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A Bi-Objective Study of the Weekly Stability of Household Waste Collection in the City of Conakry, with the Number of Single-Frequency Collection Points Is Greater than That of Double-Collection Points

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Abstract

This article examines the weekly optimization of household waste collection in Conakry, Guinea. Faced with increasing waste volumes, the study proposes an organization into two sets of routes: at the beginning (S_{deb}) and end of the week (S_{fin}). The objective is twofold: to minimize the total cost (distance traveled) and to maximize stability between these two sets, i.e., to reduce their differences. The methodology is based on a mathematical model of the Vehicle Routing Problem with Time Windows (VRPTW) type, adapted to account for collection frequency (once or twice a week). The central hypothesis is that the number of single-frequency collection points is greater than that of double-collection points. For this scenario, two heuristic methods are designed and tested on modified Solomon instances. The results indicate a trade-off between the objectives. Method 1, which first builds tours for the Z_{c_2} nodes and then inserts the Z_{c_1} nodes, generally yields better results in terms of cost reduction. Method 2, which iteratively completes each existing tour, favors better overall stability between the beginning- and end-of-week routes. Thus, the choice of method depends on the priority set by the decision-maker: cost minimization or pursuit of operational stability.

Keywords

Waste Collection, Conakry, Optimization, VRP, CARP, Waste Management

1. Introduction

In this study, we focus on the weekly organization of household waste collection in Conakry. The problem consists of defining two sets of routes for each week: the first for early-week operations, denoted S_{deb}, and the second for end-of-week operations, denoted S_{fin}. The two objectives considered are cost reduction, measured by the total distance traveled, and reduction of disparities between both sets of routes, referred to as weekly stability. We propose heuristics that simultaneously integrate cost and stability objectives for route generation. The performance of these heuristics is evaluated on benchmark instances from the literature.

The analysis of weekly stability in Conakry's household waste collection occurs in a context where waste management has become crucial for urban quality of life and environmental preservation. As the capital city, Conakry faces continuous population growth, resulting in a significant rise in waste production. This situation puts considerable pressure on the operating capacity of ANASP–CONAG, responsible for waste collection. Optimizing collection routes is therefore indispensable to ensure efficient service delivery while controlling operational costs.

The investigation focuses on two major objectives: maximizing route stability and minimizing associated costs. Stability is essential to ensure service continuity, reduce environmental impacts, and improve resident satisfaction.

Weekly stability is a central concept in this article, extending beyond mere regularity. It is conceived as an optimization criterion aimed at reducing variations between the two sets of weekly collection routes (S_{deb} and S_{fin}). This stability is assessed from three complementary perspectives: 1) *operational stability* (resources and distances), 2) *stability for the user* (predictable collection times), and 3) *stability for the collection crews* (similar routes and workloads). Pursuing this stability, while balancing it with cost minimization, contributes to a more reliable service, improved work organization, and sustainable management.

As the capital, Conakry experiences continuous demographic growth, leading to a notable increase in waste production [1] [2]. This situation exerts strong pressure on the resources of ANASP-CONAG, responsible for collection, in a context where logistical and financial resources are often limited [3] [4]. Within this framework, optimizing routes is essential to ensure an efficient service while controlling operational costs [5] [6]. The investigation focuses on two major objectives: maximizing route stability and minimizing associated costs. Stability is paramount to guarantee service continuity, limit environmental impact, and improve resident satisfaction [7] [8]. The adopted methodology combines simulations to evaluate various collection scenarios. By studying waste production variations throughout the week, this research aims to propose organizational strategies adapted to the local specifics of Conakry, while relying on proven optimization models such as the Vehicle Routing Problem (VRP) and the Capacitated Arc Routing Problem (CARP) [9] [10].

The adopted methodology combines simulations to evaluate various collection scenarios, analyzing fluctuations in waste generation over time.

1.1. Problem Description

Household waste collection by ANASP-CONAG cannot be performed in a single day due to the large number of collection points relative to available resources (vehicles and staff). To optimize operations, the territory is divided into two zones, each serviced on different days: one zone is collected on Monday and/or Wednesday, or Monday and/or Friday, or Wednesday and/or Friday; for the other zone, on Tuesday and/or Thursday, or Tuesday and/or Saturday, or Thursday and/or Saturday. This division creates two fixed clusters covering the entire territory, with points collected once or twice per week.

An initial route solution is required to establish tours, considering collection frequencies set by local authorities: some points require two weekly collections, others only one. Frequency also influences waste quantity. Observations show that end-of-week volumes are often lower than early-week volumes, making the single early-week collection heavier.

1.2. Objectives

The study aims to identify collection strategies that ensure maximum efficiency while adhering to logistical constraints. The purpose of this article is to compare different methods for constructing two sets of routes: one for the beginning of the week and one for the end of the week. One hypothesis is examined: the majority of the points in c_1. A hypothesis is examined: most points collected once per week generate larger loads than points collected twice per week. This hypothesis was tested using GPSS (General Purpose Simulation System) due to the absence of recent data.

Several route-construction methods are proposed for this scenario, seeking both economically viable and stable solutions. Trade-offs between cost and stability are essential because the municipality operates with a fixed number of daily teams, while vehicle fleets can be adjusted at the end of the week. This adjustment directly affects performance and waste-management objectives.

2. Methodology

Optimizing waste collection has become a priority due to growing environmental constraints. Waste management requires precise identification of waste flows and adequate treatment pathways. Research aims to help operators reduce costs without compromising service quality while limiting environmental impact. Although optimized waste management is a relatively recent field, many studies have been conducted over the last two decades, most relying on two model families: the Vehicle Routing Problem (VRP) and the Capacitated Arc Routing Problem (CARP). CARP, often more relevant for household-waste collection, is less developed than VRP, which is more aggregated and easier to implement.

Several studies illustrate these approaches: a "route first–cluster second" heuristic for Singapore [11]; a model for fleet sizing in Belgium [12]; a method for organizing depots in Chicago to improve service levels [13]. More recent studies, such as those on hazardous waste [14], or those examining waste collection in urban environments [15], confirm the importance of CARP and VRP approaches.

Overall, these studies highlight the need for solutions tailored to local realities for effective and sustainable waste management.

2.1. Mathematical Model

The model describing the organization of the community (ANASP–CONAG) is based on the Vehicle Routing Problem with Time Windows (VRPTW), defined on a graph: $G=(Z,A)$ where:

- $Z=\{z_0,z_1,z_2,\cdots,z_{n-1}\}$ is the set of n vertices (nodes) of the graph representing all customers, with z_0 representing the depot,
- $Z=\{(z_i,z_j): z_i,z_j \in Z; i\neq j\}$ is the set of directed arcs representing the path between two vertices.
- Let:
- $K=\{1,\cdots,m\}$: the set of available vehicles;
- Q: The maximum capacity of the vehicles, identical for the entire fleet (homogeneous vehicles);
- q_i: The capacity to collect at the node z_i;
- d_{ij}: The distance traveled along the arc (z_i, z_j).
- The decision variables used are:
- $y_i^k=1$ if the node z_i is visited by the vehicle k and 0 otherwise.
- $x_{ij}^k=1$ si (z_i, z_j) is part of the vehicle tour k and 0 otherwise.
- $[a_i,b_i]$: The time window associated with the node z_i, with a_i representing the earliest acceptable arrival date and b_i the service end-of-service deadline;
- t_i: The node's service time z_i;
- t_{ij}: The node transport time z_i at the node z_j;
- u_i^k: The temporal decision variable representing the vehicle's arrival time k in the node z_i;
- M: A sufficiently large constant (large M).

The constraints of VRPTW are then written as follows:

$$\min\left(\sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} x_{ij}^k \cdot d_{ij}\right) \tag{1}$$

$$\sum_{i=1}^{n} q_i y_i^k \leq Q \quad (k=1,2,\cdots,m) \tag{2}$$

$$\sum_{i\in Z} y_i^k = 1 \quad (i=1,2,\cdots,n-1) \tag{3}$$

$$\sum_{k=1}^{m} y_i^k = m \quad (i=0) \tag{4}$$

$$\sum_{i\in Z} x_{ij}^k = y_i^k \quad (i=0,1,\cdots,n-1);(k=1,2,\cdots,m) \tag{5}$$

$$\sum_{j\in Z} x_{ij}^k = y_i^k \quad (i=0,1,\cdots,n-1);(k=1,2,\cdots,m) \tag{6}$$

$$\sum_{i\in Z} x_{ij}^k \le |X|-1 \quad (\forall X\subset Z, 2\le |X|\le n-2);(k=1,\cdots,m) \tag{7}$$

$$x_{ij}^k \in \{0;1\} \quad (i,j=0,\cdots,n-1; i\ne j);(k=1,\cdots,m) \tag{8}$$

$$y_i^k \in \{0;1\} \quad (i=0,\cdots,n-1);(k=1,\cdots,m) \tag{9}$$

$$a_i y_i^k \le u_i^k \le b_i y_i^k \quad (i=0,1,\cdots,n-1);(k=1,\cdots,m) \tag{10}$$

$$u_i^k + t_i + t_{ij} - M\left(1-x_{ij}^k\right) \quad (i=0,1,\cdots,n-1);(k=1,\cdots,m) \tag{11}$$

In this section, we have completed this model by specifying the node collection frequency and the stability objective. We now adopt the following rating:

- Z_{c1}: all the nodes collected once a week,
- Z_{c2}: all nodes collected twice during the week.

A solution S a VRPTW problem is characterized by its set of variables (x_{ij}^k, y_j^k).

2.2. Collection Frequency

In our problem, the frequency and possible combinations of days will be defined as follows:

- $f_i = 1$ if $z_i \in Z_{c1}$ and $f_i = 1$ if $z_i \in Z_{c2}$.
- R_i: possible combination of passages on the node z_i, with $R_i = \{start, end, start-end\}$. With respectively start represents the fact that the node is collected in $start$ of the week (Monday or Tuesday or Wednesday), in end the fact that the node is collected at the *end* of the week (Thursday or Friday or Saturday) and $start-end$, the fact that the node is collected at the *start* and *end* of the week (Monday and Thursday or Tuesday and Friday or Wednesday and Saturday).

2.3. Hypothesis: The Number of Single-Frequency Collection Points Is Greater than That of Double-Collection Points

This hypothesis stems from CONAG-ANAPS's desire to reduce the number of nodes collected in order to lower costs. Therefore, we consider the following possible combinations for node collection: $R_i = \{start, end, start-end\}$ $\forall z_i \in (Z_{c1} \cup Z_{c2})$ with $R_i = \{start, end\}$ or $z_i \in Z_{c1}$ and $R_i = \{start-end\}$ for $z_i \in Z_{c2}$.

In this context, we have a VRPTW-type problem. It involves assigning a collection day to the nodes to be collected in c_1 and to determine the routes belonging to S_{deb} and has S_{fin} while minimizing:

The total distance traveled from S_{deb}

$$\min\left(\sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} d_{ij}x_{ij}^{kdeb}\right) \tag{12}$$

The total distance traveled from S_{fin}

$$\min\left(\sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} d_{ij}x_{ij}^{kfin}\right) \tag{13}$$

The differences between S_{deb} and S_{fin}

$$\min\left|\sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} d_{ij}^{k}x_{ij}^{kdeb} - \sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} d_{ij}^{k}x_{ij}^{kfin}\right| \tag{14}$$

Stability Modeling

To study weekly stability, we enrich the basic model with expressions measuring the different levels of stability presented below. The stability objective is defined by the observed variations between the sets of tours S_{deb} and S_{fin}. For all methods, these variations are obtained by comparing characteristics of S_{deb} and S_{fin}.

Overall stability: its components, described in chapter 2, are calculated as follows:

- the difference in the number of vehicles:

$$E_{nbv} = \left|m_{deb} - m_{fin}\right| \tag{15}$$

or m_{deb} (resp. m_{fin}) represents the number of vehicles used in S_{deb} (resp. S_{fin}).

- the difference between the total distance of the tours of S_{deb} and that of the S_{fin} tours:

$$E_{dist} = \left|\sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} d_{ij}^{k}x_{ij}^{kdeb} - \sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} d_{ij}^{k}x_{ij}^{kfin}\right| \tag{16}$$

or d_{ij}^{k} is the distance traveled along the arc $\left(z_i, z_j\right)$.

- the difference between the total duration of the S_{deb} tours and that of S_{fin}:

$$E_{tps} = \left|\sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} t_{ij}^{k}x_{ij}^{kdeb} - \sum_{i\in Z}\sum_{j\in Z}\sum_{k\in K} t_{ij}^{k}x_{ij}^{kfin}\right| \tag{17}$$

or t_{ij}^{k} represents the travel time on the arc $\left(z_i, z_j\right)$.

Stability from the users' point of view: this is measured by the difference between arrival times at the S_{deb} nodes compared to those at S_{fin}:

$$E_h = \sum_{i\in Z}\sum_{k\in K}\left|st_i^{kdeb} - st_i^{kfin}\right| \tag{18}$$

Stability from the employees' point of view: It is evaluated by several differences between the tours of the same vehicle k in S_{fin} and S_{deb}.

- the difference in distance traveled by vehicle k between S_{deb} and S_{fin}:

$$E_{dist-emp} = \sum_{k\in K}\left|\sum_{i\in Z}\sum_{j\in Z} d_{ij}^{k}x_{ij}^{kdeb} - d_{ij}^{k}x_{ij}^{kfin}\right| \tag{19}$$

- the difference in vehicle collection time k between S_{deb} and S_{fin}:

$$E_{tps-emp} = \sum_{k \in K} \left| \sum_{i \in Z} \sum_{j \in Z} t_{ij}^{k} x_{ij}^{kdeb} - t_{ij}^{k} x_{ij}^{kfin} \right| \tag{20}$$

- the difference in the quantity collected by the vehicle k between S_{deb} and S_{fin}:

$$E_{capa} = \sum_{k \in K} \left| \sum_{i \in Z} q_i^{kdeb} y_i^{kdeb} - q_i^{kfin} y_i^{kfin} \right| \tag{21}$$

- the difference across all nodes visited by the vehicle k between S_{deb} and S_{fin}:

$$E_{compo} = \sum_{k \in K} \left| \sum_{i \in Z} y_i^{kdeb} - y_i^{kfin} \right| \tag{22}$$

- the difference in the order in which the nodes pass for a vehicle k between S_{deb} and S_{fin}:

$$E_{ordre} = \sum_{k \in K} \left| \sum_{i \in Z} \sum_{j \in Z} x_{ij}^{kdeb} - x_{ij}^{kfin} \right| \tag{23}$$

All of these indicators together constitute the stability objective and guide the decision-maker in choosing a solution.

We present different methods, their results, and the resulting conclusions. As mentioned above, we propose approaches adapted to the case where the number of nodes c_1 is much greater than the number of nodes c_2.

2.4. Suggested Methods

In this second part of the study, the number of nodes to be collected is significantly greater than the number of nodes to be collected in c_1 and much greater than the number of nodes to be collected in c_2. Therefore, specific methods, distinct from those developed for the first hypothesis, are necessary. Indeed, with this new hypothesis, the set of nodes in c_1 can no longer be gathered solely at the beginning of the week; they must be distributed over the entire collection period, that is, over the whole week, as illustrated in **Figure 1**. We are thus faced with a PV RPTW problem. The previous route construction methods are no longer suitable, and new procedures must be developed. Despite the difference in model, the general structure of the problem remains the same as for hypothesis 1: it involves organizing two sets of routes. The proposed heuristics therefore retain mechanisms similar to those used previously.

2.4.1. Solution Principle

Both proposed methods aim to reduce the stability differences between the beginning and end-of-week routes in order to obtain solutions that are as close as possible. Two construction approaches are possible: first, build the routes from the nodes in c_1 and then insert the nodes in c_2; or first, build from the nodes in c_2 and then add the nodes in c_1. The stability issue mainly concerns the nodes to be collected in c_2, car ce sont eux qui risquent de changer d'affectation entre les deux ensembles de tournées. as these are the ones most likely to change assignment between the two sets of routes. To limit these differences, we chose to construct the routes exclusively with the nodes in c_2. The nodes in c_1 are then inserted into these routes. To generate the beginning and end-of-week routes composed solely of the nodes c_2, we use **Algorithm 1** mentioned previously. Two methods for solving the weekly collection problem are proposed below.

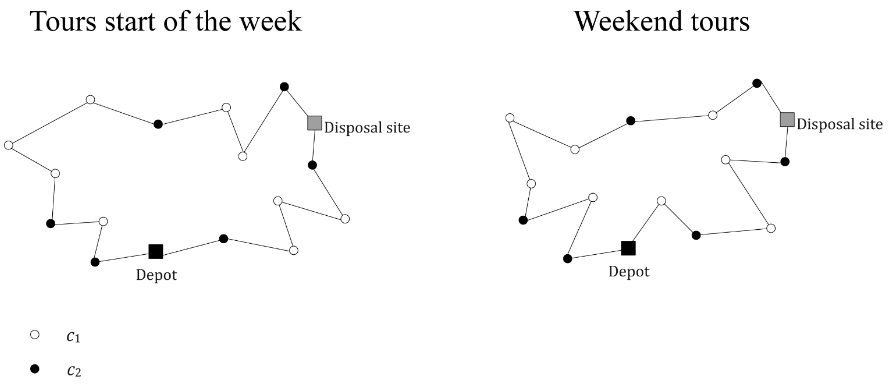

Figure 1. Diagram representing the collection if $Z_{c_1} > Z_{c_2}$.

2.4.2. Description of the First Method

For each node in c_1 remaining to be assigned, the method evaluates its best possible insertion into the already constructed routes (beginning or end of week), then selects the node offering the best insertion, as illustrated in Figure 2.

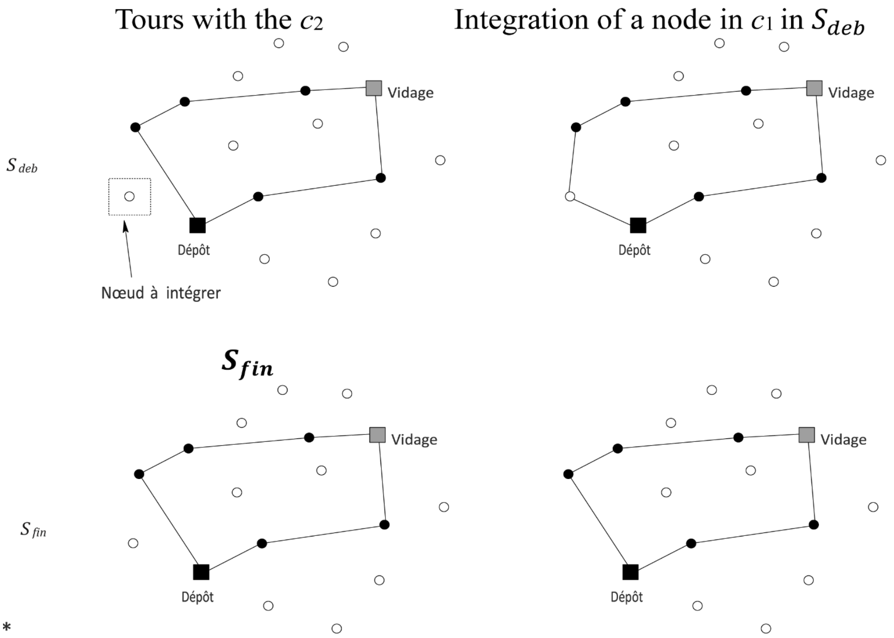

Figure 2. Method 1 for $Z_{c_1} > Z_{c_2}$.

If it becomes impossible to insert more nodes into existing routes while nodes remain in c_1, the method directly creates routes for these residual nodes using Algorithm 1. These new routes are scheduled at the beginning of the week to conform to the current operation. The method is presented in **Algorithm 1**.

```
Algorithm 1 Method 1 for $Z_{c_1} > Z_{c_2}$
Data: $PVRTW$
Result: $S_{deb}, S_{fin}$
    $Z'_{c_1} \leftarrow Z_{c_1}$
    $S_{deb} \leftarrow construction\_of\_tours\left(VRPTW_{Z_{c2}}\right)$
    $S_{fin} \leftarrow S_{deb}$
    Repeat
        $OK \leftarrow Insert\_node\_c_1\left(Z'_{c_1}, S_{deb}, S_{fin}\right)$
    Up to $OK = False$
    si $Not\ Est\_know\left(Z'_{c_1}\right)$ so
        $S' \leftarrow construction\_of\_tours\left(Z'_{c_1}\right)$
    end if
    $S_{deb} \leftarrow S_{deb} \cup S'$
    Or_opt $\left(S_{deb}\right)$
    Or_opt $\left(S_{fin}\right)$
```

The procedure $Insert\_node\_c_1\left(Z'_{c_1}, S_{deb}, S_{fin}\right)$ searches for the best possible insertion of nodes yet to be integrated into a route belonging to either S_{deb} or S_{fin}. In case of a tie, the method favors insertion into the routes of S_{deb}. This procedure returns $False$ if the node cannot be inserted. The procedure $Add\left(S', S_{deb}\right)$ adds the new tours S' to the tours of S_{deb}.

2.4.3. Description of Method 2

The second method is based on the same principle of completing existing circuits, but at each iteration it aims to enrich a specific route with nodes in c_1 not yet inserted. For each tour of S_{deb} and of S_{fin}, the best permissible insertion to augment the route is sought for each node in c_1. An example is shown in **Figure 3**.

As with method 1, if nodes in c_1, remain, dedicated tours are constructed for these nodes. The method is described by **Algorithm 2**.

The procedure $Select\_tours\_to\_complete\left(S_{deb}, S_{fin}\right)$ selects a tour to complete: it first traverses the tours of S_{deb} and then those of S_{fin} in the order of the circuits. The procedure. $Insert\_node\_c_1\_tour\left(Z'_{c_1}, k\right)$ Inserts a node at c_1 not yet included, into tour k. This node is removed from the set Z'_{c_1}. It returns $False$ if the tour can no longer accept additions.

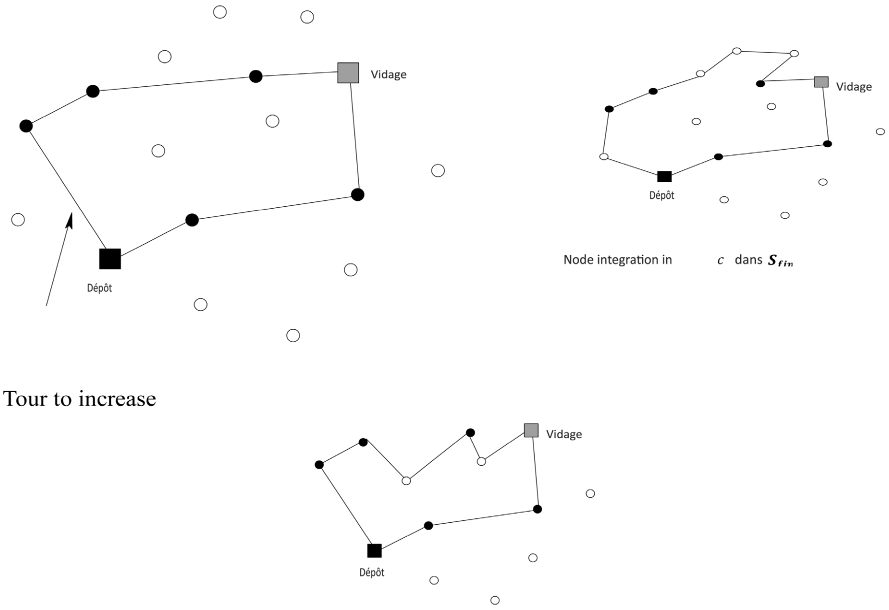

Figure 3. Method 2 for $Z_{c_1} > Z_{c_2}$.

```
Algorithm 2 Méthod 2 for $Z_{c_1} > Z_{c_2}$
Data: $PV\ RPTW$
Résult: $S_{deb}, S_{fin}$
$Z'_{c_1} \leftarrow Z_{c_1}$
$S_{deb} \leftarrow construction\_of\_tours\left(VRPTW_{Z_{c_2}}\right)$
$S_{fin} \leftarrow S_{deb}$
Repeat
    $k \leftarrow Select\_tours\_to\_complete\left(S_{deb}, S_{fin}\right)$
    Repeat
        $OK \leftarrow Insert\_node\_c_1\_tour\left(Z'_{c_1}, k\right)$
    Up to $OK = False$
Up to (more tours to complete) or $Est\_emptied\left(Z'_{c_1}\right)$
If Not $Est\_emplied\left(Z'_{c_1}\right)$ so
    $S' \leftarrow Construction\_of\_tours\left(Z'_{c_1}\right)$
end if
$S_{deb} \leftarrow S_{deb} \cup S'$
Or_opt $\left(S_{deb}\right)$
Or_opt $\left(S_{fin}\right)$
```

2.5. Experiments

The experiments were conducted on Solomon instances that we modified as follows. Let I be a test instance, containing a set Z of clients to be collected, with $Z = \{z_1, \cdots, z_n\}$ each having a quantity q_i. Initially, we select from the set Z of nodes in instance I *those collected at* c_1 and at c_2 thus $Z = Z_{c_1} \cup Z_{c_1}$. Then, we replicate the instance file three times to represent the nodes to be collected at c_1, at c_2 start of the week and c_2 at the end of the week: I_{c_1}, I_{debc_2} and in I_{finc_2}. In I_{c_1}, the quantities to be collected on the nodes in c_1 are increased.

$$q_i^{c_1} = q_i \times \alpha, \forall i \in Z_{c_1} \quad \text{with} \quad \alpha > 1 .$$

In I_{debc_2}, le the quantities of the nodes in c_2 remain unchanged: $q_i^{debc_2} = q_i$, $\forall i \in Z_{c_2}$.

In I_{finc_2} the quantities associated with the nodes to be collected in c_2 are reduced.: $q_i^{finc_2} = q_i \times \beta$, $\forall i \in Z_2$ with $\beta < 1$.

As before, the two coefficients were chosen empirically: $\alpha = 1.6$ et $\beta = 0.8$. We work with $|Z| = 100$ and test three proportions of nodes: 60%, 70% and 80%. The nodes belonging to Z_{c_1} are randomly selected for each instance.

3. Results

The results are presented according to cost and stability objectives, comparing the two methods on different Solomon instances and different node percentages (60, 70, 80). The values are averaged by instance type (C1, R1, RC1, C2, R2, RC2).

3.1. Cost Results

Figure 4 shows that Method 1 achieves the best cost results, except for instances R1 and RC1 with a high proportion of nodes in c_1 (80% et 70% pour RC1). For RC1, however, the costs of the two methods are similar.

In summary, Method 1 is generally preferable with regard to cost.

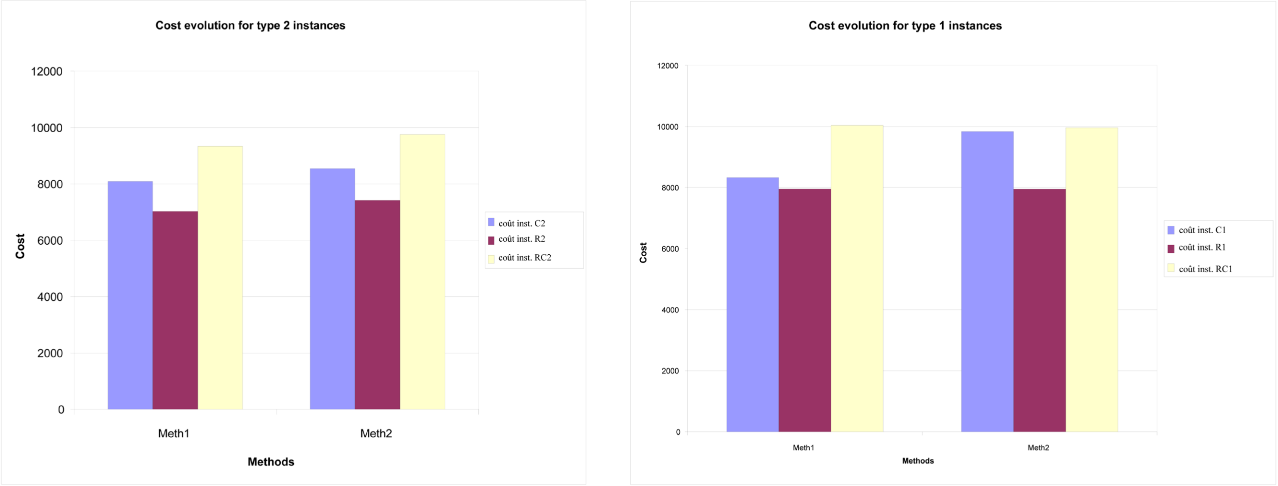

Figure 4. Comparison of methods in terms of cost per type of instance.

3.2. Results in Terms of Overall Stability

Figures 5-7 illustrate overall stability. On average, Method 1 uses as many or even more vehicles than Method 2. On instances where Method 2 requires fewer vehicles, it also has a lower or very similar cost. When the number of vehicles is the same, Method 1 shows smaller differences in distance and time. Conversely, when Method 2 uses more vehicles, it generates more pronounced differences in distance and time, particularly on RC1 instances with 80% of nodes in c1.

Thus, for overall stability, Method 2 appears to outperform Method 1.

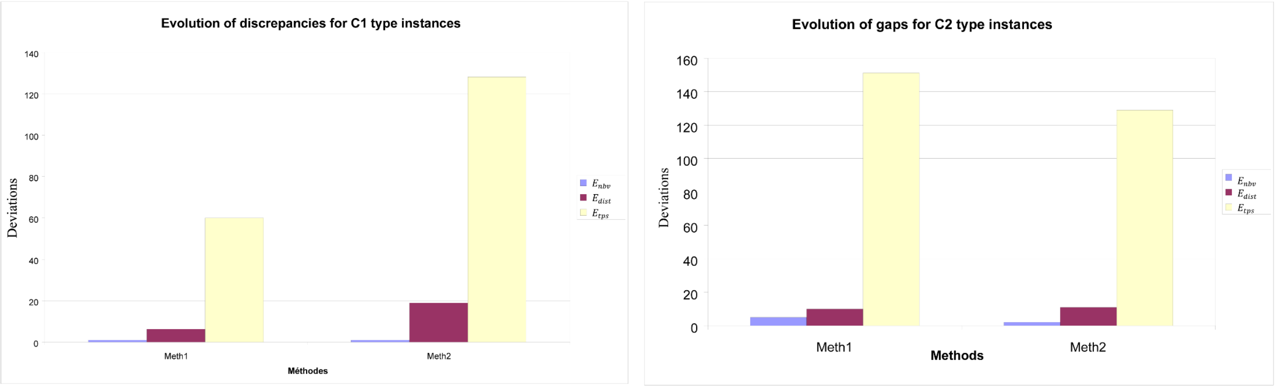

Figure 5. Comparison of methods in terms of overall stability by instance.

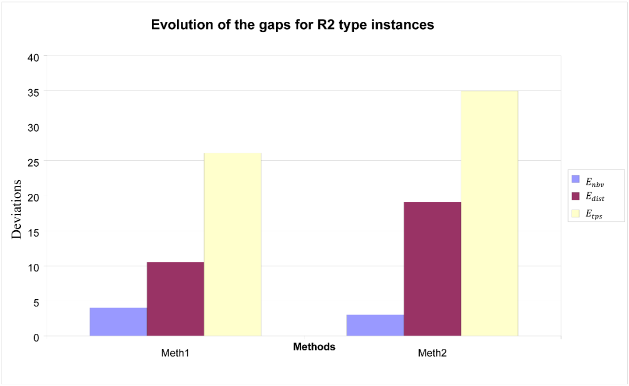

Figure 6. Comparison of methods in terms of overall stability by instance type.

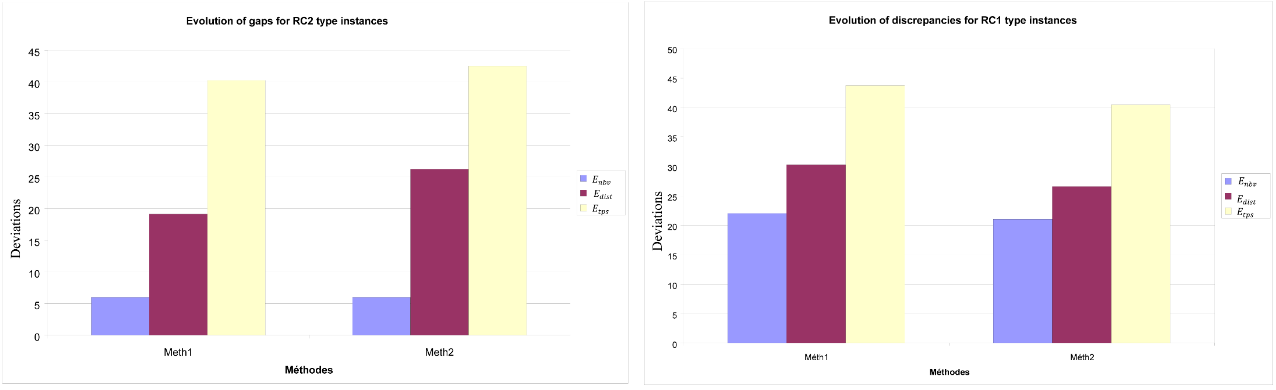

Figure 7. Comparison of methods in terms of overall stability by instance type.

3.3. Results in Terms of Stability from the User's Perspective

Figure 8 shows the hourly deviations on the nodes according to each method. These deviations are generally small. Where the deviations increase, method 1 performs better (instances C1, C2).

On the other instances, the deviations remain small and, on average, favor method 2.

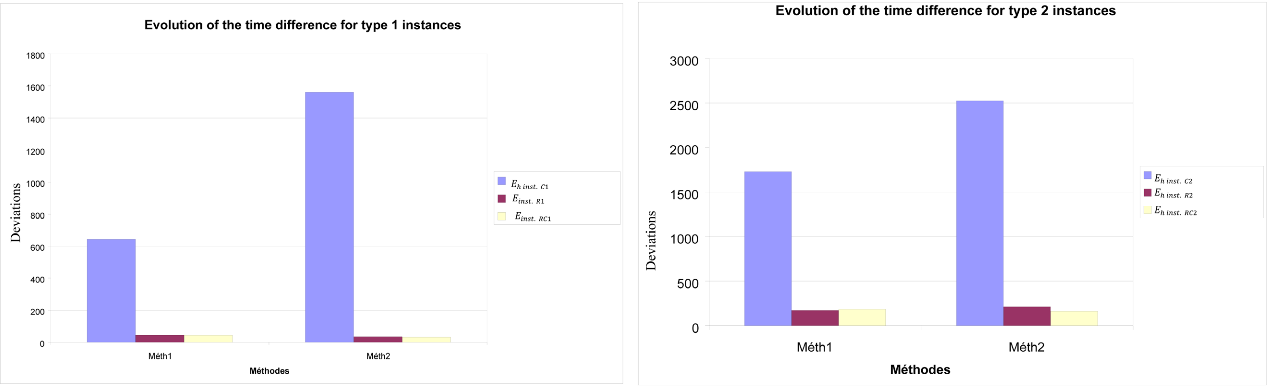

Figure 8. Comparison of methods in terms of "user" stability by instance type.

3.4. Results in Terms of Stability from the Employees' Perspective

Figures 9-11 present the stability as seen by the employees. The distance variance is greater for Method 2, which is also reflected in the variances for time, order, and capacity. In contrast, the variance in composition is zero, as the beginning and end-of-week routes rely on the same nodes in c_2.

These observations highlight certain characteristics of the methods: Method 2 inserts, on average, more nodes into existing routes than Method 1. This reduces the number of vehicles required but leads to busier routes, even when the number of vehicles remains comparable.

Thus, Method 2 continues to add nodes to existing routes. Both methods aim to minimize cost and variances between route sets.

A notable difference from Hypothesis 1 is that the stability measures here show more modest variances.

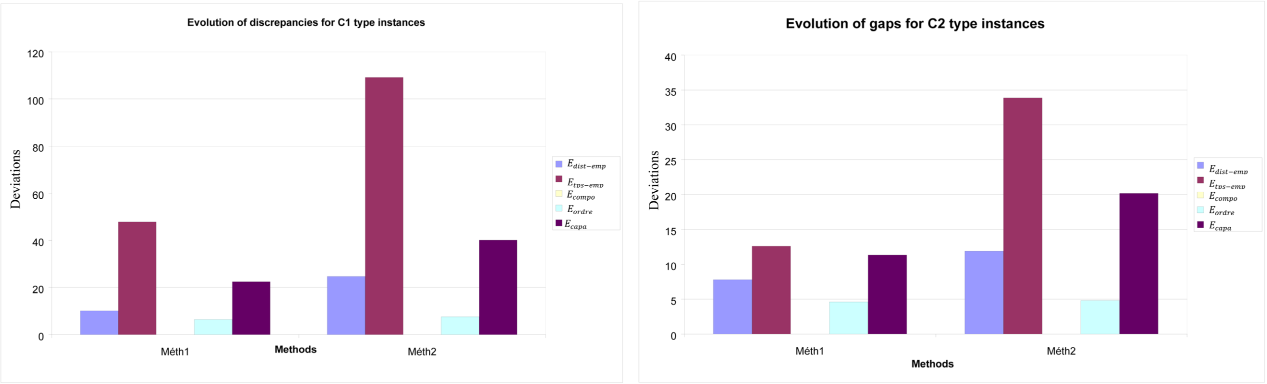

Figure 9. Comparison of methods in terms of stability "employees" by instance type.

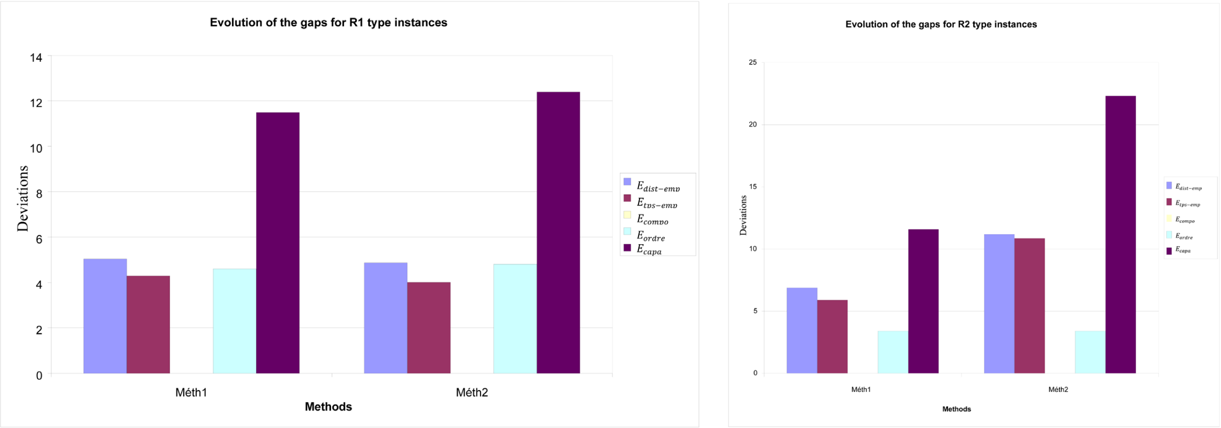

Figure 10. Comparison of methods in terms of stability "employees" by type of instance.

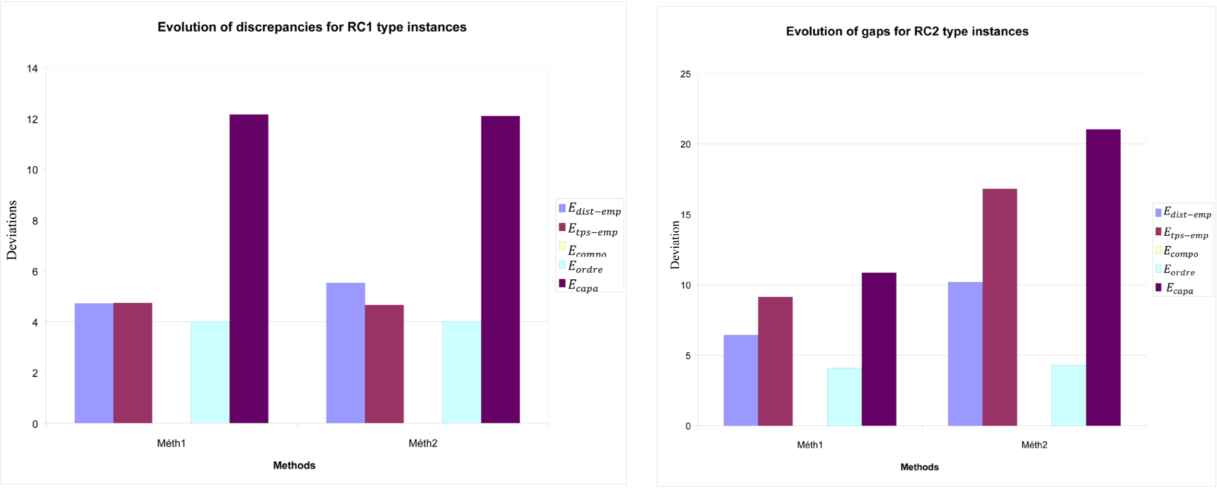

Figure 11. Comparison of methods in terms of stability "employees" by instance type.

4. Conclusions

This study has proposed an optimization framework for the weekly planning of household waste collection in Conakry, aiming to reconcile two objectives: minimizing operational costs and maximizing weekly stability. By formalizing the problem as an adapted VRPTW and developing two specific heuristic methods for the scenario where the majority of points are collected only once per week, we have demonstrated the existence of a fundamental trade-off between these two criteria.

The simulation results on modified instances indicate that *Method* 1 (initial construction on double-collection nodes, followed by insertion) tends to *minimize the total distance traveled*, thereby optimizing direct costs. Conversely, *Method* 2 (iterative completion of routes) favors *better overall stability* between the beginning-of-week and end-of-week routes, leading to more balanced and predictable planning.

5. Practical Implications for ANASP-CONAG

For Conakry's waste management authority, these results offer concrete avenues for action:

- ✓ *Informed Strategic Choice*: ANASP-CONAG must prioritize its main objective. If reducing fuel costs and fleet wear and tear is imperative, *Method* 1 forms the basis of a more efficient plan. If improving service reliability, workforce organization, and equity between zones is crucial, *Method* 2 is preferable.
- ✓ *Decision Support Tool:* The developed heuristics can be integrated into a *planning tool* to test different scenarios (changing frequencies, adding vehicles) and visualize their impacts on cost and stability.
- ✓ *Importance of Data Collection:* The full implementation of these models absolutely requires the *collection of real operational data* from Conakry (GPS coordinates of points, precise waste volumes, actual travel times). A measurement campaign would allow for the calibration and validation of the models, ensuring their applicability in the field.
- ✓ *Towards a More Robust and Equitable Service:* Adopting an approach that values *stability* can lead to a more regular service for citizens (predictable collection times) and fairer working conditions for staff (routes with similar loads and lengths), thereby strengthening the social acceptability of the public service.

6. Perspectives

To extend this work, several avenues can be pursued:

- ✓ *Integration of real data*: Applying the methods to the actual network and operational data from Conakry would allow for ultimate validation and precise fine-tuning.
- ✓ *Extension to other constraints:* Incorporating traffic, sorting logistics (flows to waste transfer stations), or seasonal variability of waste would enrich the models.
- ✓ *Interactive decision-support tool:* Developing an interface enabling ANASP-CONAG planners to visualize cost/stability trade-offs and choose in real time among different Pareto-optimal solutions would be a direct application of this research.
- ✓ *Replication in other contexts:* The methodology, designed to be general, could be adapted to other Guinean cities or regional cities facing similar challenges.

Ultimately, this research provides a validated methodological framework for optimizing collection. Its successful transfer to ANASP-CONAG will depend on *close partnership* between researchers and managers to adapt the models to local specifics and feed them with reliable data an essential step towards waste management that is both more efficient and more sustainable in Conakry.

7. Ethics of Human Participation

An information letter was sent to the Director of the National Public Health and Sanitation Agency, and permission to collect data was obtained from neighborhood leaders. The study's objective and expected results were explained to respondents in an information sheet included on the first page of the questionnaire. Participation required informed consent. All data were collected anonymously, and verbal informed consent was obtained from participants.

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Author Contributions

OT, MDB, and AT designed the study and developed the protocol. OT, HGC, ML, BMT, and BM developed the analysis plan. OT, ML, MDB, and CGH performed the data analysis, interpreted the results, and wrote the manuscript. All authors reviewed and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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