IJIE – Iberoamerican Journal of Industrial Engineering / Revista Iberoamericana de Engenharia Industrial / Revista Iberoamericana de Ingeniería Industrial
Periódico da área de Engenharia Industrial e áreas correlatas
Editor responsável: Nelson Casarotto Filho, Prof. Dr.
Organização responsável: Universidade Federal de Santa Catarina (UFSC)
Processo de avaliação de artigos por pares
Periodicidade: Semestral
Florianópolis, SC, vol. 2, nº 1, p. 124-136, jul, 2010
ISSN 2175-8018
Artigo recebido em 23/11/2009 e aceito para publicação em 15/01/2010

OPTIMIZING ROUTES FOR THE COLLECTION OF URBAN SOLID WASTE: A CASE STUDY FOR THE CITY OF JOINVILLE, STATE OF SANTA CATARINA

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ABSTRACT: This paper introduces a methodology to obtain optimal routes for the collection of urban waste. The problem is characterized as arcs coverage and for its development a combination of techniques in the Operational Research area was used. Firstly, the Teitz and Bart heuristic was used to obtain p-medians; from the definition of latter were defined groups (clusters) of demand points by designating these to the medians, by means of the Gillett and Johnson algorithm, adapted. Finally, from the definition of the groups of points, the Chinese Postman Algorithm was used, resulting in the routing (sequencing the demand points to be served) in each of the service groups. The results obtained are presented for a case study of the city of Joinville, State of Santa Catarina.
Keywords: Route Optimization. Solid Waste Collection. Chinese Postman Problem.

1 INTRODUCTION

Cleaning services absorb between 7% and 15% of the resources of a municipal budget, of which 50% are used exclusively to collect and transport waste. Indeed, its optimization can lead to a significant saving of public funds (CARVALHO, 2001).

As shown in Figure 1, below, there is a great tendency to increase the generation of household waste per capita in direct proportion to the number of inhabitants. In cities with up to 200,000 inhabitants, one can estimate the amount collected, ranging from 450 to 780 grams per inhabitant/day; over 200,000 inhabitants, this amount increases to a range between 800 and 1,290 grams per inhabitant/day.

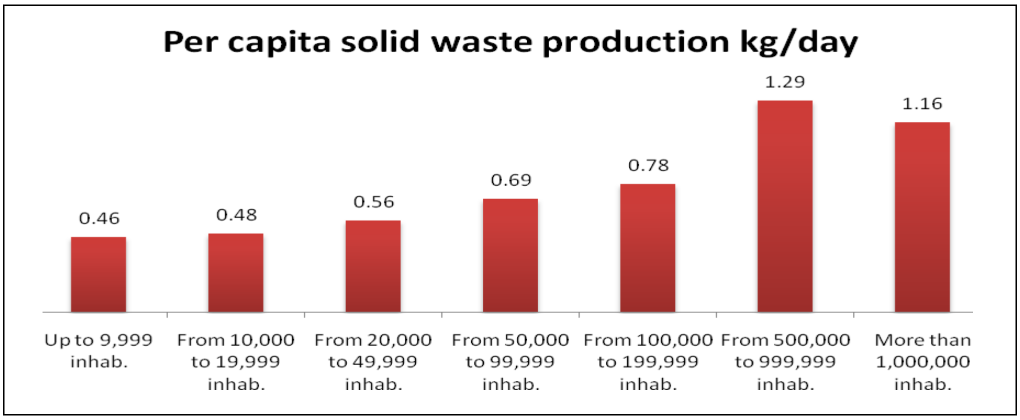

Figure 1 – Per capita production of solid waste in kg/day
Source: IBGE (2000)

With population growth and the consequent increased consumption of food goods per capita, and according to the Demographic Census of the Brazilian Institute of Geography and Statistics (IBGE, 2000), 81% of the Brazilian population is concentrated in urban areas causing an increasing volume of waste produced, thereby demonstrating the importance of waste management in urban areas.

In general, in a city there are three main types of collection used to collect waste: that one for urban waste, the one for hospital waste and the selective waste collection. The collection of urban waste, the topic covered in this work, consists of the gathering and transportation of household and urban waste produced in residences, condominiums, public institutions, and commercial, industrial and services establishments.

The methodology used in this work consisted basically of the following steps: 1) obtain data to develop the solution; 2) identify and implement the mathematical algorithms capable of solving the problem; 3) analysis of the solution obtained by checking if the results were consistent with the observed reality. In order to illustrate the proposed methodology, it was applied to the collection of solid waste in an area of the city of Joinville, State of Santa Catarina.

This work is organized as follows: in section 2 are described the problem and how data were obtained; section 3 presents the mathematical algorithms to solve the problem (step 2 of the methodology). The results are presented in section 4 and finally, in section 5 are the conclusions.

2 PROBLEM DESCRIPTION

To apply the methodology herein proposed, a pilot region of the city of Joinville was defined, as shown in Figure 2, located north of the State of Santa Catarina, covering about 9 km² and including a population of about 35,000 residents. This region is urban, predominantly with houses and residential condominiums, featuring in this way, uniformity in service with respect to collection.

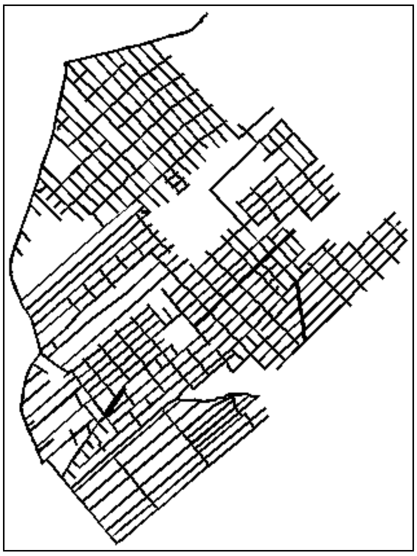

Figure 2 – Map of the region analyzed in the city of Joinville, SC.
Source: Google Earth (2009)

To obtain the data (coordinates of the demand points that represent the edges - or portions of streets - to be traveled by trucks, as well as the distance between them) used to develop the solution, was used the software Google Earth in which the geographical points were registered in two different ways.

In the first way, as shown in Figure 3, below, the points were registered in order to obtain the Euclidean distances between them. To include the analyzed area, it was necessary to register 2,128 points. It should be noted that in that way, one or more points had to be registered within the same block, depending on the distance from one crossroad to the other, so that the distance between points was no greater than the size of one block to another, so that in the final solution there were no route stretches passing "over" blocks. In the detail of Figure 3, it appears that the distances between the blocks are 78,92 and 68,97 meters and the distance between the registered points are 48,42 and 48,92 meters, this is, by registering “inside points” in the block, one can avoid the problem mentioned.

In the second way used to obtain the geographic points, as shown in Figure 4, the API feature of Google Maps was used which, in itself, prevents the passage "over" blocks, because it is able to directly calculate the smallest distance between two points, also considering the topography of the land. Thus, it is not necessary to register "internal points" (extra) within the same block thus significantly reducing the amount of points required (from 2,128) to 560.

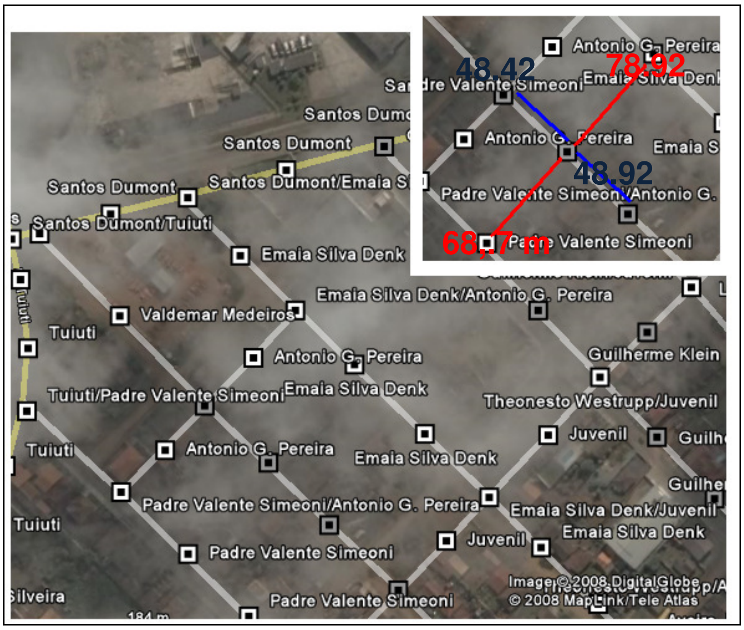

Figure 3 – First way used to obtain the geographical points.
Source: Google Maps (2009)

Figure 4 – Second way used to obtain the geographical points.
Source: Google Maps (2009)

3 MATHEMATICAL ALGORITHMS TO DEVELOP THE WORK

The proposed mathematical algorithms, which make up the methodology, were defined as follows and whose application should occur in sequence: 1) the Teitz and Bart heuristic algorithm to obtain the p-medians and each one of them "should work" as a fictitious deposit for the later grouping of demand points, 2) the modified Gillett and Johnson heuristic algorithm so that by defining the p-medians, it groups the demand points to them, forming p-groups, 3) the exact Chinese Postman algorithm to obtain the routing (or sequence) of points to be crossed within each group.

3.1 The Teitz and Bart Heuristic Algorithm

The Teitz and Bart's heuristics (TB; TEITZ and BART, 1968) is based on the replacement of vertices and its purpose is, from an initial solution, to improve the value of the objective function at each iteration.

The basic procedure of the TB *p*-medians algorithm is described below.

- **Step 1.** Select randomly a $V_p \subset V$ set with $|V_p| = p$ to form an initial solution for the problem.
- **Step 2.** Label all vertices $v_i \in \{V - V_p\}$ as "not examined".
- **Step 3.** While there are non-analyzed vertices in $\{V - V_p\}$ do the following:

Select a $v_i \in \{V - V_p\}$ non-analyzed vertex and calculate the Δ_{ij} reduction in the transmission number for all v_j vertices belonging to V_p, this is:

$$\Delta_{ij} = \sigma(V_p) - \sigma(V \cup \{v_i\} - \{v_j\}), \forall v_j \in V_p$$

Make $\Delta_{ij\_máximo} = \text{maximum}\lfloor \Delta_{ij} \rfloor$, for every Δ_{ij} previously calculated.

If $\Delta_{ij\_máximo} > 0$ then:

Make $V_p = (V_p \cup \{v_i\} - \{v_j\})$ and insert v_j into $\{V - V_p\}$

Label v_j as "analyzed".

Else, continue.

- **Step 4.** If during the execution of step 2 there is a change in set V_p, then back to step 3 and continue the execution of the algorithm.

Else, stop and submit set V_p as an approximate solution for the *p*-medians problem.

This heuristic is easy to implement and produces satisfactory solutions. However, here is proposed a change in it in order to reduce processing time without altering the final result.

The proposed change is in step 2 of this algorithm, which consists in initially testing the distance between each one of the v_j vertices belonging to V_p and vertices $v_i \in \{V - V_p\}$. One can see that in case the vertices of a new formation $V \cup \{v_i\} - \{v_j\}$ are very close, the algorithm will be performing an inadequate combination of *p*-medians, this is, "unnecessary". Thus, including a parameter that determines a minimum distance between the candidate *p*-

medians, the number of combinations to calculate Δ_{ij} is reduced and the algorithm will have its computational time significantly decreased.

For this study, the value of *p = 5*, this is, 5-medians are set so that later 5-groups, which is the number of groups recorded during the research, are defined in order to be able a comparison between their settings (current and optimized).

3.2 Modified Gillett and Johnson Heuristic Algorithm

Once the medians are obtained, one must then determine which will be the group of demand points to be attended to by each of the medians (trucks). This is obtained from the designation algorithm proposed by Gillett and Johnson (G&J) (BODIN *et al.*, 1983) described below and adapted as proposed here to include the restriction feature.

- **Step 1.** Calculate the distance between each *i* demand point not yet appointed until each one of the medians (trucks), whose corresponding trucks have no "capacity". In this work this is the distance the truck shall travel. The average "capacity" of each truck was defined in terms of distances as follows, where "5" means the number of trucks:

  Capacity = (total distance to be traveled / 5),

- which in this work will be approximately 70 km.
- **Step 2.** For each demand point *i* from the previous step, obtain t_i^1 as the closest median to *i* and t_i^2 as the second nearest median to *i*, with distances equal to c_i^1 and c_i^2, respectively.
- **Step 3.** For all *i* demand points in the previous steps calculate the ratio $r_i = c_i^1 / c_i^2$. Sort nodes *i* in according with the r_i values, in ascending order. This list determines the order in which the demand points will be assigned to each one of the medians; those points relatively close to a median will be considered first.
- **Step 4.** Scroll through the list in step 3, designating the *i* points to the closest medians, until the "capacity" of some of them is exhausted. In this case, remove all nodes *i* already designated, as well as the median (truck) with exhausted "capacity", and go back to step 1.

By designating the demand points to each one of the 5-medians, the result is obtained for the service areas, this is, and the groups of points (clusters) to be served by each truck are defined.

3.3 Chinese Postman Algorithm (Exact)

Each group of demand points, this is, edges (or block stretches, as illustrated in Figures 3 and 4 above) to be traveled by the trucks, should be covered so as to form an Eulerian circuit. The Chinese Postman Problem (CPP) is an optimization problem that aims to cover with a single route all the edges of a road network, in the case of the application discussed here, minimizing the total distance traveled.

Its study is highlighted by some researchers, for example, Costa et al. (2001) proposing a solution to the problem of mail delivery carried by the postal services, where the Chinese Postman Algorithm is compared with several node covering algorithms. In their turn, Stern and Dror (1978) apply the Chinese Postman Algorithm in the study of routes of power meter reading; Eglese and Murdock (1991) present software to optimize the streets cleaning service with broom-vehicles. Ghiani and Improta (2000) present a variant of the classic CPP, the Hierarchical Chinese Postman Problem, whose arcs are divided into groups (clusters), the preceding relation, is defined in the clusters and its practical application can be seen in the snow and ice control on streets and roads.

The solution to the CPP can be obtained from the CPP's mathematical model, or else by the Chinese Postman Algorithm, both of which provide the exact solution, according to Bodin *et al*. (1983). Here is the algorithm in a brief way.

- **Step 1.** Be $[c_{ij}]$ the array of costs of the edges of graph $G(X, A)$, where X is the set of nodes and A is the set of edges. Using Floyd's (CHRISTOFIDES, 1974) algorithm, form the array $D = [d_{ij}]$ of size $| X^- | x | X^- |$, where d_{ij} is the cost of the shortest path between vertices $x_i \in X^-$ and $x_j \in X^-$, and X^- is the set of vertices of odd degree, as is the array of paths $\theta = [\theta_{ij}]$ of size $| X^- | x | X^- |$ through which these minimum costs were achieved.
- **Step 2.** Find the "matching" M^* among the vertices of X^-, this is, the best combination of vertices of odd degree, taken two by two, so as to produce the minimum cost according to the array D.
- **Step 3.** If a vertex x_α is associated with a vertex x_β in M^*, identify the path of least cost $\mu_{\alpha\beta}$, corresponding to cost $d_{\alpha\beta}$ in step 1. Enter artificial edges in G, corresponding to the edges of $\mu_{\alpha\beta}$, repeating this procedure for all other vertex combinations of the "matching" M^* in order to obtain the s-graph $G^-(M^*)$.

- **Step 4.** The total cost of array [c_{ij}] for all edges in $G^{-}(M^*)$, taking the cost of artificial edges to be equal to the cost associated with the real edge in parallel, is the minimum cost for the CPP. The number of times a *(xi, xj)* edge is "crossed" by the circuit is equal to the number of edges in parallel between x_i and x_j existing in $G^{-}(M^*)$.

4 OBTAINING RESULTS

The algorithms presented in section 3 of this work were implemented using the Oracle Database 10G Express technology, distributed freely at the supplier's the site.

4.1 Results of the TB Algorithm

In applying the TB algorithm, were considered the points registered by the two ways presented in section 2 (Figures 3 and 4), which generated 2,128 and 560 demand points, respectively. In Table 1 (self-explanatory) below, we have the results of the computational implementation of the TB algorithm.

Table 1 – Comparison between the performances algorithms Classic Teitz and Bart and Modified Teitz and Bart

Distance Array	N°. of Points	Classic Teitz and Bart		Modified Teitz and Bart		Result 5-Medians
		Time	Iterations	Time	Iterations	
Euclidean	2,128	05:50:16	12	00:35:59	12	216;777;877; 1009;1455
Shortest distance between the points	560	00:04:12	9	00:02:24	9	71;477;560; 229;300

Source: Research

The 5-medians found by the TB algorithm using the Euclidean distances (Table 1) are illustrated in Figure 5 (red dots), where one can see that there are two very close points (777 and 877). In Figure 6, using the shortest distances between points, the 5-medians were more apart, this is, and they were more evenly distributed.

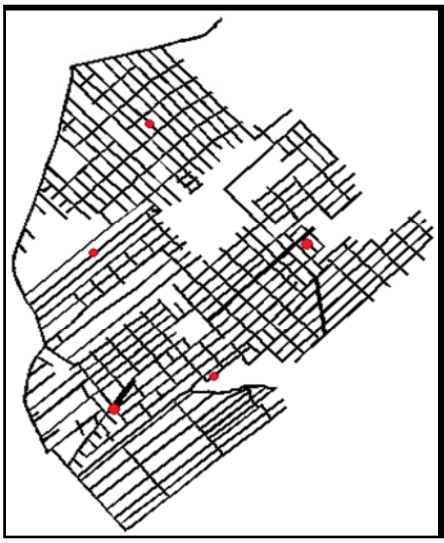

Figure 5 – Obtaining the 5-medians (Euclidean distance)
Source: Research

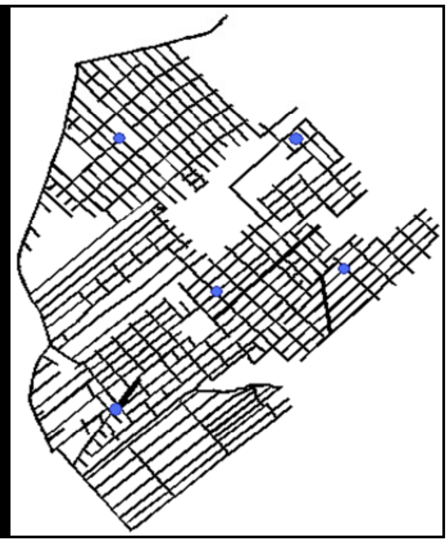

Figure 6 – Obtaining the 5-medians (Smaller distance)
Source: Research

4.2 Results of the Modified GJ Algorithm

Figure 7 below shows how they were, by the time of the research, the service areas for each truck in the studied area, and in Figure 8 is the result of the designation after the implementation of the Modified GJ algorithm.

Figure 7 – Division during the research
Source: Research

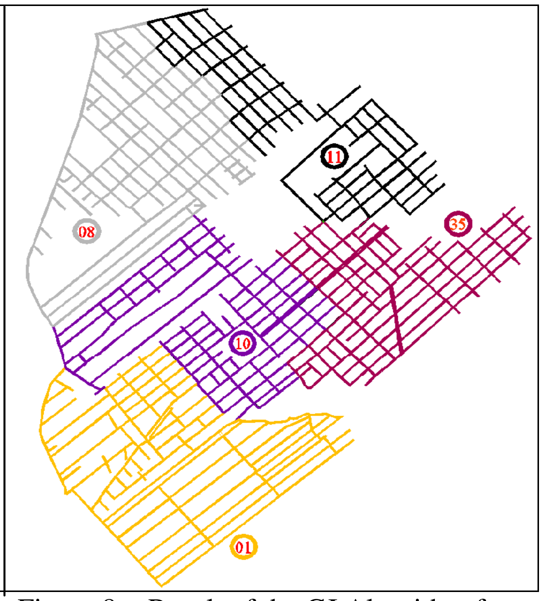

Figure 8 – Result of the GJ Algorithm for the waste collection
Source: Research

4.3 Results of the Chinese Postman Algorithm

The Chinese Postman algorithm was applied on Route 08 (light gray) in Figure 7, this is, making use of the division made during the research by the company responsible for waste collection in Joinville, so that the routes (the company's and the optimized one) could be compared. The total cost (in terms of distance) to travel this route is 19,355 meters, as shown in Figure 9. It was found that the best place to start collection was the Santos Dumont street, corner with the Valdemar Medeiros street (red point in Figure 9), because after collection, the truck should go to the landfill to dump the solid waste.

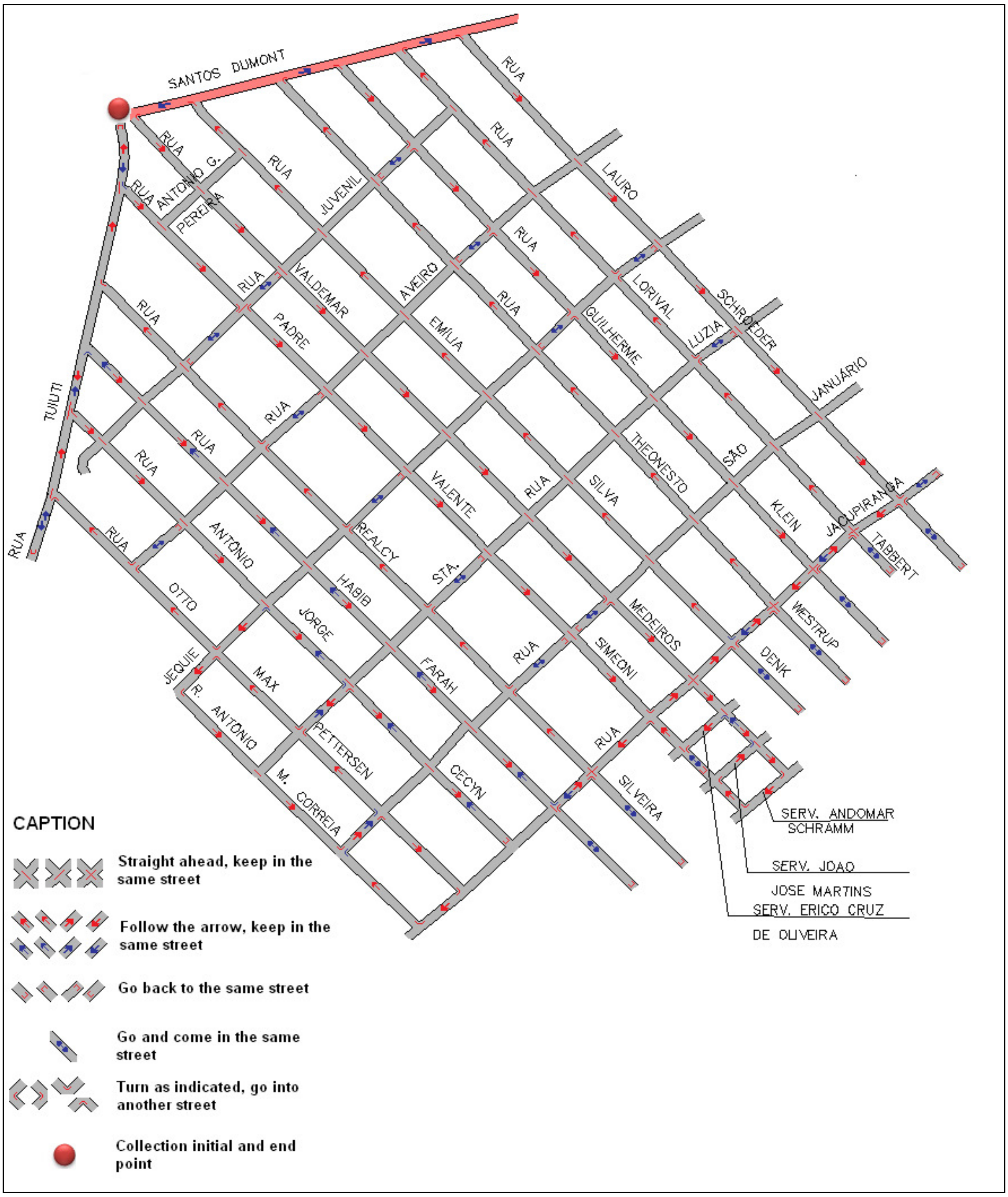

Figure 9 – Path obtained by the Chinese Postman Algorithm for Route 08.
Source: Research

Table 2 below presents a comparison between the averages of 17 collections recorded on Route 08 during the months of March and April 2009, and the result achieved, this is, the optimal solution with the Chinese Postman Algorithm. The paths considered were (Table 2): a) since the truck left the garage to the beginning of collection, b) during the collection of solid waste (Route 08), c) leaving this area to the landfill to dump the waste and, finally, d) its return, this is, from the landfill to the garage.

Table 2 – Comparison between the current average for waste collection and the result reached by the Chinese Postman Algorithm for Route 08.

Paths	*Average of the Company (m)*	*Optimized Solution (m)*	*Difference (m)*	*Difference in Results %*
a) Barra Velha Street (leaving the garage) to the Santos Dumont Street	14,500	14,500	0	0.00 %
b) Routing of solid waste collection (Route 08)	**21,000**	**19,355**	**-1,645**	**7.83 %**
c) Santos Dumont Street to Bororós Street (leaving Route 08 to the landfill)	12,000	10,300	-1,700	14.17 %
d) Bororós Street to Barra Velha Street (arriving at the garage)	18,500	14,500	-4,000	21.62 %
Total ≈	**66,000**	**58,655**	**-7,345**	**11.13 %**

Source: Research

With the implementation of the Chinese Postman Algorithm a 1,645 meters gain for Route 08 was obtained, which is equivalent to 2.49% (1,645/66,000) of the total gain, and a gain of 7.83% (1,645/21,000) if considered only the routing in the area of solid waste collection (item b, Table 2). We can see that if an optimization process is adopted in the different routing paths (items a, c, d, Table 2), besides Route 08, one can reach a gain of approximately 5,700 meters (7,345-1,645) which is equivalent to 8.6% (5,700/66,000) of the total gain.

5 CONCLUSIONS

The purpose with this paper is to introduce a methodology composed of mathematical algorithms and computer implementation for the optimization of routes in a problem of arcs covering. Obtained the coordinates of the geographic points through which the trucks will run through, the TB algorithm was used providing a satisfactory solution for the determination of 5-medians, especially when used the option of seeking the shortest distance between the demand points considering the path of the streets, making use of the API feature of Google Maps. The change in the TB algorithm to include a parameter to compare distances between the medians in the generated combinations before using the algorithm enables the problem to be solved in a much smaller computational time (Table 1).

By adapting the GJ algorithm, a satisfactory result was obtained in the formation of areas (groups of points or edges) to be served by each one of the trucks. The difference between the areas defined by the responsible company and the areas obtained by this heuristic can be seen (Figures 7 and 8).

The use of the Chinese Postman Algorithm ensures optimal routing. Table 2 shows that in addition to implementing the Chinese Postman Algorithm to the area of solid waste collection (Route 08), which already accounts for gains, it would also be interesting for the company to optimize the various paths from when the truck leaves the garage until it starts the collection, from the end of the collection to the landfill and the return to the garage. By implementing this procedure one can obtain a gain of approximately 8.6% in the total distance spent daily, in addition to the gain for Route 08. Considering that the city of Joinville is made up of about 70 routes and, moreover, this service must be run daily, we have that the saving is, in fact, substantial.

The result achieved provides quite a satisfactory solution to the problem of minimum distance for the collection of urban waste. The methodology presented here can be used in similar problems such as, for instance, reading power, water (SMIDERLE; STEINER, 2001) or gas consumption, among other situations.

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