    if the numbers of assigned trips exceed the given limit, then
      Add a penalty cost to the unassigned arcs which are connected to r
    end
  end
end
```[DynamicPenalty]

Figure 2: Routine DynamicPenalty

The given limit of each recycling facility is related to the capacity of all recycling facilities and the total number of collection trips. The differentiation between collection trips and recycling facilities in the network is easily programmed in the algorithm implementation. The given capacity limit and penalty values are determined by computational tests.

Although in the feasible network, the direct connections among collection trips do not exist, some problems might be caused by the introduction of dummy trips. Consider a situation where a schedule, in the final solution, has the following format: “depot→RFA node→regular node→RFA node→depot”. The appearance of a dummy trip as the first trip in a truck schedule violates the problem requirements. In order to avoid such situation, if it is found that the RFA node is backward assigned to the depot (i.e., having the schedule “depot→RFA node”, since this RFA node selects the depot as the best object in auction algorithm), this RFA node is forced to be forward assigned to the depot. As a result, this dummy node will appear only in the format: “depot→RFA node→depot”, which is discarded in the final solution. Using penalties, our modified algorithm is described as follows:

Algorithm Auction_SWC: Algorithm for Solid Waste Collection

**Step 1-3**: Same steps as in algorithm Auction_SDVSP

**Step 4**: If RFA trips are assigned to depot in backward auction iterations, forward assign them to the depot.

**Step 5**: Call procedure DynamicPenalty. Return to Step 1.

5. Computational Result and Analysis

The main purpose of our experiment is to investigate the operational planning of the solid waste collection in Porto Alegre for each working day during a week, then to compare the results with the scheduling strategy defined by human schedulers. As mentioned in section 3, the collection route includes the starting time, ending time and a covered area. Since DMLU managers are satisfied with the current collection routes, these routes are selected as the input to our algorithm in the experiment.

Two criteria are selected in our study to compare the results by manual planning with the results by optimization method: the total costs, including operational costs (distances travelled)
and fixed truck costs (number of trucks used), and the number of trips assigned to each recycling facility. A balanced scheduling is preferred, even with the slight higher costs. To implement the proposed heuristic algorithm, we developed a computer program written in C++. The experiments were carried out on a 900Mhz Sun Workstation.

In order to simplify the analysis, we consider the distance by the collecting trucks as the only operational cost involved. The total cost is defined as follows, 

\[ C = \sum_{i=1}^{V} c_i d_i + \sum_{i=1}^{V} f_i, \]

where \( c_i \) is the average operational cost of vehicle based on its diesel consumption (we used a value of US$ 0.127/Km, considering the current diesel price in Brazil and the average diesel consumption of the vehicles), \( f_i \) is the average diary fixed cost (includes maintenance, taxes, etc.) of vehicle \( i \) (defined as a constant equal to US$ 21.00, based on DMLU databases), \( d_i \) is the distance traveled by vehicle \( i \) (excluding the waste collection trips), and \( V \) is the total number of trucks used to collect the solid waste.

Table 1 presents the number of used trucks, traveled distances as well as the total costs respectively by manual planning and optimization algorithm. The last three columns present the saving in the number of trucks (\( ST \)) used, the traveled distance (\( SD \)), and total costs (\( SC \)) respectively, resulting from the optimization algorithm. These measures are defined as follows:

\[
ST = 100 \times \frac{T_M - T_O}{T_M} \%
\]
\[
SD = 100 \times \frac{D_M - D_O}{D_M} \%
\]
\[
SC = 100 \times \frac{C_M - C_O}{C_M} \%
\]

where \( T_M (T_O) \), \( D_M (D_O) \), and \( C_M (C_O) \) are the number of required trucks to conduct the daily collection tasks, the total traveled distance in Km and the total costs given by manual planning (optimization algorithm), respectively.

Table 1: Results by manual planning and optimization method

<table>
<thead>
<tr>
<th>Day</th>
<th># of trips</th>
<th>Manual planning</th>
<th>Optimization method</th>
<th>( ST(%) )</th>
<th>( SD(%) )</th>
<th>( SC(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon</td>
<td>29</td>
<td>23</td>
<td>639.70</td>
<td>404.51</td>
<td>457.10</td>
<td>296.05</td>
</tr>
<tr>
<td>Tues</td>
<td>27</td>
<td>23</td>
<td>514.00</td>
<td>387.28</td>
<td>376.85</td>
<td>271.86</td>
</tr>
<tr>
<td>Wed</td>
<td>23</td>
<td>21</td>
<td>463.30</td>
<td>352.84</td>
<td>349.80</td>
<td>254.42</td>
</tr>
<tr>
<td>Thur</td>
<td>31</td>
<td>23</td>
<td>512.15</td>
<td>387.04</td>
<td>439.60</td>
<td>321.83</td>
</tr>
<tr>
<td>Fri</td>
<td>13</td>
<td>13</td>
<td>279.05</td>
<td>217.44</td>
<td>262.65</td>
<td>215.36</td>
</tr>
</tbody>
</table>

Table 1 shows that our method reduces significantly the costs components in comparison with the solution of manual planning. The average reduction in the number of vehicles is 22.33%, while the average reduction in the distances is 22.00%. The capability of assigning several trips to a single truck in our algorithm is a good explanation for the significant reduction in the number of trucks. In the manual planning, a truck is usually designed to finish only one collection task, forming a cycle: “depot→collection trip→recycling facility→depot”. Only after returning to the depot, a truck can serve a next compatible collection trip. This rule in manual planning also leads to more travelled distances on deadheading trips, since a trucks needs to travel back to the depot, resulting in an unnecessary additional deadheading trip. Our approach, based on an optimization method, is capable of assigning a truck from the recycling facility to the starting point of the next compatible trip, reducing the number of deadheading trips.

The average total cost per day is reduced from $349.82 to $271.90, resulting in an estimated saving of 22.27%. The optimization method improved very slightly on Friday since all of collection trips in this day happens in the morning and lasts for around 3 hours. As a result, each truck covers only one trip, which makes it impossible for our approach to reduce the number of trucks. If considering the schedules from Monday to Thursday, the average reduction in the number of vehicles is 25.56%, while the average reduction in the distances is 24.11%.

The annually potential cost saving using our approach can be estimated in around $18,700. It should also be noted that the decrease in the total number of trucks can lead to the
reduction of total numbers of crew members needed for driving and waste collecting. Therefore, we can include the cost savings for wages of the driver and collectors. Considering that the monthly wage for a team in each truck is $2,600, and DMLU needs to keep a maximum of 20 teams based on the results presented in Table 1. This will save around $153,900 annually, which is approximately equivalent to 4% of the budget assigned to the solid waste collection program.

Table 2 presents the number of trips assigned to each recycling facility. $R_i$ denotes the recycling facility $i$. $SV$ denotes the sampling variance of trip assignments.

<table>
<thead>
<tr>
<th>Day</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_4$</th>
<th>$R_5$</th>
<th>$R_6$</th>
<th>$R_7$</th>
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The results in Table 2 show that the sampling variance is reduced considerably using our optimization method. For example, on Friday's schedule by manual planning, only 4 out of 8 facilities are used. With our approach, all of the recycling facilities is used. The sampling variance of assignment was reduced from 3.98 to 0.93. From the viewpoint of overall trip assignments on the whole week, the optimization approach also considerably outperforms the manual planning. In the manual planning, recycling facility 4 only receives 4 collection trips for the whole week, while facility 1 receives 26 collection trips. In the optimization method, the facility 7 receives the minimal trips (13 trips), and the facility 8 receives the maximal trips (20 trips). The result shows that the developed heuristic obtains much more balanced trip assignments into the recycling facilities. The routine DynamicPenalty, embedded in the auction algorithms, has successfully distributed the number of collection trips to the operational recycling facilities. It should be noted that sampling variance for the whole week, say 46.84 and 5.98, is calculated based on the trip assignments using a one-week horizon rather than being simply summarized the daily sampling variance.

Overall, our approach has simultaneously reduced the collection costs and balanced the number of trips assigned to the operational recycling facilities. The human schedulers were very impressed with the results and are willing to implement the schedules provided by the heuristic. A computational system, with a friendly interface, is being developed to help human designers to interactively use the heuristic.

6. Conclusion

This paper presented a model to design a schedule for trucks to collect the solid waste in Porto Alegre, Brazil, and unload it in recycling facilities. We modeled the problem as a single-depot vehicle scheduling problem with the following features: (i) total costs, including operating and fixed costs, are minimized, whereas most approaches employing VRP models, obtains only minimal operating cost. This feature was led to by the fact that the waste collection in Porto Alegre does not impose constraints on the capacity of trucks; (ii) our model attempts to balance the collection trips assigned to recycling facilities, which prevents that some recycling facilities are overloaded and others are idle. This aspect was considered due to the social benefit of the solid waste program in Porto Alegre.

Since the direct connections between the collection trips do not exist in the problem, a vehicle-schedule network with a special structure was created to follow this requirement. Due to its simplicity and efficiency, the auction algorithm was selected to solve the SDVSP. In order to balance the trip assignments, we designed a variation of auction algorithm incorporating a procedure which dynamically adds penalties to a recycling facility if its capacity limit is reached.
Our approach improved significantly the system performance in comparison with manual planning. The average number of vehicles was reduced from 20.6 to 16 vehicles, resulting in a saving of 22.33%; the average traveled distance (excluding waste collection trips) decreased from 483.64 km to 377.20 km, resulting in a saving of 22.00%. As a result, the total cost was reduced from $349.82 to $271.90, resulting in an estimated saving of 22.27%. On average, the sampling variance of daily trip assignments into the recycling facility was reduced from 4.78 to 1.43, while sampling variance of overall trip assignments during one-week horizon was reduced from 46.84 to 5.98 using our approach. These results show that our modeling approach successfully reduces the total costs, and simultaneously improves the social aspects of the solid waste management program.

The research team is proceeding to develop models and algorithms to consider dynamic aspects in the truck scheduling, such as a truck breakdown. The main idea is to adjust the penalty-auction algorithm to solve some dynamic scheduling problems, mainly when the severe disruption happens in midst of operations.

References


