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"That's (not) Rubbish!" Planning the Reverse Logistic for Recyclable Solid Waste Using a Vehicle Routing Problem: A Case Study in Vitória/ES

Hendrigo Venes*, Tânia Galavote, Rodrigo de Alvarenga Rosa, Renato Ribeiro Siman

Department of Environmental Engineering, Federal University of Espírito Santo, Vitória 29075-910, Brazil

Corresponding Author Email: hendrigo.pereira@ufes.edu.br

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ABSTRACT

The rapid growth of urban populations has led to a significant increase in municipal solid waste generation, raising concerns about waste disposal, environmental impact, and associated costs. This paper aims to plan a strategy for the reverse logistics of selective waste collection in a medium-sized city in Brazil to achieve more effective and economical waste collection. Firstly, the methodology of the Brazilian National Foundation of Health was applied to determine the fleet of vehicles needed to collect recyclable waste from Volunteer Delivery Stations. Subsequently, a Vehicle Routing Problem with Multiple Trips (VRPMT) was proposed as a case study for the city of Vitória, Brazil. This study represents the first application of VRPMT to a medium-sized city with geographically dispersed collection points, introducing multiple routes within a single day and presenting a paradigm shift. The results obtained from the mathematical model indicate a potential route savings of 48.7% using linear programming analysis compared to the existing municipal solid waste collection planning. The model can serve as a tool to support the planning of reverse logistics for recyclable solid waste, assisting city councils in reducing logistics costs by automatically planning standardized trips with only the input data required. However, the model's applicability is limited to small instances. Future research could consider employing a Simulated Annealing (SA) metaheuristic to solve larger instances, enabling the planning of future expansions of the selective waste collection system.

1. INTRODUCTION

Considering the population growth in recent years, it is possible to establish a relation between this populational expansion and the significant increase in the generation of Municipal Solid Waste (MSW). This increase leads to inefficient management of MSW and eventually overloads the capacity of existing sanitary landfills. Moreover, due to the lately concerns regarding the interest in sustainable resource utilization and quality of life, most institutions and municipalities are moving towards efficient solutions to control urban waste collection issues.

The urban cleaning and Solid Waste Management System (SWMS) includes the activities of collection, transshipment and transport, sorting for reuse or recycling, sweeping, weeding and pruning of trees on roads and public places and other eventual services related to the urban public cleaning [1]. In municipal solid waste management, up to 70% of the budget is spent on collection and transport [2]. Specifically, in the municipalities of low-income countries, it can represent the highest budget item, accounting for approximately 20% of municipal costs [3].

In 2018, 62.8 million tonnes of MSW was collected from households and public buildings, according to the National System of Sanitation Information [4]. The resources spent within waste management operations accounted for approximately BRL 16 billion, and about BRL 6 million was spent only on transportation and collection of solid waste. Recyclable solid waste can be collected in two different ways: door-to-door collection (when the collection occurs directly in a building) and in Volunteer Delivery Stations (VDS), Figure 1, when citizens deliver the recyclable waste to stations.

Figure 1. Volunteer Delivery Stations of selective waste (The authors, 2022)

Considering the integrated management of solid waste, selective collection and recycling, in addition to reuse and decrease in the waste generation, are considered alternatives to the final treatment of residues. Reverse logistics is the process of returning packings or any part of the product to the manufacturer using a reverse supply chain system for re-manufacturing or recycling. This process is directly linked to the recycling sector. The selective collection, for recycling and reuse, has grown considerably worldwide especially considering that future cities tend to care more about sustainability. In Brazil, especially after the approval of the Brazilian National Policy on Solid Waste [5], the indexes of selective collection have increased and currently, there are 22% of Brazilian municipalities with selective collection, it aims to achieve 100% of the population of the state of Espírito Santo, until 2040 [6]. Due to this fact, the costs to manage SW have increased, since the municipality has implemented selective collection and it is more expensive than the regular collection, about 4.5 times more expensive than the conventional collection.

In addition, due to the rapid development and diffusion of Internet of Things (IoT) and Information and Communication Technology (ICT) applications, urban informatization has grown briskly and the term Smart City (SC) has been broadly used. The SC idea was first proposed by IBM at the Council on Foreign Relations in New York (2008), it is defined by the application of ICT to acquire, analyze and integrate important information about cities [7]. The SC concept is widely used to deal with challenging issues such as resource scarcity, environmental pollution, traffic congestion among others. When talking about a smart environment, it is necessary to think not only about intelligent structural systems, but also about population, its solid waste generation, and how technology will impact the way municipal solid waste will be treated.

Cities proposing the waste collection route by the intelligence of the demand can bring better results, eliminating the exceeding waste and deposing favorable, preserving the environment and contributing to the visual health of the municipality. A mathematical model to plan the collection of waste can be used as a tool to support the planning of the reverse logistics of the RSW, and it may help the city council to reduce the logistics cost. In addition, planning the routes of collection no longer need to be made manually, it is possible to automatically plan the routes in a standard way, requiring only input data. Using vehicle routing problem with multiple routes during one day can be a paradigm shift, and it has not been applied to the selective waste collection of a medium-sized city. Therefore, this paper aims to analyze and propose planning strategies for the reverse logistics of selective collection currently carried out in a medium-sized city of Brazil in order to achieve more effective and economic reverse logistics of this type of waste. It was also analyzed the possible gains of the selective collection carried out in the city of Vitória – Espírito Santo, when the collection routes are optimized.

This paper is organized as follows: Section 2 presents a literature review of Vehicle Routing Problem. Section 3 presents the methodology and the studied problem. Section 4 presents the results and discussions. The last section presents the conclusions of the study and suggestions for future research.

2. LITERATURE REVIEW

In this section, some vehicle routing concepts are presented, in addition to a taxonomy of solid waste collection route optimization problems.

The Vehicle Routing Problem (VRP) has been widely studied in the last years and during this time, many mathematical models and heuristics have been suggested for many cases. To address these cases, different extensions of the VRP have been proposed adding different constraints for each type of problem. One of these extensions is the Vehicle Routing with Multiple Trips (VRPMT), which is important in the context of transport companies that perform many trips during the day. Despite its importance, VRPMT has been only investigated in the last two decades, and few papers were published so far [8].

Optimization models are commonly used in order to reduce waste collection costs [9]. The first study on economic optimization was carried out by Anderson and Nigam [10], and since then, several authors have worked with cost minimization in the objective function.

The traditional MSW collection method consists of collecting household waste (door-to-door collection) and dry waste from Voluntary Delivery Points (VDSs) with predefined stops and routes and transporting the waste to the disposal station in trucks along the stipulated routes. This process generates labor costs, fuel costs, maintenance, among others, being considered a very high cost and responsible for most expenses with urban waste [11].

Using dynamic routing model, Abdallah et al. [11] developed a model to reduce costs and carbon dioxide emissions. In the study, it was possible to reduce 10% of the costs and between 5 and 22% of emission, using a model associated with IoT based bins.

Using a multi-objective optimization model to design a cost-effective waste management supply chain, Olapiriyakul et al. [5] considered sustainability issues such as land-use and public health impact. The model presented 20% cost reduction and above 50% satisfaction level.

Rizvanoğlu et al. [12] applyed more than one technique to develop ideal routing for the collection and transport of solid waste, aiming to reduce costs to a minimum, along with the geographic information system to determine the best route it was possible to save 28% of the route with GIS analysis and more than 30% with linear programming analysis according to existing routes for collecting and transporting urban solid waste.

Generally, collection and transport are the most important and expensive aspects of the process due to the labor intensity of the work and the massive use of vehicles in the collection and transport process [13].

Marseglia et al. [14] developed a mathematical model, based on the Bin Packing and VR schemes, for the deployment of routes of mobile containers in the selective collection of urban solid waste. The authors obtained above 19%, on average, of improvement. In the number of vehicle routes dispatched from the depot, the improvement remains inconclusive.

Jorge et al. [15] used a hybrid metaheuristic to solve the smart waste collection problem with workload concerns. The authors developed a look-ahead heuristic to decide the days on which collection is necessary and which bins need to be collected and also a simulated annealing/neighborhood search algorithm to choose the bins that are profitable to collect and the best routes to visit the bins. The results achieved by the hybrid metaheuristic were at least 45% higher than the profit obtained by the company.

Rathore and Sarmah [16] published a study that examines the economic, environmental and social viability of circular economy in MSW management. A concept is proposed for utilizing collected organic MSW, converting it into biogas and then using it as fuel in a thermal power plant to reduce the load on coal mines. For this, a nonlinear mixed integer program (MINLP) model is formulated for the minimization of the total cost which is the sum of (i) running cost, (ii) transportation cost, (iii) rental cost, (iv) environmental cost, (v) social cost, and (vi) penalty cost. With the application of the model in a case study in the city of Bilaspur, India, it was possible to verify the reductions in carbon emissions, reductions in social costs and even a 60% reduction in the cost of transport due to the optimization of routes and reduction of the amount of vehicles. The authors conclude that it is possible to apply the model globally, however, according to the analysis of collection costs, the model performs better in high-income countries compared to low-income countries for the same scenario.

Using a novel robust bi-objective multi-trip periodic capacitated arc routing problem under demand uncertainty to treat the urban waste collection problem, Tirkolaee et al. [17] aimed to minimize the total cost and minimize the longest tour distance of vehicles. The largest change in the total cost was the reduction of 11.97% which occurred for 20% increase in the longest allowable tour, and the largest change in the longest tour was the reduction of 25.29% for a decrease of the parameter.

Braier et al. [18] used mathematical programming techniques to optimize the routes of a recyclable waste collection system. The study was applied to the city of Morón, a large municipality outside Buenos Aires, Argentina and it was possible to achieve improvement while in some cases actually reducing total vehicle distance compared with the old manual routes. In a few cases, distance did increase, but only slightly.

Jatinkumar Shah et al. [19] developed a stochastic optimization model based on chance-constrained programming to optimize the planning of waste collection. The study aimed to minimize the total transportation cost while maximizing the recovery of value still embedded in waste bins. The authors considered High and Low-capacity trucks (LCT), and as the low-capacity vehicles increase, the value of the objective function or the transportation cost decreases. This conclusion was based on the point that the fixed cost of adding new LCT.

The VRPMT is an important mathematical model for real situations occurring in daily logistics and yet it has few published papers. Most of the published papers deal with new methods to solve it. Very few papers deal with real cases.

3. METHODOLOGY AND STUDIED PROBLEM

All municipalities face the challenge to maintain the same current budget and also to perform conventional waste collection along with the selective collection. One possible way to maintain the current budget is to plan better routes, aiming to minimize traveled distance by the trucks during the collection, as well as minimize the number of trucks required to collect the waste.

In first place, the methodology proposed by the National Foundation of Health [20] was applyed to dimension the fleet of vehicles needed to collect the recyclable waste from the VDSs. The daily amount of recyclable waste to be collected is calculated in Eq. (1):

$$Q = H\,G/1000 \tag{1}$$

where:

H: Urban population with regular collection service [21];

G: Estimated amount of daily recyclable waste generated by inhabitant (kg/inhabitant/day), adopted 0.01 [22].

Calculation of the time spent, per trip, with transportation from the collection site to the final destination of the waste, Eq. (2):

$$Tv = \frac{2D}{Vt} + T1 \tag{2}$$

where:

D: Distance from the beginning of the trip until the unloading point (km);

Vt: Average speed from the depot to the VDS (km/h), adopted 30 km/h;

*T*1: Time spent with access, unloading the VDS and exit of the site (h), adopted 0.35 h.

The number of daily possible trips per vehicle is calculated below, Eq. (3):

$$NV = \frac{Q\ VC\ J}{(L\ c)+(Q\ VC\ TV)} \tag{3}$$

where:

VC: Average collection speed (km/h), adopted 10 km/h;

J: shift time (h), adopted 8 hours;

L: extension of the streets traveled in the collection (km), adopted 546 km [21].

Finally, the calculation of the necessary fleet for solid waste collection is shown in Eq. (4):

$$F = \frac{1}{NV}\,\frac{Q}{c}\,(1+K) \tag{4}$$

where:

c: capacity of cargo per trip, adopted 3.96 tons for a 6m³ truck [20];

K: number of spare vehicles, adopted 0.1.

The distances between VDSs were extracted from Google Maps®. Based on Ávila and Gil [23], the fixed and variable costs of a collection truck without compression were set to BRL 8,538.98 and BRL 2.72/km, respectively. The number of collection trucks was defined using the dimension methodology provided by the National Brazilian Health Foundation [20], according to Table 1.

Table 1. Input data to calculate the necessary fleet of truck

P	Number of VDSs	73
H	Population to be served by the fleet (inhabitant) (IBGE 2010)	365,855.00
L	Total extension of municipal streets (km)	546
L	Total extension of municipal streets to be served by the fleet (km)	546
D	Average distance from the depot to the unloading point (km)	65
J	Daily hours of work (h)	8
	Frequency of collection	Daily
F	Fleet to collect waste - Munk truck 10 m³	3.75

The necessary fleet found by the calculation proposed by FUNASA [20], 3.75, was altered to the higher integer number, in this case to 4 trucks to collect the recyclable waste in the city of Vitória.

4. PROPOSED MATHEMATICAL MODEL

The trucks, for collection of selective waste, start the trip from the central depot at the beginning of the shift work. From the depot, the trucks must go through all VDS in one shift and one trip finishes when the truck's capacity is reached. After reaching full capacity, the truck must return to the depot to unload. After the truck is unloaded, another trip is started in order to collect the VDS that were not collected yet. This process continues until the end of the work shift of the driver and the assistants.

The VRPMT applied to waste collection consists of routing vehicles from a fleet to collect solid waste while minimizing travel costs and distances. The VRPMT differs from the traditional VRP because the collecting trucks must empty the load at disposal sites. The problem is illustrated in Figure 2, for multiple vehicles and a single disposal site.

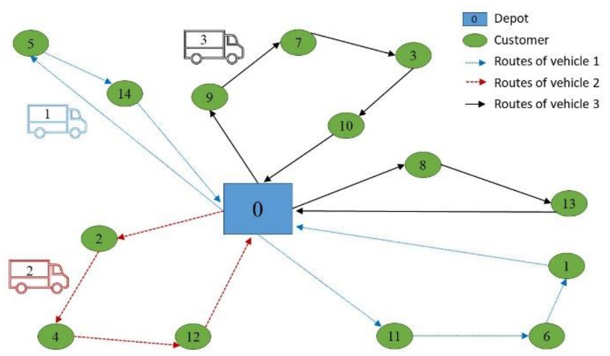

Figure 2. Schematic vehicle routing with multiple trips [24]

The proposed mathematical model is presented in five parts: the parameters, the sets, the decision variables, the objective function and the constraints. The VRPMT considers *np* the number of VDS; *nv* the number of vehicles in the fleet; *nt* the number of trips.

Mathematical model sets are:

C	set of VDS to be collected, $C \in \{1 \dots np\}$;
$C0$	set of VDS to be collected and the depot, $C0 \in \{0 \dots np\}$;
CV	set of VDS to be collected and the virtual depot, $CV \in \{1 \dots np+1\}$;
CT	set of VDS to be collected, the depot and the virtual depot, $CT \in \{0 \dots np+1\}$;
K	set of vehicles available, $K \in \{1 \dots nv\}$;
T	set of vehicles' trips, $T \in \{1 \dots nt\}$.

Mathematical model parameters are:

ds	distance between VDSs, depot and virtual depot;
vv	average speed of the vehicle;
dm	capacity of each VDS;
Q	capacity of each vehicle;
tu	shift work period;
M	parameter used for logic of the mathematical model, adopted the value of 9999;
m	parameter used for logic of the mathematical model, adopted the value of 0.01;
cf	fixed costs of each vehicle $k \in K$;
cv	variable costs of each vehicle $k \in K$;
lk	minimum number of vehicles in the fleet used for the collection;
nk	maximum number of vehicles in the fleet used for the collection.

Mathematical model decision variables are:

x_{ijkt}	binary variable that assumes a value 1 if *i* and *j* are visited in the same trip *t* of the vehicle *k*;
tc_{ikt}	Arrival time at node *i* of vehicle *k* in route *t*;
z_k	binary decision variable equals 1 if the truck *k* made at least one trip *r* and 0 otherwise.

Objective Function:

$$Minimize \sum_{k\in K} cf_k\, z_k + \sum_{i\in CT}\sum_{j\in CT}\sum_{k\in K}\sum_{t\in T} ds_{ij}\, cv_k\, x_{ijkt} \quad (5)$$

Subject to:

$$\sum_{k\in K}\sum_{j\in CV}\sum_{t\in T} x_{ijkt} = 1 \quad \forall\, i \in C \quad (6)$$

$$\sum_{j\in CV} x_{0jkt} = 1 \quad \forall\, k \in K, t \in T \quad (7)$$

$$\sum_{k\in K}\sum_{t\in T} x_{i0kt} = 0 \quad \forall\, k \in K, i \in CT \quad (8)$$

$$\sum_{k\in K}\sum_{j\in CT}\sum_{t\in T} x_{np+1jkt} = 0 \quad \forall\, k \in K \quad (9)$$

$$\sum_{i\in CT} x_{ihkt} - \sum_{j\in CT} x_{hjkt} = 0 \quad \forall\, h \in C, k \in K, t \in T \quad (10)$$

$$\sum_{i\in C} dm_i \sum_{j\in CV} x_{ijkt} \le Q_k \quad \forall\, k \in K, t \in T \quad (11)$$

$$\sum_{i\in C0}\sum_{j\in CV}\sum_{t\in T} \frac{ds_{ij}}{vv_k}\, x_{ijkt} \le tu_k \quad \forall\, k \in K \quad (12)$$

$$x_{iikt} = 0 \quad \forall\, i \in CT, k \in K, t \in T \quad (13)$$

$$x_{ijt} \in \{0,1\} \quad \forall\, i \in CT, j \in CT, k \in K, t \in T \quad (14)$$

$$tc_{jkt} \ge tc_{ikt} + \frac{ds_{ij}}{vv_k} - \left(1 - x_{ijkt}\right) M \quad \forall\, i \in C0, j \in CV, k \in K, t \in T \quad (15)$$

$$tc_{ikt} \ge 0 \quad \forall\, i \in CT, k \in K, t \in T \quad (16)$$

$$tc_{ikt} \le tu_k \quad \forall\, i \in CT, k \in K, t \in T \quad (17)$$

$$\sum_{j\in CV}\sum_{t\in T} x_{0jkt} \ge z_k m \quad \forall\, k \in K \quad (18)$$

$$\sum_{j \in CV} \sum_{t \in T} x_{0jkt} \leq z_k M \quad \forall\, k \in K \tag{19}$$

$$z_k \in \{0,1\} \quad \forall\, k \in K \tag{20}$$

$$lk \leq z_k \leq nk \quad \forall\, k \in K \tag{21}$$

The Objective Function (OF), Eq. (5), aims to minimize the total distance of all trips during the collection. The set of constraints (6) ensures that each VDS i is visited by a single vehicle k on a single trip t. Constraints (7) ensure that all vehicles must leave the depot, including to the virtual depot. Constraints (8) ensure that no vehicle return to the depot. Constraint (9) ensure that no vehicle can leave from the virtual depot. Constraints (10) represent flow networks, every vehicle arriving at node i must leave this node. Constraints (11) are capacity constraints, the total loaded on each vehicle k in a trip t cannot exceed the capacity Q_k of the vehicle. Constraints (12) guarantee that all vehicles must have a maximum time of travel and it must be inferior than the work shift. Constraints (13) guarantee that arches from a node to itself cannot exist. Constraints (14) ensure that variables x_{ijkt} are binary. The set of constraints (15) ensure that sub-tours are not created. Constraints (16) and (17) ensure that time must be inferior than the work shift and it cannot be negative. Constraints (18) and (19) were created for the logic in the model, variable z_k receives value 1 in case vehicle k performs a trip t and 0 otherwise. Constraints (20) ensure that variables z_k are binary. Constraints (21) guarantee the minimum and the maximum number of vehicles used to collect recyclable waste.

5. RESULTS

One scenario is proposed to assess the selective waste collection in the city of Vitória (Espírito Santo), a middle-sized city with 365,855.00 inhabitants, 83 neighborhoods and 73 VDSs geographically dispersed, as shown in Figure 3.

It was used CPLEX to run the mathematical model using a computer with Intel Xeon processor and 28 GB of RAM. Table 2 presents the results found by CPLEX. It has 7 columns: Column 1 shows the scenario number, Column 2 presents the number of VDSs, Column 3 is the OF, which represents the total cost of all trips of all trucks, Column 4 shows CPLEX's running time, Column 5 and 6, respectively, present the available number of trucks and the number of trucks used, Column 7 shows the total kilometers traveled by the trucks.

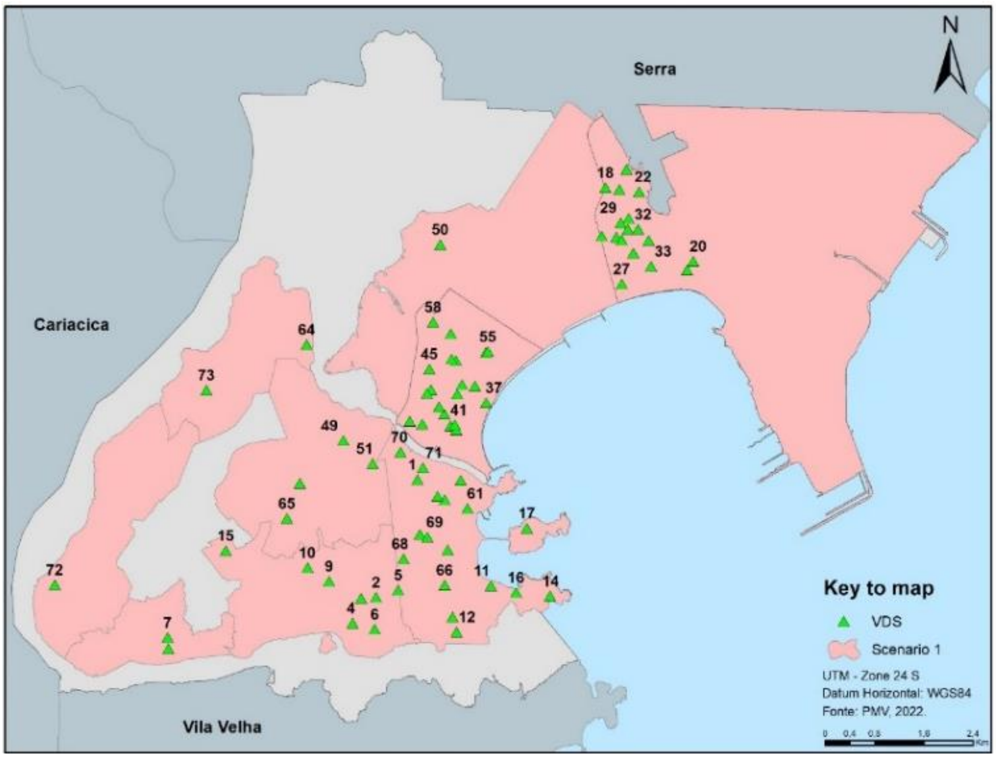

Figure 3. Location of the VDSs in the city of Vitória, Espírito Santo

Table 2. Results found by CPLEX

Scenario	Number of VDSs	OF (BRL)	Running Time (s)	Trucks Offered	Trucks Used	Km Driven
1	73	35,061.88	4,573.02	4	4	335.8

Table 3. Costs of the collection achieved by CPLEX

Fixed Costs (BRL)	Variable Costs (BRL/Km)	Daily Total Distance (Km)	Monthly Total Distance (Km)	Total Cost Per Month (BRL)
8,538.98	2.72	335.8	10,050.00	61,497.92

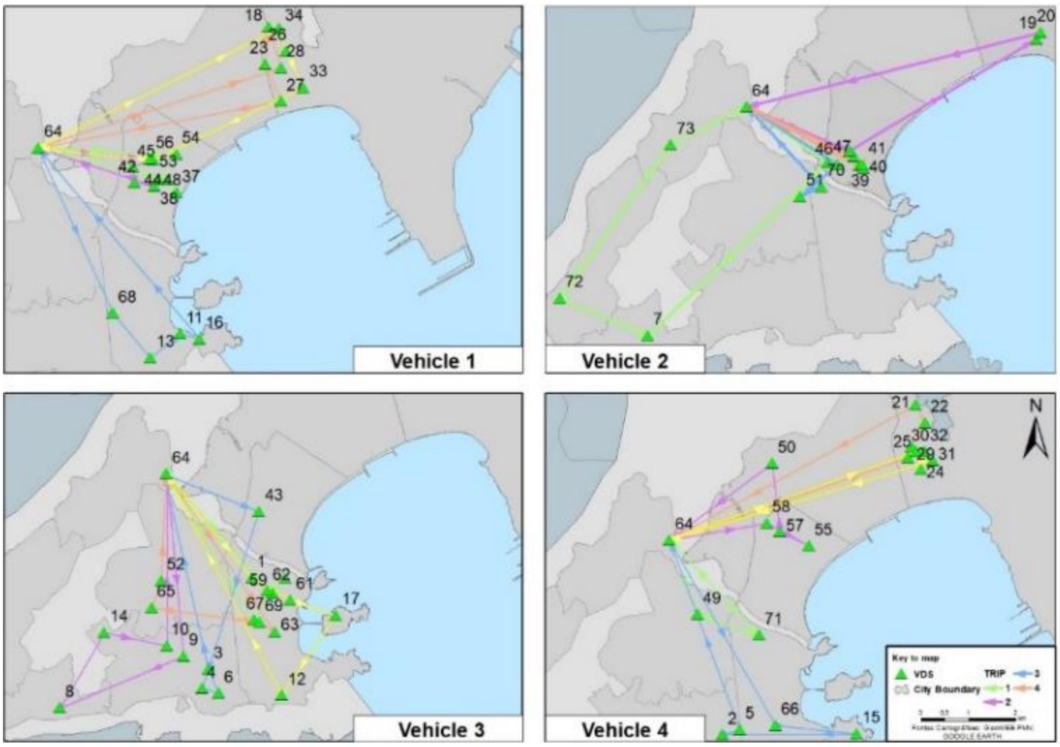

Figure 4. Routes to collect recyclable solid waste in Vitória – ES

In addition to the most economic scenario in 8 hours shift work, CPLEX also found the best routes to the collection of recyclable waste. as presented in Figure 4. Vehicles 1, 2 and 3 performed 4 trips, unloading at the depot when maximum capacity was reached. Vehicle 4 performed 3 trips, also unloading at the depot when maximum capacity was reached.

In order to simplify the process, the planners separate the trucks per neighborhood and designate the driver to perform the most convenient trip. CPLEX tries to find a solution by gathering all the VDSs close to each other on the same trip, without considering any border of the district, in order to maximize the capacity of the truck.

Analyzing the terms and conditions of contract 487/2014 [25] between the city council and the private company responsible for waste management in Vitória, it is possible to verify that the amount spent in the collection of selective waste to all VDSs in the city of Vitória was BRL 119,871.62 in December 2020 (PMV, 2022). Table 3 shows the costs for the collection achieved by CPLEX.

Therefore, the collection planned by CPLEX presents a solution 48.70% less expensive than the collection planned manually. This result reinforces the statement by Olapiriyakul et al. [26], in which the author state that with linear programming analysis, according to existing routes for collecting and transpotation of solid waste, it is possible to save more than 30% of the routes. Also, using multiple trips in a shiftwork period, presents better results. Ashik-Ur-Rahman et al. [27] developed ideal routes to transport municipal waste and compared them to the existing collection routes focusing in time and distance reduction. In their study, the author reduced 17 km travel distance, while the model proposed for 4 trucks in Vitória can save more than 50km travel distance.

With a hybrid metaheuristic, Jorge et al. [15] solved the smart waste collection problem with workload concerns, and the results achieved were at least 45% higher than the profit obtained by the company. These results are similar to the less expensive results achieved by CPLEX than the collection planned manually for the city of Vitória, Brazil. The use of multiple trips presented great differences in comparation of single trips, as the vehicles are not underemployed. A strong waste collection planning can aid the decision-maker choose the best alternatives. The use of multiple trips in vehicle routing allowed a better use of each truck in the fleet, and the tool assisted to calculate the routes and reducing the values.

6. CONCLUSION

There is an accelerated and constant increase in the urban population worldwide, and it has led to an exorbitant rise in municipal solid waste generation. Nowadays, there is a growing preoccupation concerning the disposal of the waste collected for the environment and society as well as the expenses associated with it.

This study developed a mathematical model to plan the reverse logistics of RSW collection, employing linear programming, to a medium-sized city in Brazil. First, the methodology developed by FUNASA [14] was applied to dimension the fleet of trucks, and then a mathematical model based on the VRPMT was proposed to optimize the routes to collect recyclable waste in the city of Vitória, Brazil. Simulating one scenario, where the fleet of trucks must collect the recyclable waste in VDSs geographically in an 8-hour work shift, the model presents economic benefits by promoting a reduction of costs associated with the collection. The results showed that it is possible to reduce the costs by 48.70%, compared to the manual planning currently performed by the city council, therefore, presenting a more efficient collection. The model can be used as a tool to support the planning of the reverse logistics of the RSW, and it may help the city council to reduce the logistics cost. In addition, the trips no longer need to be made manually, it is possible to automatically plan the routes in a standard way, requiring only input data. The introduction of multiple routes during one day proved to be a paradigm shift, and it has not been applied to the selective waste collection of a medium-sized city. A strong waste collection plan can aid the decision-maker choose the best alternatives, reducing fuel consumption and costs associated with the travel distances of the fleet of trucks. It should be stressed that the model is limited by small instances, since it cannot plan the routes of collection for a large number of VDSs with a small GAP.

Therefore, for future directions, a SA metaheuristic can be considered. Considering that exact methods are not able to solve large instances of the problem due to the combinatorial aspects of the mathematical model, the SA metaheuristic developed for VRPMT can solve bigger instances, since the problem is different from the classical VRP. The use of VRPMT and SA metaheuristic will allow to plan future expansions of the selective collection system with geographically dispersed points to large instances.

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NOMENCLATURE

H	Urban population with regular collection service
G	Estimated amount of daily recyclable waste generated by inhabitant, kg/inhabitant/day
D	Distance from the beginning of the trip until the unloading point, km.
Vt	Average speed from the depot to the VDS, km/h.
T1	Time spent with access, unloading the VDS and exit of the site, hours
VC	Average collection speed, km/h.
J	Shift time, hours.
L	Extension of the streets traveled in the collection, km.
c	Capacity of cargo per trip, m³
K	Number of spare vehicles