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Developing Optimization Tools for Municipal Solid Waste Collection in the Argentine City of Berazategui

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Abstract. We apply mathematical and computational techniques to the development of an approach for optimizing the waste collection system of the Argentine city of Berazategui, 26 km south of Buenos Aires. Taking full account of the city's particular characteristics, our objective is to not only improve the system's efficiency but also ensure equitable workloads for waste collection truck crews, including both drivers and collectors. The optimization problem is partitioned into three stages. In the first stage, a heuristic constructs structurally simple collection zones that are balanced in terms of collectors' walking distances. In the second stage, a mixed-integer linear programming model designs a collection truck route for each zone and minimizes its length. In the third and final stage, each truck is assigned to two zones in such a way as to equalize to the extent possible the length of drivers' working day. Because working-day length is influenced by multiple factors, we formulate this objective as a biobjective optimization problem and solve it by integer linear programming coupled with an iterative algorithm. The city implemented the approach in early 2020, resulting in a markedly more equitable workload distribution and significant fuel savings and maintenance expense for the city.

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Keywords: municipal solid waste • vehicle routing • integer lineal programming • multiobjective optimization • heuristics

Introduction

This article reports on a project for the development of a set of algorithms based on integer linear programming aimed at designing and implementing a more efficient local waste collection system for the Argentine city of Berazategui. Managing municipal solid waste (MSW) is a growing challenge for many local authorities because of the high cost of collection and transport coupled with the pressure of ever-larger volumes on limited treatment facility capacities. Of the various activities associated with MSW, collection and transport account for the largest proportion of total cost, so improvements in those areas can mean significant savings (Tirkolaee et al. 2019). Berazategui is situated 26 km south of Buenos Aires City, the national capital. Covering an area of 217 km^2, it had in 2020 an estimated population of 365,000. Over the years, each time the municipality acquired new garbage trucks in response to population growth, the definitions of the collection zones and truck-to-zone assignments in the city's MSW collection system were modified manually. The result of these many ad hoc changes made without regard to overall system organization was an increasingly unequal distribution of the workload across truck crews and a decline in quality of service that led to growing complaints from residents. Because the system had no set truck routes, the improvised routes that were actually followed tended to be significantly suboptimal, inflating fuel and maintenance costs. This unsatisfactory state of affairs prompted municipal officials to request the assistance of the present authors in an effort to improve the waste collection service. In specific terms, the project required a redefinition of the collection zones and the design of efficient truck routes that would ensure a fair distribution of the workload. The objective here, therefore, is to present the development and implementation of the heuristics and algorithms based on integer linear programming that were used to improve Berazategui's MSW collection and transport. The idea was to come up with tools that provided solutions that were not only of good quality but also efficient as regards execution time while also being easily reusable each time additional vehicles were acquired. However, given the complexity associated with the problems of defining collection zones, designing collection truck routes, and assigning trucks to zones (Solomon 1987, Nauss 2003), finding an optimal solution that encompassed all three problems simultaneously was well-nigh impossible. What follows is a description of how they were addressed individually in the Berazategui project by applying different mathematical and computational techniques. Briefly, to design the collection zones, we began by implementing a heuristic that first constructs them iteratively and then attempts to improve the shape of their frontiers so that the collection truck drivers find them easier to memorize. Next, we implemented a mixed-integer linear programming (MILP) model to design efficient truck routes. Finally, based on the results of the previous two stages, we solved a biobjective optimization problem that identifies a workload distribution that was balanced across drivers. The application of these operations research techniques resulted in a significant improvement of that distribution and considerable savings in fuel and maintenance expense because of the reductions achieved in the truck routes' total distance. The remainder of this paper is organized into five sections. The section immediately following reviews the literature on MSW management optimization. The third section describes the overall problem. The fourth section develops the mathematical and computational procedures and models applied in the solution approach to each of the three specific problems. The fifth section sets out the numerical results of the implementation of the overall approach. Finally, the sixth section presents our conclusions and some comments on future research.

Literature Review

One of the earliest works on MSW collection that explores different mathematical techniques for solving this class of problems was published by Beltrami and Bodin (1974). Numerous others have followed, reflecting the great diversity in the range of potential applications. Male and Liebman (1978) proposed one of the first algorithms aimed at defining simultaneously the collection zones and vehicle routes for a waste collection system. A variety of applications have appeared since then using mathematical optimization techniques to solve MSW collection problems for different cities. Kim et al. (2006) model the routing problem using time windows, generating solutions from an extension of the insertion algorithm from Solomon (1987). Sahoo et al. (2005) optimize the collection routes of an American waste management firm, obtaining significant logistical savings. Cortinhal et al. (2016) apply local search heuristics to minimize vehicle travel time and balance workloads. Mostafayi Darmian et al. (2020) develop a multiobjective optimization model that determines collection center locations and urban area zones and apply it to two case studies in Iran. Other examples with brief descriptions of their methodologies are set out in Table 1.

As will be described in the next section, Berazategui has a number of characteristics that require the development and application of tools specially tailored to its peculiarities. For example, unlike the published studies just examined, balancing the workload distribution meant considering the truck drivers and their collectors working on foot separately. Thus, the present paper makes three specific novel contributions that could be readily adapted to waste collection systems in which procedures and data availability are similar. The first contribution is the development of a zoning heuristic that attempts to balance the collectors' workload while constructing simply structured collection zones based on a squareness metric. The second is the design of an MILP model to identify efficient routes for cases in which the truck must visit every corner and every block side of a certain minimum length within a collection zone. The third is the application of a multiobjective optimization method to obtain an equitable distribution of the workload across drivers.

Description of the Problem

The curbside waste collection system operated by Berazategui's Urban Sanitation Department (hereafter "the Department" or "USD") is built around collection trucks that pick up bags of household refuse put out in resident-owned bins along the residential blocks of the municipality. Each truck is crewed by a driver and two or three waste collectors who collect the bags and load them into the truck's container over the course of a working day divided into a morning shift, from 4 a.m. to 10 a.m., and an afternoon shift, from 10 a.m. to 4 p.m. The collectors work a single shift daily covering one zone, whereas the drivers generally work both the morning and afternoon shifts, covering one zone in each, in the same truck. A driver's itinerary is as follows: depart from the USD vehicle depot with the morning shift collectors, service the first zone, return to the building to drop off the collectors and pick up the afternoon shift collectors, service the second zone, and return again to the depot. At day's end, the waste is driven to a treatment facility run by a national government agency (Coordinación Ecológica Área Metropolitana Sociedad del Estado (CEAMSE))

Table 1. Applications of Various Methodologies for Solving Real Instances of MSW Collection Problems

Reference	City	Methodology
Eisenstein and Iyer (1997)	Chicago, USA	Models garbage weight and the time required to collect it from a block as a random variable and designs truck routes as a Markov decision process
Chang and Lu (1997)	Kaohsiung, Taiwan	Uses a fuzzy multiobjective mixed-integer programming model to account for uncertainty in the conditions that influence MSW management system planning
Huang et al. (1998)	Hamilton-Wentworth, Canada	Applies a gray linear programming method that considers various system components with uncertain parameters in the case study
Mourão and Almeida (2000)	Lisbon, Portugal	Presents two lower-bounding methods based on mixed-integer linear programming for the capacitated arc routing problem and a three-phase heuristic to generate a near-optimal solution from the result obtained by the first method
Arribas et al. (2010)	Santiago de Chile, Chile	Employs a three-phase approach: clusterization of bins in collection zones, the use of a topological road network in a geographic information system environment to devise the vehicle routes, and an integer linear programming model to design the vehicle fleet
Bonomo et al. (2011)	Ciudad de Buenos Aires, Argentina	Reduces the routing problem to the classic traveling salesman problem using the Concorde solver to obtain a set of optimal solutions and choosing the one for which the truck's mechanical work is the lowest
Braier et al. (2017)	Morón, Argentina	Models the problem as a case of the generalized directed open rural postman problem. Develops an integer programming model with a solving procedure built around a subtour-merging algorithm and the addition of subtour elimination constraints
Fadda et al. (2018)	Turin, Italy	Combines data from several sources (on-vehicle weight systems and sensor network) and applies a heuristic optimization algorithm and the GUEST OR methodology
Herrera-Granda et al. (2019)	Ibarra, Ecuador	Performs districting with geolocated data and uses an integer linear programming model to determine the optimal number of trucks
Salah Sahib and Hadi (2021)	Karbala, Iraq	Approximates solid waste generated by each block and uses the WinQSB software to design the vehicle routes based on three different objective functions
Delle Donne et al. (2021)	Trenque Lauquen, Argentina	Uses a heuristic for districting, integer lineal programming for defining efficient leaf-sweeper routes, and the Concorde solver to find the shortest collection truck routes

located 23 km outside of the municipality. If the truck reaches its capacity limit before the route is completed, the crew must make a trip to the facility and return to pick up their collection rounds where they left off. This considerably increases the length of the working day, fuel consumption, and vehicle wear and tear. Waste quantities in Berazategui are such that at most one such midroute trip to CEAMSE might be needed. The USD defined three objectives for construction of collection zones: (i) uniformity as regards truck route length, route driving times, and waste-load quantities; (ii) maintaining the established practice of assigning each truck to two zones per day; and (iii) avoiding, to the extent possible, definitions that result in a truck becoming fully loaded before completing its route, thereby obviating the need for a second trip to the treatment facility. In addition, the USD requested that each zone's truck route be designed to minimize travel distance and facilitate the *achique* strategy. The latter refers to the system used by truck crews in which the driver advances slowly along a street on their route while the waste bags left out along the blocks running off it are picked up on foot by one or two collectors, who deposit them back at the corners of the aforementioned street, where the other collector then loads them into the truck's container. This strategy obviates the need for the vehicles to travel every street in the municipality, thus significantly cutting collection times and fuel consumption costs.

Certain characteristics peculiar to the present problem required the design of ad hoc methodologies that differ from those found in the literature on collection problems reviewed in the previous section. First, the objective here was not only to find an appropriate zoning and design efficient routes but also to ensure a balanced distribution across all collectors and all drivers of their respective workloads, a point insisted on by the Department. In both cases, we had to take into account factors influencing each of the two groups' working-day length. For collectors, the single factor was the collection distance—that is, the sum of the length of the block sides to be serviced. This criterion was the measure of the physical effort they expended in servicing a zone. For drivers, interviews determined that the two factors influencing the length of their working day were the total collected waste load (by weight) and total truck route length. Thus, the truck-to-zone assignments had to consider two independent objectives to ensure a fair distribution of the workload: minimization of the maximum disparities in amount of waste collected and minimization of the maximum differences in truck route length. The optimization problem was therefore a multiobjective one.

The second significant characteristic peculiar to the Berazategui waste collection system that motivated the design of specific tools is the *achique* system. With this setup, the trucks need only visit each corner in their assigned zones at least once rather than having to travel every block side. The sole exceptions are block sides longer than 130 m, which the trucks must cover because they are too long for the collectors to service them on foot.

However, the town center, two other districts of the municipality, and the various gated communities within it have special collection arrangements. They were therefore excluded from the project as regards zoning and truck-to-zone assignments, although for some of them the Department did request new route designs.

Once all the necessary data were compiled and processed, the problem to be solved was partitioned into three stages. The first stage was the construction of collection zones that were structurally simple and balanced regarding the collection distance to ensure a balanced distribution of work among collectors. The second stage consisted of designing optimal truck routes through each of the zones constructed in the first stage. In the third and final stage, each truck was assigned to two zones in such a way as to maintain a balance in working-day length across all drivers.

In broad terms, the desired solution was one that improved significantly on the manually designed zones, truck routes, and truck-to-zone assignments in use when we began work on the Berazategui waste collection project. All three sets of definitions were clearly inefficient, resulting in complaints of poor service from residents and worker protests because of the highly unequal distribution of workloads.

Solution Approach

The first task in the design of a solution approach for the Berazategui waste collection problem was to gather and process all the relevant data. The information collected was as follows:

1. A map of the municipality showing each street's traffic direction and other traffic restrictions (e.g., prohibited turns) as well as railway lines and crossings, watercourses, and other permanent obstacles
2. The collection zones then in use
3. The amount (in kilograms) of waste collected daily by each collection truck; this information was obtained from the treatment facility's dumped-waste records
4. Geolocated demographic data: population density of each block, locations of public buildings, schools, hospitals, and so on
5. Global positioning system (GPS) data on the daily collection truck routes

The GPS data were used to implement a routine that determined the route each truck followed. These results were processed in combination with the information on the amount of waste collected, the zones each truck serviced, and the demographic data to arrive at an approximate figure for waste collected from each block. This was essential for determining the fairest possible workload distribution across all drivers and avoiding a second daily trip to the treatment plant. Also, we conducted interviews with truck drivers and collection system supervisors to get a general overview of the collection problem and a better understanding of the factors influencing working-day length.

With all these data thus gathered and processed, we then carried out the three stages of the solution approach as described in the three subsections that follow.

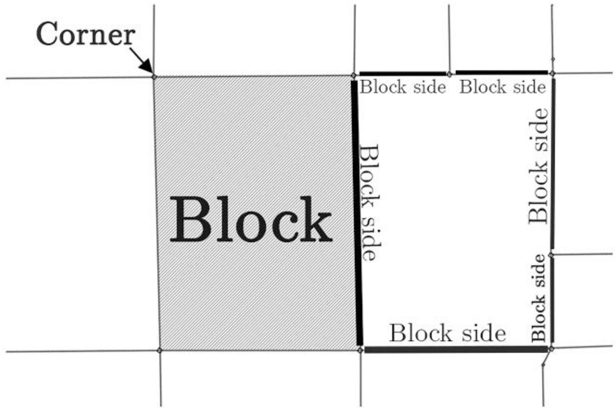
Design of Zones

The design of the waste collection zones and the definition of the routes are based on the street plan of the municipality ("the plan") in the OpenStreetMap (OSM) database. The plan consists of an XML file that contains, among other elements, two types of objects: nodes, representing latitude and longitude coordinates, and ways, which are lines connecting the nodes. Hereafter, we refer to each node as a corner and each line connecting two corners as a block side.

The basic unit of our zoning model for constructing the collection zones is the block, defined as a space on the plan bordered by the street segments forming the block's sides. A zone is a set of such blocks that satisfy two specific characteristics. First, no block can contain other blocks. Second, a block cannot be crossed by railway lines or highways, a restriction imposed to avoid delays caused by trucks having to detour around them. An example of a block, block sides, and a block corner is shown in Figure 1.

Two blocks are said to be adjacent if they have at least one block side in common—that is, bordering the same street segment. Also, given a set of blocks, we

Figure 1. Example of a Block, One of Its Corners, and Six Block Sides of One of Its Adjacent Blocks



define its collection distance as the sum of the lengths in meters of all the block sides within it that must be serviced. To avoid double counting, only one of each pair of mutually facing block sides within a zone is included in the summation.

The process of zoning the municipality was guided by two desirable zone characteristics: balance in collection distance and squareness of its frontier. The first attribute sought to ensure relative fairness across the system in working-day length and the collectors' physical effort expended, whereas the second attempted to simplify the geographic definition of the zones and thus facilitate their memorization by the truck drivers. The only constraint was that each zone had to be composed of adjacent blocks. To satisfy this condition, the zoning process was applied in each section of the plan not crossed by railway lines or highways. For each such section, we calculated the collection distance and then determined the number of zones it would be divided into in collaboration with the Department. The new zoning of each section thus consisted of defining collection zones with similar collection distances and a frontier as square as possible. The modeling was approached as a balanced graph vertex partition problem, set out here formally in Appendix A. Because this class of problems is known to be NP-complete (Andreev and Racke 2006) and, in our case, there is also a zone squareness condition, we opted to develop a heuristic that would find a sufficiently good solution within a reasonable time period.

The zoning heuristic consists of two phases. The first phase designs a zoning that prioritizes balance in collection distance, whereas the second attempts to improve zone squareness. Because the zones must be connected, the heuristic was run for each section of the plan. The squareness metric is given in Appendix A.

The first phase requires two input parameters: the number of zones to be created and the minimum desirable collection distance for a zone. As will be explained, the second parameter acts as a threshold in the subroutine that determines how to proceed if at any point in the procedure the area not yet zoned is disconnected. Naturally, it must be sufficiently small to be compatible with the first parameter. In the present case, the values suggested by the USD presented no problems; had it been otherwise, a manual adjustment would have been required.

The desirable collection distance for each zone is the ratio of the collection distance to the number of zones to be defined. The first zone of a section is generated starting from a block located at one of the section's extremes. The criterion behind the choice of the initial block is detailed in Appendix A. The zone is expanded iteratively, acquiring from among the various adjacent blocks the block that maximizes the squareness metric of the expanded zone as of that point. The iteration stops once the collection distance is no longer less than the desirable value. These steps are then repeated for the section that results from the elimination of the blocks that already belong to a zone. The entire procedure continues until the number of zones to be defined has been completed.

It may occur that as blocks are eliminated from a section, what remains of the section consists of separate subsections. Appendix A explains how the procedure decides the number of zones to be defined for each such subsection whose total collection distance or waste load exceeds a certain threshold. Any block in a subsection that does not exceed the threshold is distributed between the previously defined zones that border it.

Because the procedure's zone generation stopping criterion is related to collection distance, it may be that the frontier can be improved by adding or subtracting blocks. With this possibility in mind, the heuristic's second phase comes into play. It consists essentially of the application of an algorithm based on steepest-ascent hill climbing (Michalewicz 2010), whose objective is to minimize the number of vertices in each zone frontier. At each iteration for each zone, the algorithm checks whether adding or subtracting a block to or from an adjacent zone reduces the number of frontier vertices. The algorithm stops when either a set number of iterations is reached or a complete iteration generates no changes in any zone.

Design of Truck Routes

The next stage was to identify minimum-length truck collection routes. Recall that the waste collection workers use the so-called *achique* system (see Description of the Problem section) for blocks shorter than 130 m to reduce truck route length. This means that each truck has to visit every street corner in its assigned zone and service long block sides directly. We modeled the search for an efficient route through each zone as an instance of the asymmetrical traveling salesman problem (ATSP), which we then solved using a mixed-integer linear programming model whose formulation is set out in Appendix B. Our block-level waste generation approximations for the present case study indicated that every individual zone could be serviced without exceeding truck capacity. We were therefore able to ignore the capacity factor in determining each zone's efficient route. But because trucks must service two zones daily, we took capacity into account in truck-to-zone assignments, so in cases in which the whole-day waste total did exceed capacity, we assumed that the driver made the additional trip to the treatment facility between completing the first zone and starting the second one. With these considerations in mind, we proceeded to construct a weighted directed graph based on the plan in which each vertex represented a corner of a zone and each arc connecting two vertices was weighted in an amount equal to the minimum path length between the corresponding corners. Added to the graph were the vertices for the trucks' departure and arrival points, both of them corners at the USD vehicle depot, and the corresponding arcs to and from the rest of the vertices with their respective weights. The model attempted to solve the ATSP on the graph, which represents a minimum-length collection truck route that visits each corner in the zone at least once. The route was obtained by joining end to end in proper sequence the minimum paths represented by the arcs that form part of the solution.

However, given the specific characteristics of the Berazategui waste collection system, the following constraints had to be considered:

- Restrictions on the search for a circuit that passes through each vertex exactly once. These were based on the model proposed by Desrochers and Laporte (1991), which was the one that performed best for our application, even though others have tighter linear relaxations (Roberti and Toth 2012).
- The route must start and end at the vertices corresponding to the departure and arrival corners at the USD vehicle depot.
- Every street longer than 130 m must be part of at least one of the minimum paths in the solution so that the truck will be sure to service it.
- If the segment formed by joining two paths violates a traffic restriction, then no more than one of the corresponding arcs can be part of the circuit.
- If the segment formed by joining three paths violates a traffic restriction, then no more than two of the corresponding arcs can be part of the circuit.

Because the minimum paths calculations must take traffic restrictions such as prohibited turns into account, we used the algorithm developed by Di Puglia Pugliese and Guerriero (2013) to find the minimum path between each pair of vertices that excluded prohibited paths reflecting such restrictions.

Assignment of Trucks to Zones

The third and last stage of the waste collection problem consists of assigning each of the trucks to zones in such a way as to balance the length of the working day across all drivers. As already noted, each vehicle is assigned two zones per day, and after servicing, each one must return to the USD building to drop off the collectors. Because the round trip to the treatment facility is the same for all trucks, we excluded it from the truck route calculation procedures. A truck's total trip distance for a zone is thus fully given by the route length calculated in the preceding section.

According to USD officials, the two characteristics influencing a driver's working-day length are the route lengths for the two assigned zones and the quantity of waste to be collected. However, there is no easy way of determining what proportion of the impact each one accounts for. We therefore approached the problem as one of biobjective optimization—that is, finding an assignment that minimizes disparities in route length while simultaneously minimizing disparities in waste-load weights.

It is often the case in multiobjective combinatorial optimization that no solution exists that satisfies both objectives simultaneously (Ehrgott and Gandibleux 2002). The goal, therefore, was to find a set of what are called efficient solutions. In the present context, given two feasible assignments A and B, A is said to dominate B if and only if one of the following is true:

1. The route length disparity in A is strictly less than in B and the weight disparity in A is less than or equal to that in B.
2. The weight disparity in A is strictly less than that in B and the route length disparity in A is less than or equal to that in B.

A solution is said to be nondominated or efficient if there exists no other solution that dominates it. The set of such solutions is known as the Pareto front.

We approximated the Pareto front using the epsilon-constraint method (Haimes et al. 1971). This approach solves optimization problems for one of the objectives while incorporating the other as a constraint, bounding the latter by a value that is systematically modified by subtracting another fixed value (Hwang et al. 1979). We applied the method to the MILP model set out in Appendix C, which incorporates the following assignment constraints:

- Each truck must be assigned to exactly two zones.
- Exactly one truck must be assigned to each zone.
- The capacity of a truck must not be exceeded (based on capacity values derived from waste generation estimates for each block).

Municipal officials also emphasized that a second trip to the treatment facility should be avoided wherever possible. In our case study, the zoning in the first stage was such that there were various assignments in which no truck capacities were exceeded; therefore, we formulated truck capacity as a hard constraint.

Results

This section presents the results of the solution approach developed previously. They are compared with the situation in Berazategui prior to the implementation of the project based on the data supplied by the municipality and listed at the beginning of the Solution Approach section. More specifically, we compare (i) the zone definition results with the definitions that were in use in March 2020; (ii) the average truck route length results with those determined using GPS data for the period from July 2019 to February 2020; and (iii) the truck-to-zone assignment results with those that were in use in March 2020. In the area included in the case study, about 15,000 block sides segmented into 42 zones are serviced every day.

We implemented the procedures in each of the three stages of our proposed approach in Python 3.7, and the MILP models were solved using CPLEX 12.8. The solution times reported in the following sections were obtained on a computer with an Intel Core i5 2.60-GHz processor and 16 GB of RAM.

Zoning

The Department requested that certain zones from the previous manual definitions be maintained; a few others were omitted from the project altogether. This was due to the special arrangements in place for waste collection in the municipality's El Pato and Juan María Gutiérrez districts as well as certain central core areas and gated communities.

We applied the heuristic set out in the Design of Zones subsection to each of the connected components within the plan sections covered by the project, imposing the condition that each zone so generated must account for a minimum collection distance of 3,150 m. The zones we obtained after applying the two phases of the heuristic are shown on the plan illustrated in Figure 2. Table 2 displays the minimum and maximum collection distances and their respective standard deviations for the municipality's previous manually designed zones together with the corresponding values we obtained in the first and second phases of the heuristic.

As can be seen in the table, the heuristic generated a much better balance of collection distances, which vary over a much narrower range than was the case under the manual system. The second phase improved the squareness of the zones while introducing only a slight deterioration in the distance variation compared with the first phase. This implies that the balance and squareness objectives are competitive, as typically occurs in multiobjective problems. As well as achieving a zoning with a more equitable distribution of the workload across collection workers, all the zones generated were connected.

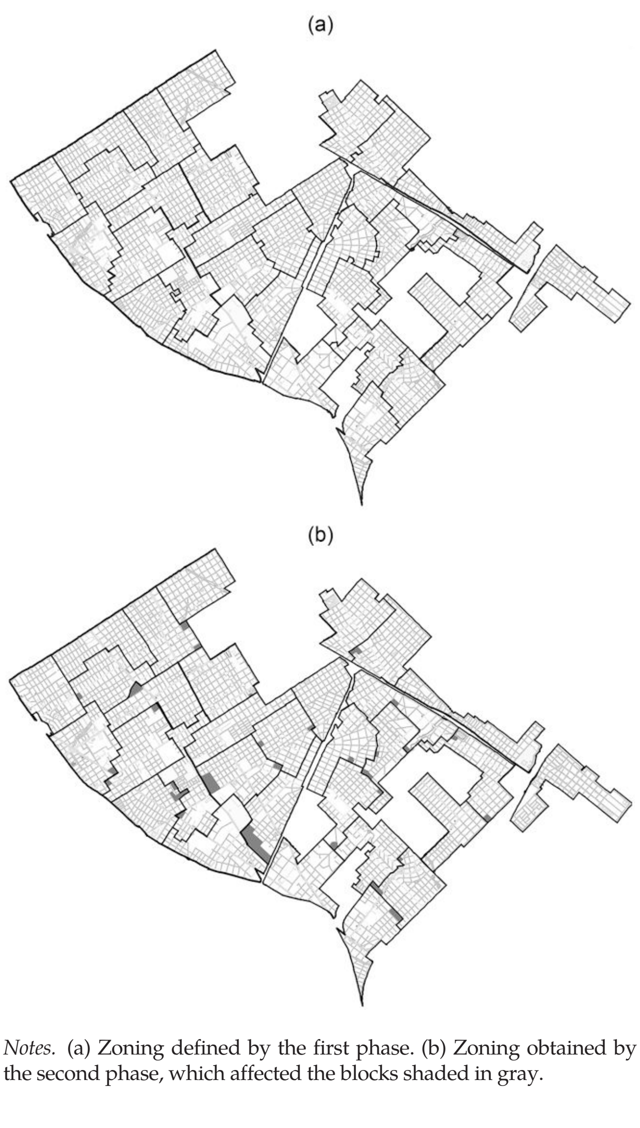
Table 2. Comparison of Collection Distances Under the Preproject Manual and Two Heuristic Phase Definitions

	Manual (km)	First phase (km)	Second phase (km)
Standard deviation	7.84	1.82	1.89
Maximum	46.15	26.62	27.13
Minimum	5.03	20.53	20.34

Truck Route Design

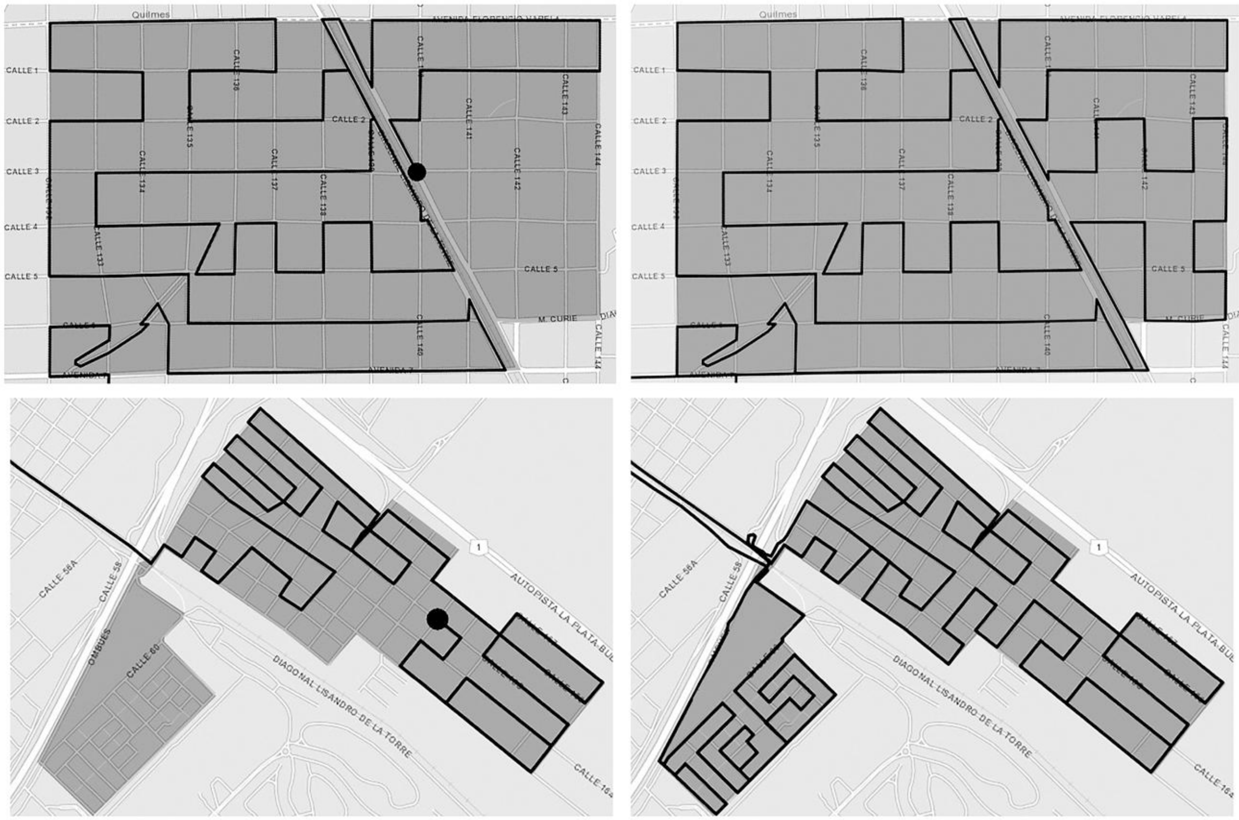
Truck routes were designed for all the zones except El Pato and the gated communities. Efficient routes for each one were identified by the MILP model described in the Design of Truck Routes section. If after 45 minutes the solver still had not found an optimal solution, we ran it for an additional 45 minutes in search of a solution with an optimality gap of under 1%. If that also was not found, the solver was executed for another 90 minutes

Figure 2. Results Obtained by the Zoning Heuristic



Notes. (a) Zoning defined by the first phase. (b) Zoning obtained by the second phase, which affected the blocks shaded in gray.

Figure 3. Top and Bottom Rows Each Illustrate an Efficient Route (Black Line) Designed by the Proposed Model for a Single Zone (Shaded in Gray)



Note. For greater clarity, the left-column diagrams show only part of the routes (the block dot represents the truck's position); the right column diagrams show the complete routes.

after being configured to improve the lower bound on the optimal value, given that it was observed that after the first 90 minutes the solver generally did not find better feasible solutions.

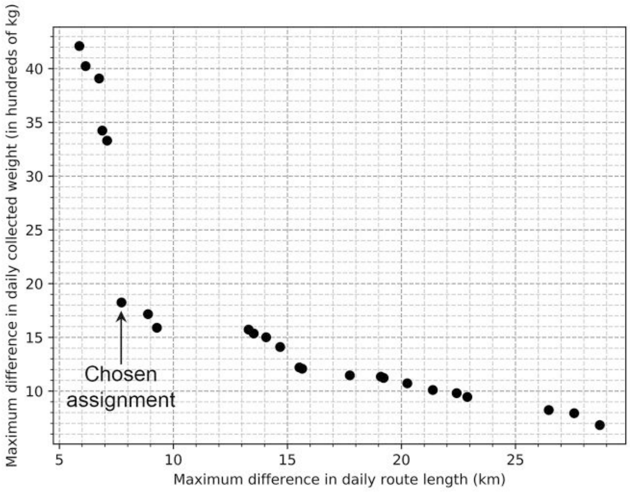
Of the 38 zones for which routes were designed, optimal ones were found for 20 with solution times averaging 11 minutes and 25 seconds. For another 17 zones, our solution approach identified routes with an optimality gap of no more than 1% and an average solution time of 87 minutes. In these latter cases, the optimality gap average was 0.7%, whereas the absolute gap averaged 172.54 m. The size of these instances varied between 52 and 195 nodes, averaging 139. The solution time for the single remaining zone, which covered the Juan María Gutiérrez district, was twice as long given that it has 308 nodes, more than double the average number for all the others. In this case, the solution was found after 164 minutes with an optimality gap of 3.31% and an absolute gap of 1.61 km.

In contrast to the previously used manually defined routes whose average length was 62.87 km, our model-based designs cut that figure to 48.63 km, a reduction of 22.6%. Given that the routes were designed for a fleet of 20 collection trucks, this improvement translates into 284.79 fewer kilometers driven daily over the whole system. On Berazategui's six-day-a-week collection service, the reduction in total truck route length on an annual basis would total 88,854.48 km, which translates to savings in fuel and to a decrease in vehicle wear and tear. The total collection distance on the zones we designed routes for is approximately 884 km, whereas total truck route length (that is, excluding travel to and from the USD building) is 649 km. This implies that the *achique* system saves at least 234 km in total zonal truck travel. The routes we obtained for two zones are depicted in Figure 3, illustrating how *achique* reduces the number of block sides traveled by the vehicles. To simplify the diagrams, travel to and from the USD building is not shown.

Truck-to-Zone Assignments

Based on the route length for each zone and an approximate calculation of the corresponding amount of waste, two zones were assigned to each truck such that the drivers' workloads were as balanced as possible. Applying the epsilon-constraint method, the principal objective was to minimize the differences in waste loads collected by each truck, with the differences in route length as the

Figure 4. Nondominated Solutions of the Pareto Front Approximation for the Biobjective Optimization Problem



Note. Each solution represents a truck-to-zone assignment.

epsilon constraint. The initial ε value was given by the maximum route length difference of the assignment that minimized the difference in waste-load weight while ignoring the other objective. At each iteration, this parameter declined by $\delta = 250$ m until the problem became infeasible. Finally, the solution was found by taking as the sole objective the difference in route length. The result approximated the Pareto front for the biobjective optimization.

The epsilon-constraint method obtained a total of 24 nondominated solutions (truck-to-zone assignments). The nondominated solutions and the assignment finally chosen by the USD are shown in Figure 4. As already noted, because the existing assignments for the El Pato and Juan María Gutiérrez districts, the central core, and the gated communities were to be maintained, they were excluded from this stage. Under the preproject manually designed system, the maximum difference in waste-load weight collected across all trucks was about 6,070 kg, whereas the maximum disparity in route length was approximately 44.5 km. The corresponding differences in the model-generated assignment chosen by the municipality were much lower at approximately 1,825 kg and 7.72 km, respectively.

According to the USD, although no complications arose in the implementation of the model results, there was much initial resistance from the collection workers, who were accustomed to the old system that had been in place for many years. Furthermore, some of them got the wrong impression that the zone areas were proportional to collection distance and thus felt that the workload was unfairly distributed. The Department, however, was able to show that the new distribution was in fact fairer than before given that, among other things, the amount of waste collected as demonstrated by the treatment facility load delivery slips was similar across all trucks. This plus a few minor manual modifications to the zones and routes made by the Department after consulting with system supervisors slowly overcame the workers' objections.

Conclusions

We developed a three-stage strategy to improve the waste collection system in the Argentine city of Berazategui. The first stage implemented a heuristic for defining collection zones that considerably reduced disparities across the previous manually defined zoning in the quantity of work each zone represented for collection workers. The second stage applied MILP models to design more efficient collection truck routes and better organize the *achique* collection procedure. The routes so designed cut total route length by 22.6%, generating savings in fuel and significant reductions in vehicle wear and tear. The third stage found more equitable assignments of the two zones allocated to each truck, which resulted in a more balanced distribution of workloads across drivers.

The solutions generated by the strategy were implemented by the Berazategui municipal government beginning in 2020. According to municipal officials, the solutions have resulted in a better-ordered and more balanced zoning and a set of routes that, in addition to being significantly shorter, will help improve control of the *achique* system.

Given the adaptability of the proposed approach, the tools described here could be used to redesign the zoning and route definitions if and when the municipality acquires additional vehicles to handle further population growth merely by changing certain parameters. Although the models were developed with Berazategui's specific attributes in mind, they should be adaptable to other urban areas with similar characteristics. The zoning heuristic is applicable in principle to any street plan, whereas the route design model could be used in any system in which collection vehicles do not have to cover every street.

Regarding future work on the methodology behind the approach, the squareness metric could be further developed to make it more sensitive at the iterative zoning procedure stage so that the correction algorithm would not have to make as many later adjustments. A more suitable algorithm parameter could be identified that would limit zone growth to better adapt to street plans with significant variation in block dimensions. In our case, using average block size meant that the first zones generated were somewhat larger than the last ones.

Another likely area for improvement is the reduction of the MILP route design model's solution time to optimality. In most cases, the model found solutions in less than 90 minutes that either were optimal or had an optimality gap of no more than 1%. The sole exception was a district serviced under special arrangements in which the number of nodes was double the average for the rest of the municipality. This suggests that better solution times could be achieved for instances with more than 300 nodes. The model is therefore best suited for application to instances not significantly larger than those involved in the project described here, wherein its performance was very satisfactory.

In conclusion, we note the words of Berazategui mayor Juan Patricio Mussi:

> "Before embarking on the project, we had added more trucks, but were not sure how to take advantage of the enlarged fleet to improve the system's efficiency. The mathematical programming algorithms devised in this work provided the necessary solution, which was to come up with a system design that improved and balanced collection crews' working conditions, reduced both fuel consumption and vehicle wear and tear, and provided Berazategui residents with an all-round better service. The new system was implemented in 2020 to great success. No doubt we will be able in the future to apply similar techniques to the improvement of other municipal activities."
>
> —Juan Patricio Mussi, 2022

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Appendix A

A.1. Zone Squareness Metric

Two different formulae were considered for the zone squareness metric. The first one, which we will denote $\mathcal{Q}$, was originally proposed by Rosin and Žunić (2011) for use in image processing, whereas the other, here denoted $\mathcal{M}$, is a convexity metric used by Delle Donne et al. (2021) to optimize a city's leaf-sweeping operations. For any bidimensional shape whose frontier is a simple closed curve, both metrics take values on the interval $(0, 1]$ and are invariant to translation, rotation, and scaling. If the shape is a quadrilateral, they will both take a value of one.

However, although either metric may be applied to a zone with such a frontier, experiments revealed that neither one by itself gave results that were completely satisfactory. The first metric barely registered small disturbances in the frontiers of zones with dozens of blocks, whereas the second one generated very high values for zones with a frontier resembling an elongated rectangle. We therefore decided to use as our definitive metric a convex combination of the two. Letting $A \subset \mathbb{R}^2$ be a bounded set such that ∂A is a simple closed curve, we define $\mathcal{S}$ as

$$\mathcal{S}(A) = \lambda \mathcal{Q}(A) + (1 - \lambda)\mathcal{M}(A). \tag{A.1}$$

If ∂A is square-shaped, then $S(A) = 1$. A series of tests found that a parameter value of $\lambda = 0.75$ gave the best results for the Berazategui zoning process.

A.2. Zoning Heuristic—First Phase

We constructed a graph $G = (V, E)$ in which the blocks are represented by vertices, any two of which are connected by an edge if and only if the corresponding blocks are adjacent. A set of blocks A is said to be connected if and only if the subgraph induced in G by the vertices representing the blocks in A is connected. An example of the bi-univocal relation between blocks on a map and vertices in a graph is shown in Figure A.1.

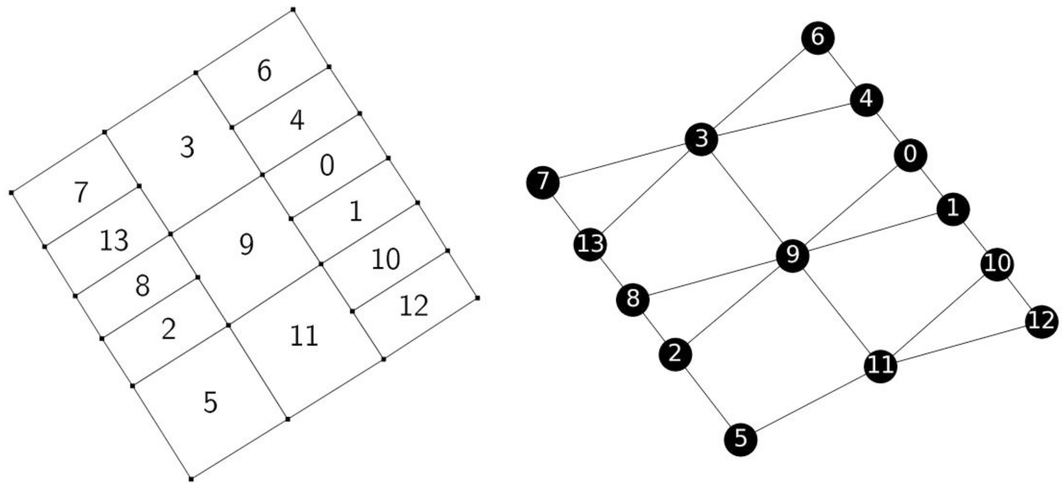
For each section s of the municipal street plan, a new zoning was designed. This procedure consisted of defining n_s collection zones such that each one had both balanced collection distances and as square a frontier as possible. Thus, considering only the former of these two criteria, for each G_s, the process attempted to find a balanced partition into n_s subsections.

To simplify the heuristic notation, we write $G = (V, E)$ instead of G_s and n instead of n_s. As is shown in the following, in each iteration of the procedure, at least one collection zone is defined. The pseudocode notation for the first phase is as follows:

- B_v: The block represented by vertex $v \in V$.
- v_B: The vertex representing block B.
- $m(A)$: Given a set A of blocks, we define its collection distance $m(A)$ as the sum of the lengths in meters of all the block sides within it that must be serviced (each block side is summed once).
- $\mathcal{B}(F)$: Given a subgraph $F = (V_F, E_F)$ induced in G, we define $\mathcal{B}(F) = \{B_v\}_{v \in V_F}$.
- $m(F)$: Given a subgraph $F = (V_F, E_F)$ induced in G, we define its collection distance $m(F) := m(\mathcal{B}(F))$.
- $\mathcal{A}(Z)$: The set of blocks in $\mathcal{B}(G) \setminus Z$ adjacent to the blocks in zone Z.
- m_{MIN}: A zone's minimum desirable collection distance.
- $\mathcal{Z}$: The set of zones in the plan that the heuristic has already defined (initially, $\mathcal{Z} = \emptyset$).
- $|\mathcal{Z}|$: The cardinal of $\mathcal{Z}$.
- $\mathcal{S}$: The squareness metric.

Recall that in the Design of Zones section, it was explained that when the procedure defining a zone concludes, the blocks it contains are eliminated from that section of the plan. This is the equivalent of eliminating those blocks' corresponding vertices from G and may leave the graph disconnected. If that is the case, we must determine how many zones can be defined from the connected components with collection distances greater than m_{MIN} (large components) and how to distribute the blocks in the connected components

Figure A.1. Section of the Street Plan and Its Graphical Representation



Note. Each vertex represents a block, and two vertices are connected by an edge if and only if their corresponding blocks are adjacent in the plan.

with collection distances less than m_{MIN} (small components) among the zones bordering on them.

To decide how many zones to create in each large connected component, we developed an MILP model denoted MILP1, whose objective is to minimize the maximum of the absolute value of the difference between the collection distance of each zone to be defined in each such component and the average collection distance of the zones already defined. The model's formulation is simple and therefore omitted for the sake of brevity. Its constraints, however, are as follows:

- At least one zone must be created in the largest connected component.
- No more than $m(G_i)/m_{MIN}$ zones may be defined in each connected component G_i.
- The number of zones to be defined must equal $n - |\mathcal{Z}|$.

Once the model is solved, the new zones to be created in each large connected component are delimited (except for the largest one, which will be addressed in the following iteration) by executing the heuristic recursively for that component, with $\mathcal{Z}$ introduced as the initial zoning. If, for any given connected component, the model indicates that no zones are to be created, that component is thereafter considered as a small one.

For each small connected component, its blocks are distributed among the q zones that surround them. The heuristic is run recursively on the component to define q subzones using its blocks, and another MILP model denoted MILP2 (also omitted because of its simplicity) is applied to decide which of the bordering q zones each of the subzones will be annexed to, thus ensuring its connectivity. If any of the subzones does not border on a zone, the heuristic is again run recursively, and the model then executed to distribute the sub-subzone's blocks among the neighboring subzones. The objective of MILP2 is to minimize the absolute value of the differences in collection distance among the q zones following the annexation of the subzones.

The pseudocode for the main body of Phase 1 of the heuristic is presented as Algorithm A.1. Lines 2–4 define the last remaining blocks of the zone to be assigned. For every other case, lines 6–11 construct a new zone that is then added to the zoning. Lines 12–16 analyze whether the connected components subroutine needs to be applied. This latter procedure is set out as Algorithm A.2. In it, lines 1–4 order and classify connected components by size. Line 6 handles the specific case in which only one zone remains to be defined. Lines 8–13 apply Algorithm A.1 recursively to define zones in large components. Finally, lines 14–18 divide small components into subzones and annex them to the zones adjacent. Note that the procedure cannot enter an infinite recursion because the number of blocks in the plan is finite. Also, it can be readily applied with zoning balance criteria that are different from those adopted here. For example, the amount of waste collected could be used instead of the collection distance.

A.3. Zoning Heuristic—Second Phase

We implemented a local search algorithm with a tabu list whose objective is to minimize the number of vertices on each zone's frontier. Letting s and t be two block sides on the frontier of zone Z that have a common corner c, and denoting as $\alpha \in (-\pi, \pi]$ the angle between s and t, we say that Z has a vertex at c if and only if $|\alpha| \in \left(\frac{1}{5}\pi, \frac{4}{5}\pi\right)$. The number of vertices of Z is denoted $\eta(Z)$.

Now let $\mathcal{B}$ be the set of blocks in the plan. We then say that a block $b \in Z$ is a frontier block in Z if there exists a block $\hat{b} \in \mathcal{B} \setminus Z$ in the plan such that b is adjacent to $\hat{b}$. In such a case, we also say that $\hat{b}$ is adjacent to Z. The set of frontier blocks in Z is denoted ∂Z, whereas the blocks adjacent to Z are denoted $\mathcal{A}(Z)$. At each algorithm iteration, each zone has either an adjacent block added or a frontier block subtracted, whichever obtains the greatest reduction (if any) in the number of vertices.

The pseudocode of the algorithm is set forth in Algorithm A.3, where (X, Y, b) expresses the transfer of block b from zone X to zone Y and $W(b)$ denotes the zone to which b belongs. Lines 4–21 describe the procedure for each zone Z in an iteration. Lines 7–12 calculate the number of vertices that result from annexing separately each block adjacent to Z and register the annexations, if any, that minimize that number.

Lines 13–18 perform the analogous process for the case in which Z cedes a frontier block to an adjacent zone. Finally, lines 19–21 execute the block transfers, if any, that minimize the number of vertices in Z and update the tabu list.

Algorithm A.1 (First Phase Algorithm)

Input: $G, \mathcal{Z}, n$
Output: $\mathcal{Z}$
while $|\mathcal{Z}| < n$ **do**
  if $|\mathcal{Z}| = n - 1$ **then**
    $Z \leftarrow \mathcal{B}(G)$
    $\mathcal{Z} \leftarrow \mathcal{Z} \cup \{Z\}$
  else
    $\bar{v} \leftarrow$ vertex with maximum eccentricity in G
    $Z \leftarrow \{B_{\bar{v}}\}$
    while $m(Z) < \frac{m(G)}{n-|\mathcal{Z}|}$ **do**
      $\tilde{B} \leftarrow \arg\max_{B \in \mathcal{A}(Z)} \mathcal{S}(Z \cup \{B\})$
      Add $\tilde{B}$ to Z
    $\mathcal{Z} \leftarrow \mathcal{Z} \cup \{Z\}$
    $H \leftarrow$ subgraph induced in G by $V \setminus \cup_{B \in Z} v_B$
    if *H is connected* **then**
      $G \leftarrow H$
    else
      $G, \mathcal{Z} \leftarrow$ CONNECTED_COMPONENTS_SUBROUTINE$(H, \mathcal{Z}, n)$
return $\mathcal{Z}$

Algorithm A.2 (Connected_Components_Subroutine)

Input: $H, \mathcal{Z}, n$
Output: $G, \mathcal{Z}$
$CCH \leftarrow$ connected components of H sorted in decreasing order by m
$G \leftarrow H_1$ (largest connected component in terms of m)
$H_{LARGE} \leftarrow \{H_j \in CCH : m(H_j) \geq m_{MIN}\}$
$H_{SMALL} \leftarrow CCH \setminus H_{LARGE}$
if $n - |\mathcal{Z}| = 1$ **then**
  $H_{SMALL} \leftarrow H_{SMALL} \cup (H_{LARGE} \setminus \{H_1\})$
else
  $S \leftarrow$ MILP1's solution (S_j: number of zones to define in $\mathcal{B}(H_j)$)
  foreach $H_j \in H_{LARGE} : j \neq 1$ **do**
    if $S_j > 0$ **then**
      $\mathcal{Z} \leftarrow$ ZONING_ALGORITHM$(H_j, \mathcal{Z}, |\mathcal{Z}| + S_j)$
    else
      $H_{SMALL} \leftarrow H_{SMALL} \cup \{H_j\}$
foreach $H_j \in H_{SMALL}$ **do**
  $A \leftarrow$ adjacent zones to $\mathcal{B}(H_j)$ in $\mathcal{Z}$
  subzones $\leftarrow$ ZONING_ALGORITHM$(H_j, \emptyset, |A|)$
  Solve MILP2
  Annex each subzone to the zone in A indicated by MILP2's solution
return $G, \mathcal{Z}$

Algorithm A.3 (Second Phase Algorithm)

Input: $\mathcal{Z}, \mathcal{B}, r, iter\_max$
Output: $\mathcal{Z}$
1 $T \leftarrow$ initialize empty tabu list of length $|\mathcal{Z}|$
2 $it \leftarrow 0$
3 **while** *$it \leq iter\_max$ and at least one zone changes* **do**
4   **foreach** $Z \in \mathcal{Z}$ **do**
5     $V \leftarrow \eta(Z)$
6     $best\_change \leftarrow \emptyset$
7   **foreach** $b \in \mathcal{A}(Z) : W(b) \setminus \{b\}$ *is connected* **do**
8       $Z \leftarrow Z \cup \{b\}$
9   **if** $\eta(Z) < V$ *and* $(Z, W(b), b) \notin T$ **then**
10         $V \leftarrow \eta(Z)$
11         $Z \leftarrow Z \setminus \{b\}$
12         $best\_change \leftarrow (W(b), Z, b)$
13   **foreach** $b \in \partial Z : Z \setminus \{b\}$ *is connected* **do**
14       $Z \leftarrow Z \setminus \{b\}$
15   **if** $\eta(Z) < V$ *and* $(W(b), Z, b) \notin T$ **then**
16         $V \leftarrow \eta(Z)$
17         $Z \leftarrow Z \cup \{b\}$
18         $best\_change \leftarrow (Z, W(b), b)$
19   **if** $best\_change \neq \emptyset$ **then**
20   Update T by adding $best\_change$
21   Make the block transfer indicated by $best\_change$
22   $it \leftarrow it + 1$
23 **return** $\mathcal{Z}$

Appendix B. MILP Model for the Design of Truck Routes

The plan of the city can be represented as a mixed graph denoted $P = (V_P, A_P, E_P)$, where A_P is the set of arcs representing one-way block sides and E_P is the set of edges representing two-way block sides.

A directed graph $G = (V, A)$ is constructed in which $V = V_P, (i,j) \in A \ \forall (i,j) \in A_P$, and for each $(i,j) \in E_P$, the arcs (i, j) and (j, i) are in A. Each arc (i, j) in G is weighted by the length of the block side it represents and is denoted $\ell(i,j)$. The traffic restrictions are processed as paths in G and stored in set F. For example, if travel from $(i,j) \to (j,k)$ is forbidden, $(i,j,k) \in F$. The paths associated with restrictions have three or four nodes.

To find the shortest path between nodes, we used the algorithm developed by Di Puglia Pugliese and Guerriero (2013), which seeks the shortest path (not necessarily a simple one) without traveling along any of the forbidden paths in F. If $(i,j) \notin A$, we denote as γ_{ij} the shortest path between i, j in G that has no forbidden paths as subpaths; otherwise $\gamma_{ij} = (i,j)$. Given a path $\gamma = (i_0, i_1, \ldots, i_N)$, its length in meters is $\ell(\gamma) = \sum_{k=0}^{N-1} \ell(i_k, i_{k+1})$.

In what follows, $s \in V$ and $t \in V$ denote the nodes representing the trucks' departure point and their arrival point, respectively, each corresponding to a different corner of the USD building.

Finally, we define the complete digraph $T = (V_T, A_T)$, where $V_T = V_Z \cup \{s,t\}$ and the weight w_{ij} of arc (i, j) is given by $\ell(\gamma_{ij})$. Because the trucks must visit every corner in Z starting from s and ending at t, the problem to be solved is an ATSP in T with additional constraints.

Turning now to the formulation of the model, we begin by defining the following parameters:

- $\mathcal{L} = \{e \in A_S \cup E_S : \ell(e) > 130\}$ is the set of block sides that cannot be serviced under the *achique* system.
- L_e: For each $e \in \mathcal{L}$, $(i,j) \in A_T$ belongs to L_e if any of the arcs representing e are part of γ_{ij}.
- V_{ij}: For any $i,j \in V_T$, $i \neq j$, V_{ij} is the set of all $k \in V_T$ such that if u is the second-to-last node in γ_{ij} and v is the second node in γ_{jk}, then $(u,j,v) \in F$.
- F_4: Forbidden paths with four nodes.
- B_δ: For each $\delta = (u_1, u_2, u_3, u_4) \in F_4$, $v \in V_T$ belongs to B_δ if and only if the last arc in γ_{vu_2} is (u_1, u_2).

- $\hat{B}_\delta$: For each $\delta = (u_1, u_2, u_3, u_4) \in F_4$, $v \in V_T$ belongs to $\hat{B}_\delta$ if and only if the last two arcs in γ_{vu_3} are (u_1, u_2) and (u_2, u_3).
- E_δ: For each $\delta = (u_1, u_2, u_3, u_4) \in F_4$, $v \in V_T$ belongs to E_δ if and only if the first arc in $\gamma_{u_3 v}$ is (u_3, u_4).
- $\hat{E}_\delta$: For each $\delta = (u_1, u_2, u_3, u_4) \in F_4$, $v \in V_T$ belongs to $\hat{E}_\delta$ if and only if the first two arcs in $\gamma_{u_2 v}$ are (u_2, u_3) and (u_3, u_4).

For each arc $(i, j) \in A_T$, a binary variable x_{ij} is defined that is equal to one if and only if γ_{ij} is part of the route. Also, for each $i \in V_T$, a nonnegative real variable u_i is defined that indicates the location of node i on the route in graph T.

$$\min \quad \sum_{i\in V_T} \sum_{\substack{j\in V_T \\ j\neq i}} \ell(\gamma_{ij}) x_{ij} \tag{B.1}$$

$$\text{s.t.:} \quad \sum_{i\in V_T} x_{ij} = 1 \qquad \forall j \in V_T \tag{B.2}$$

$$\sum_{j\in V_T} x_{ij} = 1 \qquad \forall i \in V_T \tag{B.3}$$

$$u_i - u_j + (n-1)x_{ij} + (n-3)x_{ji} \le n-2 \qquad \forall\, i, j \in V_T \setminus \{s\} \tag{B.4}$$

$$-u_i + (n-3)x_{is} + \sum_{\substack{j\in V_T\setminus\{s\} \\ j\neq i}} x_{ji} \le -1 \qquad \forall i \in V_T \setminus \{s\} \tag{B.5}$$

$$u_i + (n-3)x_{si} + \sum_{\substack{j\in V_T\setminus\{s\} \\ j\neq i}} x_{ji} \le n-1 \qquad \forall i \in V_T \setminus \{s\} \tag{B.6}$$

$$\sum_{(i,j)\in L_e} x_{ij} \ge 1 \qquad \forall e \in \mathcal{L} \tag{B.7}$$

$$x_{ts} = 1 \tag{B.8}$$

$$\sum_{k\in V_{ij}} x_{jk} \le 1 - x_{ij} \qquad \forall i, j \in V_T \tag{B.9}$$

$$\sum_{v\in B_\delta} x_{vu_2} + x_{u_2u_3} + \sum_{v\in E_\delta} x_{u_3 v} \le 2 \qquad \forall \delta \in F_4 \tag{B.10}$$

$$\sum_{v\in \hat{B}_\delta} x_{vu_3} + \sum_{v\in E_\delta} x_{u_3 v} \le 1 \qquad \forall \delta \in F_4 \tag{B.11}$$

$$\sum_{v\in B_\delta} x_{vu_2} + \sum_{v\in \hat{E}_\delta} x_{u_2 v} \le 1 \qquad \forall \delta \in F_4 \tag{B.12}$$

$$u_i \ge 0 \qquad \forall i \in V_T$$

$$x_{ij} \in \{0, 1\} \qquad \forall (i, j) \in A_T$$

The objective function (B.1) minimizes the length of the route that visits each node in T exactly once. Constraints (B.2)–(B.6) are from the Desrochers and Laporte ATSP model with departure node s. Constraints (B.2) and (B.3) make certain that each node in T is visited exactly once, whereas (B.4)–(B.6) avoid the formation of subtours. Constraint (B.7) ensures that the trucks directly service all block sides that are too long to be handled under the *achique* system. Constraint (B.8) imposes that t is the last node visited. By construction, γ_{ij} has no prohibited paths, but in passing from the end of one shortest path to the start of the next, a traffic restriction could be violated. Constraints (B.9)–(B.12) therefore prevent this by anticipating cases of forbidden paths with three or four nodes. Based on its solution, the entire path Γ for servicing zone Z is put together by joining the shortest paths γ_{ij} such that $x_{ij} = 1$.

Appendix C. MILP Model for the Truck-to-Zone Assignment

In the following, we present the assignment of trucks to zones as a mixed-integer linear programming model, which is used to apply the epsilon-constraint method. The parameters of the problem are as follows:

- T: The set of trucks
- Z: The set of zones
- c_i: The container load capacity of truck $i \in T$
- w_j: The waste-load weight generated by zone $j \in Z$
- ℓ_j: The truck route length for zone $j \in Z$
- ε: The fixed value corresponding to the iteration of the epsilon-constraint method

For each $i \in T$, $j \in Z$ a binary variable x_{ij} is defined that indicates whether zone j is assigned to truck i. A real variable y is used to minimize the maximum disparity in waste load. We formulate the model as

$$\min \quad y \tag{C.1}$$

$$\text{s.t.:} \quad \sum_{j\in Z} x_{ij} = 2 \qquad \forall i \in T, \tag{C.2}$$

$$\sum_{i\in T} x_{ij} = 1 \qquad \forall j \in Z, \tag{C.3}$$

$$\sum_{j\in Z} x_{ij} w_j \le c_i \qquad \forall i \in T, \tag{C.4}$$

$$\sum_{j\in Z} (x_{ij} - x_{kj}) w_j \le y \qquad \forall i, k \in T, \tag{C.5}$$

$$\sum_{j\in Z} (x_{ij} - x_{kj}) \ell_j \le \varepsilon \qquad \forall i, k \in T, \tag{C.6}$$

$$x \in \{0, 1\}^{n\times m},$$

$$y \in \mathbb{R}.$$

The objective function (C.1) and Constraint (C.5) model the minimization of the maximum disparity in waste load. Constraint (C.2) stipulates that each truck is assigned to two zones, Constraint (C.3) imposes that exactly one truck is assigned to each zone, Constraint (C.4) ensures that no truck's load capacity is exceeded, and Constraint (C.6) is the epsilon constraint involving the second objective.

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Verification Letter

Juan Patricio Mussi, Mayor of Berazategui from December 2011 to December 2019, writes:

"Berazategui is an Argentine city located on the south side of the Buenos Aires metropolitan region 26 km south of Buenos Aires City, the national capital. It covers an area of 217 km^2 and is home to an estimated 365,000 inhabitants.

"The logistics of Berazategui's waste collection service, run by the city's Urban Sanitation Department, had for many years reflected the knowledge built up over time by the system's supervisors. Based simply on long experience, a series of collection truck routes had *been* traced out that until recently had performed efficiently. But with the growth of the city's population and its urban fabric, it had become increasingly evident that the routes would have to be redesigned if they were to continue serving effectively the waste collection needs of all residents.

"Thus, in 2019 we sought the collaboration of the *Institute de Cálculo* at the University of Buenos Aires on a project that would bring about a series of improvements to our waste collection system. Before embarking on the project we had added more trucks, but were not sure how to take advantage of the enlarged fleet to improve the system's efficiency. The mathematical programming algorithms devised by the *Instituto* provided the necessary solution, which was to come up with a system design that improved and balanced collection crews' working conditions, reduced both fuel consumption and vehicle wear and tear, and provided Berazategui residents with an all-round better service. The new system was implemented in 2020 to great success.

"I had the honour to serve as mayor of Berazategui for eight years through 2019, the year the project was launched, and in that position I always supported the idea of using mathematical and technological tools to improve management of public resources. The success of the waste collection project clearly demonstrates that the adoption of a scientific approach was the right decision. No doubt we will be able in the future to apply similar techniques to the improvement of other municipal activities."

Federico Bertero holds a BS in computer science from the University of Rosario. He leads the technology area of a company in Buenos Aires, Argentina, dedicated to the development of software and artificial intelligence solutions for the financial sector. His professional interests include integer programming, applications of operations research, statistics, and data science.

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