MGSC-662

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Optimization Project

Report: Optimization for City Waste Management

Presented by Group 5

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Presented to

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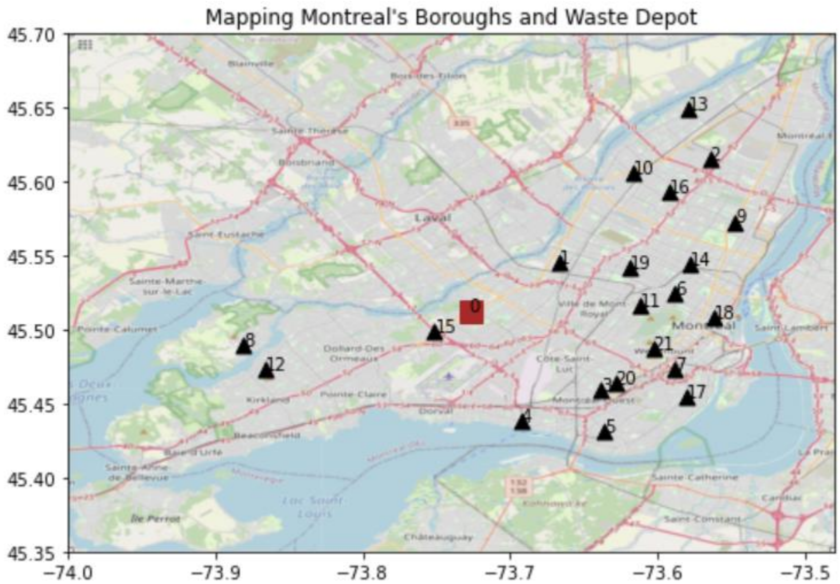
Introduction:

Waste management is an important consideration in the growth and development of a city and is quintessential to ensuring the well-being of the citizens. With the rise of urbanization, capitalism and growing populations, cities are faced with the challenge of ensuring efficient garbage collection and management from the households and commercial sites. The waste collection process inherently involves expenditure with respect to capital (trucks involved), labor (drivers and helpers) and other incidental operational costs. A typical waste collection process involves garbage collection trucks leaving the depot and following a fixed route until all garbage is collected. This process, albeit being straight forward, may not always be efficient. Thus, through optimization of the waste collection routes in a city based on data regarding the city's demographics, one can increase time efficiency and reduce fuel costs and GHG emissions. In our project, we aimed to provide insights to the City Council of Montreal for efficient garbage collection from the 21 neighborhoods of Montreal.



Each neighborhood consists of numerous households that produce a certain amount of household waste that must be collected daily. The problem aims to find the optimal path that the garbage collection trucks would have to take to collect waste from all the neighborhoods in the city of Montreal.

To compute an optimal solution that reflected the challenges of the real world, considerations regarding the capacity of the trucks, volume of waste generated, and hours of work had to be considered. The goal of the project is to provide the City of Montreal with data-driven decision-making abilities and leverage population data to save travel distance and prescribe the optimal number of trucks involved in the collection process to reduce fuel and GHG emissions. Thus, ensuring that the city's activities are implemented in a sustainable and time efficient manner.

Problem Description and Formulation:

The problem thus considers 21 neighborhoods of Montreal and one garbage disposal site. The main objective of our model is to minimize the distance travelled while collecting garbage from all the neighborhoods. We assume that the City of Montreal has multiple trucks available at its disposal thus there are no restrictions on the number of trucks deployed. Thus, the objective function can thus be mathematically represented as the following,

- A is a set of all the paths being considered in the model (paths between the garbage disposal site and the 21 neighborhoods); paths are created between i and j, where i is the initial point and j is the next point.
- Distance Traveled_{ij} is the distance between two points being considered:

$$\text{Minimize} \sum_{i,j \in A, i \neq j} \text{Distance Travelled}_{ij}$$

It is important to note that minimizing distance in our objective would implicitly result in minimizing the costs. This is because the costs for garbage collection would involve fuel costs and labor costs. We know that fuel is a function of the distance travelled, and the fuel costs incurred are likely to increase as the distance increases. However, this problem also involves the truck moving within neighborhoods, where the truck would be stopping regularly for collecting garbage from the innumerous households in the neighborhoods. Estimating the fuel requirements for this part would be difficult because the trucks tend to utilize more fuel when they are stopping at regular intervals.

Furthermore, minimizing distance would also yield optimal paths to be taken from the garbage depot site, thus, an optimal number of trucks needed from the city's fleet can thus be found as a function of the number of optimal paths outputted by our basic model. The number of trucks dictated by the model would give us the number of drivers and helpers needed during the daily collection shift (assuming that each truck is manned with 1 driver and 1 helper). This indicates that in this case, minimizing distance would lead to minimization of paths and trucks and in turn, the labor requirements and labor charges.

Time can also be considered as a function of distance, and with the time constraint in place, the distance minimization would give us the most optimal results for this problem statement, as it also considers minimizing the costs and time. The model solution would aid the government in making informed decision making for deciding the number of trucks required for garbage collection and the optimal paths for trucks.

The following constraints would have to be added to our basic model to incorporate the restrictions that the City of Montreal faces in the garbage collection process.

- Path Restrictions:

  Household waste is collected once from each neighborhood daily. Each neighborhood must be visited once. Therefore, once the garbage is collected from a certain neighborhood then that neighborhood must not be visited again. Furthermore, all garbage trucks must originate from the depot and end their journey at the depot after visiting all the neighborhoods in its path.

- Garbage Volume from Different Neighborhoods and Truck's Capacity Constraint:

  The garbage trucks must collect household waste from all the neighborhoods that it visits while ensuring that the volume of garbage collected does not exceed the truck's maximum capacity which is set to be 28,000 lbs in our basic model.

- Time Considerations:

  The time involved in the garbage pick-up would vary across each neighborhood and would be a function of the population density in that neighborhood as it would dictate the volume of waste generated. Neighborhoods that have higher population density would implicitly result in longer pick-up times. Furthermore, we would have to ensure that the cumulative time spent collecting garbage from each neighborhood in a truck's path would have to be accounted for such that the total time does not exceed the time allocation for the day, that is, between 6AM and 1PM.

Details of the constraints and the decision variables in place are added in the numerical implementations and results section.

Numerical Implementation and Results:

For the implementation, we have used a combination of real and synthetic data. The data for Montreal Waste Management was not publicly available. Therefore, we formulated the problem description, followed by data preparation. We implemented 546 decision variables and 1974 constraints for obtaining the minimized distance paths for garbage collection. A minimized distance of 308.7 km and 8 optimal truck paths were obtained by running the model. Below is a summary of the tasks implemented:

1. Problem formulation and identification of the required datasets

   The problem is to identify the routes for garbage collection across various neighborhoods in the city. Each route will be taken by a single truck. We identified all the 21 listed neighborhoods in Montreal city. We also identified a garbage disposal center, Montreal Junk and Garbage Removal, which would be the starting and ending point for all the trucks. Next, we used web scraping to create a 22 x 22 distance matrix for all points (21 neighborhoods and 1 disposal center). For each of these 22 points, we also identified the coordinates for mapping them over a map (for representation purposes). The actual solution is being implemented using actual distances, but all points have been plotted on a map while showing the Euclidean distance lines between all points. This would be helpful in visually representing the optimal paths of each truck.

   We added estimations and synthetic data for the following data points:

   - Number of households in each neighborhood: we estimated that each household has 20 members on an average (since households can include buildings and individual bungalows).
   - Based on the country statistics, we considered that each individual produces 2.7 lbs of garbage daily. Therefore, quantity of garbage produced by each neighborhood = (number of households * 2.7 * 20).
   - From our studies, we noted that a garbage truck can usually hold upto 30,000 lbs of garbage. Therefore, we allocated each truck's capacity as 28,000 lbs.
   - We estimated the speed of the truck to be 30 km per hour, that is, 2 mins for traveling 1 km. This speed is applicable when the trucks are traveling between the 22 points. Once the truck enters a neighborhood, we estimate the pickup time per household to be 1 minute. Therefore, the pickup time per neighborhood would be (number of households * 1). The total time traveled by each truck would be the sum of travel time between points and garbage pickup times within neighborhoods.

Please refer to *Appendix 1* for the representation of the datasets used in the model.

2. Decision Variables and Constraints

We have a total of 546 decision variables for our model. The descriptions for each of the decision variables are mentioned below:

x decision variables:

The objective function is defined to minimize the distance traveled by the trucks. We have labeled all the 21 neighborhoods as natural numbers between [1,21], and the garbage disposal center is labeled as 0. To achieve the objective, we would be required to identify the active paths for each truck. For instance, if the truck is moving across the path: 0 -> 2 -> 13 -> 16 -> 0, the active paths will be (0,2), (2,13), (13,16), and (16,0). Hence, all the potential paths would be decision variables (named x in the model) of type binary. Gurobi will compute the value for these decision variables as 0 or 1, and therefore all the active paths can be extracted by filtering where the value of x is equal to 1. The pairs like (0,0) or (1,1) are not being considered as potential paths since these are equivalent to points. Therefore, the total number of x decision variables are (22*22)-22 = 462.

Thus, the objective constraint can then be represented as the following:

$$\text{Minimize} \sum_{i,j \in A} dist_{ij} x_{ij}$$

For the formulation of constraints, we have added dummy decision variables as follows:

u1 decision variables:

The garbage collection trucks can only carry garbage quantity that is less than or equal to the garbage carrying capacity of the truck. Therefore, we need to calculate the cumulative garbage quantity collected from each neighborhood to ascertain that the (garbage collected so far and the garbage to be collected from the next neighborhood) does not exceed the truck's garbage carrying capacity. For instance, if the truck is moving across the path: 0 → 9 → 11 → 0, the u1 value for 9th point is 11664 (that is the garbage quantity in the 9th neighborhood). The u1 value for the 11th point is 19656 (that is the sum of garbage quantities at 9th and 11th neighborhoods). Total number of u1 decision variables are the number of neighborhoods, since only garbage is picked up only from neighborhoods. Therefore, there are 21 u1 decision variables.

u2, u3, u4 decision variables:

The trucks can only collect the garbage within 7 hours, that is, 420 minutes. The trucks spend time traveling between the points (neighborhoods and garbage disposal center) and garbage pickup within neighborhoods. The u2 decision variables have been created for the cumulative time of (garbage pickup time + travel time within neighborhoods). u3 decision variables have been created for calculating the travel time between the garbage disposal center and the first neighborhood. Likewise, u4 decision variables have been created for calculating the travel time between the last neighborhood and the garbage disposal center. For instance, if the truck is moving across the path: 0 → 9 → 11 → 0, the u2 value for the 9th point is 216 (that is, garbage pickup time in the 9th neighborhood). The u2 value for the 11th point is 383.6 (that is, garbage pickup times at 9^{th} and 11^{th} neighborhood + travel time from 9^{th} neighborhood to 11^{th} neighborhood). The u3 value for 9^{th} point is 40.6, that is the travel time between the disposal center and 9^{th} neighborhood. The u3 value for the 11th point is 0, since the truck does not travel between these points. Likewise, the u4 value for the 11th point is 20.3, that is the travel time between the 11th neighborhood and the disposal center. The u4 value for 9^{th} point is 0, since the truck does not travel between the disposal center and the 9th neighborhood. Total number of u2, u3, u4 decision variables are the number of neighborhoods. Therefore, there 63 decision variables for u2, u3, u4.

Constraints:

There are a total of 1974 constraints for our model. The descriptions for each of the constraints are mentioned below:

- Each truck must enter each neighborhood exactly once. Likewise, each truck must exit each neighborhood exactly once. There are 21+21=42 constraints in place for this. These constraints can be mathematically represented as the following:

$$\sum_{i \in V, i \neq j} x_{ij} = 1$$

$$\sum_{j \in V, j \neq i} x_{ij} = 1$$

- Since each neighborhood can only be entered and exited from only once, only the garbage disposal center would allow multiple trucks exiting and entering. Therefore, there is an implicit constraint that all paths must originate from and end at the garbage disposal center.
- The cumulative amount of garbage collected for each truck (calculated using the u1 dummy decision variable) must be less than the truck's garbage carrying capacity. There are 462 constraints for calculating the cumulative garbage collected using the u1 decision variable. This was formulated as the following:

$$\text{If } x_{ij} = 1 \text{ then } u_{1i} + q_i = u_{1j}; \text{ where, } i, j \in A \text{ and } j \neq 0, i \neq 0$$

- There are additional 21+21=42 constraints for ensuring that the cumulative garbage quantity is greater than or equal to the individual garbage quantity of each neighborhood (q_i), and that the cumulative garbage quantity is lesser than or equal to the truck's capacity (Q). This can be represented as the following:

$$u_{1i} >= q_i; \text{ for all } i \in \ A$$

$$u_{1i} <= Q; \text{ for all } i \in \ A$$

- There are constraints that define the cumulative garbage pickup time and truck travel time for each truck (calculated using the u2, u3, u4 dummy decision variables). There are 462+462+462=1386 constraints for calculating the cumulative time using the u2, u3, u4 decision variables. This constraint can be represented as the following:

$$\text{If } x_{ij} = 1 \text{ then } u_{2i} + t_j + (dist_{i,j} * \text{time\_perkm}) = u_{2j}; \text{ where, } i, j \in \ A \text{ and } j \neq 0, i \neq 0$$

$$\text{If } x_{ij} = 1 \text{ then } (dist_{0,j} * \text{time\_perkm}) = u_{3j}; \text{ where, } i, j \in \ A \text{ and } j \neq 0, i = 0$$

$$\text{If } x_{ij} = 1 \text{ then } (dist_{0,j} * \text{time\_perkm}) = u_{4j}; \text{ where, } i, j \in \ A \text{ and } j = 0, i \neq 0$$

- There are additional 21+21=42 constraints for ensuring that the cumulative time is greater than the individual garbage pickup time of each neighborhood (t_i), and that the cumulative garbage time is less than the daily time limit of 7 hours (daily_min_limit). This is represented as the following:

$$u_{2i} >= t_i; \text{ for all } i \in \ N$$

$$u_{2i} + u_{3i} + u_{4i} <= \text{daily\_min\_limit}; \text{ for all } i \in \ N$$

3. Model Results

We noted that the minimized distance obtained through the model is 308.7 km, that is, daily, the combined distance traveled by the garbage pickup trucks is 308.7 km.

We identified 8 optimal paths for 8 garbage collection trucks. Each neighborhood is represented by a natural number between [1,21], and the garbage disposal center is represented by 0. We have formatted the model results to obtain the output as the following:

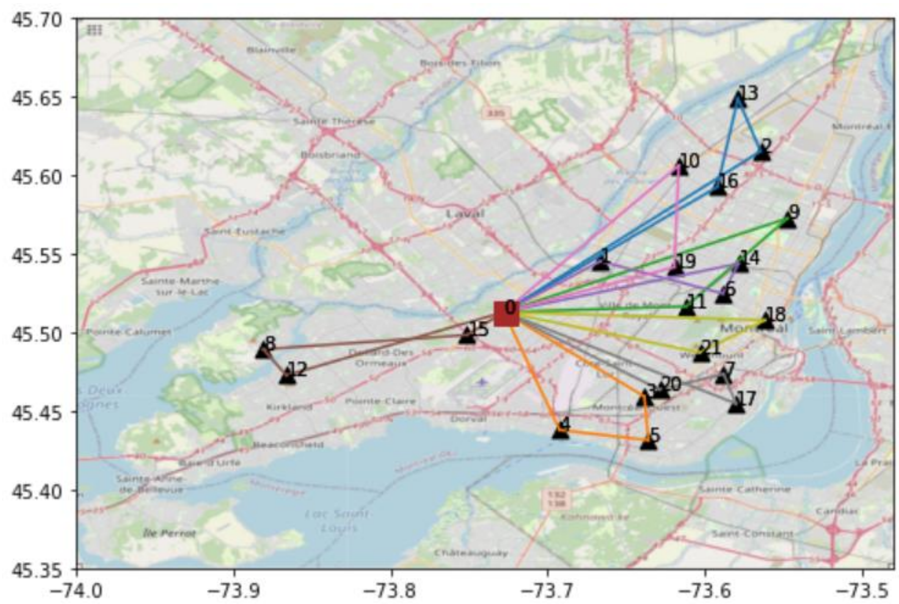
```
Minimized distance: 308.7

Truck Paths:

Truck 1 Path: 0 -> 2 -> 13 -> 16 -> 0
Truck 2 Path: 0 -> 3 -> 5 -> 4 -> 0
Truck 3 Path: 0 -> 9 -> 11 -> 0
Truck 4 Path: 0 -> 14 -> 6 -> 1 -> 0
Truck 5 Path: 0 -> 15 -> 8 -> 12 -> 0
Truck 6 Path: 0 -> 19 -> 10 -> 0
Truck 7 Path: 0 -> 20 -> 7 -> 17 -> 0
Truck 8 Path: 0 -> 21 -> 18 -> 0
```

We have also plotted the routes on maps. Each path is represented by a different color.

Note: This map has been created for representation purposes. The model results use the actual distance between the points instead of the Euclidean shortest path distance (displayed in the image).



The solutions obtained are aligning with our goals and understanding of the business problem. We have achieved the optimal paths, and therefore, the number of trucks that would be deployed are equal to the number of paths.

We cross-verified the solution with the decision variables, i.e., x decision variables for optimal paths, and u1, u2, u3, u4 decision variables for constraints. For instance, we checked that all the active paths (where x=1) were complete and originating from and ending at the garbage disposal center. Also, each neighborhood was visited exactly once and there was no overlap between any of the paths. For the u1, u2, u3, and u4 decision variables, we verified all the cumulative numbers and whether the cumulative values were lesser than the maximum allowed values.

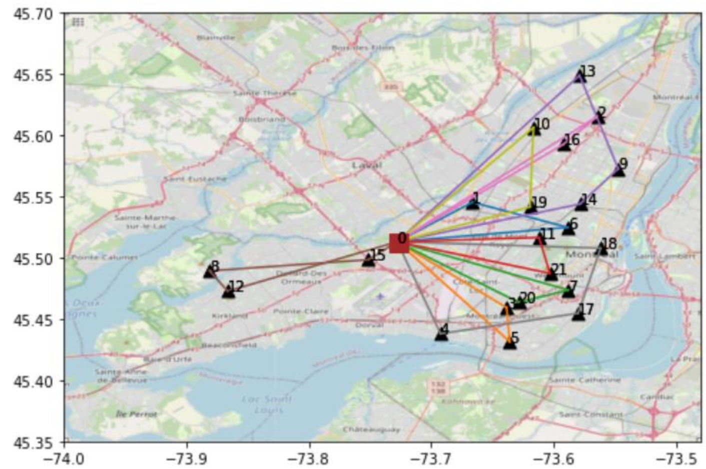
Problem Extensions:

<u>Model Extension 1:</u> While performing the research about the waste management practices, we noted that garbage trucks have a range of varieties and differ from each other in terms of garbage carrying capacity. For our model, we had considered the garbage holding capacity to be 28,000 lbs. However, we inspected the change in the number of paths and trucks by varying the capacity number. We inspected if the trucks with a lower capacity (18,000 lbs capacity) can be used in the same setting. We re-ran the same model by changing the capacity to 18,000 lbs, and noted the following results:

```
Minimized distance: 351.7

Truck Paths:

Truck 1 Path: 0 -> 1 -> 6 -> 0
Truck 2 Path: 0 -> 5 -> 3 -> 0
Truck 3 Path: 0 -> 7 -> 20 -> 0
Truck 4 Path: 0 -> 13 -> 9 -> 14 -> 0
Truck 5 Path: 0 -> 15 -> 8 -> 12 -> 0
Truck 6 Path: 0 -> 16 -> 2 -> 0
Truck 7 Path: 0 -> 18 -> 17 -> 4 -> 0
Truck 8 Path: 0 -> 19 -> 10 -> 0
Truck 9 Path: 0 -> 21 -> 11 -> 0
```



We noted that the minimized distance is 43 km more than the previous model. Also, even after decreasing the capacity of the whole fleet, the requirement of additional trucks only increased by 1 truck. Therefore, fuel efficiency can be calculated for both the cases- that is, 8 trucks each of 28000 lbs capacity traveling for a total of 308.7 km, and 9 trucks each of 18000 capacity traveling for a total of 351.7 km. Accordingly, fleet management activities can be carried out by the Waste Management department of the government.

<u>Model Extension 2:</u> Finding the optimal allocation of garbage collection hours

The basic model developed initially considers the total number of daily garbage collection hours to be set at 7 hours. However, it would be in the interest of the city to explore the option of extending the number of garbage collection hours. The rationale behind this suggestion is that longer hours of operation would allow the trucks to take continuous paths that would not have been permitted due to the stricter daily collection time constraint placed by the initial model. Due to this, the distance would be minimized further than what would have been obtained in our initial model. This could be an important consideration for the city as with shorter distances the incidental GHG emissions would be reduced (through fuel cost savings). With the assumption that reduction of GHG emissions is of higher importance than the increase of labor cost, such consideration would allow the city to optimize the waste collection process in a manner that prioritizes environmental sustainability. In order to find the optimal garbage allocation hours, the following modifications to the initial model were made:

- Introducing dummy binary variables {y1, y2, y3} such that their sum is equal to 1. These dummy variables would aid in the selection of the optimal number of hours allocated.

$$y_1 + y_2 + y_3 = 1$$

- The collection hours are set as a decision variable in the model and is a function of the new dummy binary variables and the different hours being considered.

$$z = 480 * y_1 + 420 * y_2 + 360 * y_3$$

- Lastly, the time constraint in the previous model is modified to be set to the decision variable pertaining to the optimal number of collection hours.

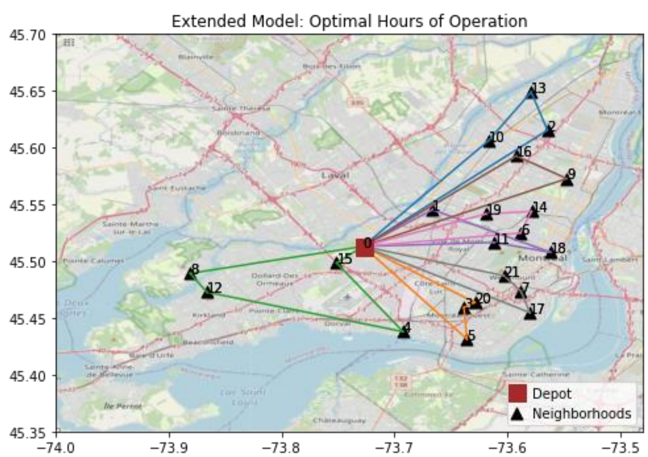
$$u_{2i} + u_{3i} + u_{4i} <= z; \text{for all } i \in N$$

The modified model outputs the following results where y1 = 1; thus, the model output shows that the optimal collection hours should be set to 8 hours. Through such modifications the distance is minimized more than what was proposed in the original model. The savings in total distance is found to be 33.4 km which is nearly 11% of the initial route; thus, a unit increase in collection hours would result in considerable reduction of GHG emissions. Trucks produce 260.39 grams of CO_2 emissions per km[1]; thus, the implementation of an extension would result in the decrease of CO_2 emissions from 80382.39 gms to 71,685.37 gms.

```
Minimized distance: 275.3

Truck Paths:

Truck 1 Path: 0 -> 2 -> 13 -> 10 -> 0
Truck 2 Path: 0 -> 5 -> 3 -> 20 -> 0
Truck 3 Path: 0 -> 8 -> 12 -> 4 -> 15 -> 0
Truck 4 Path: 0 -> 11 -> 18 -> 1 -> 0
Truck 5 Path: 0 -> 16 -> 9 -> 0
Truck 6 Path: 0 -> 19 -> 14 -> 6 -> 0
Truck 7 Path: 0 -> 21 -> 7 -> 17 -> 0
```



As we were implementing the model, we also explored other related potential problems and solutions. We have not implemented these due to complexity and time constraints. There were also some constraints in terms of Gurobi's power to handle the decision variables and constraints on an Academic License.

Please refer to *Appendix 2* for details of the other potential model extensions to our model.

[1] Mathers, Jason. Clean Air Innovation: https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/

Recommendations and Conclusions

This model optimizes the distance associated with garbage pickup based on a number of different factors. The distances are calculated by adding constraints on the traveling time between different locations and on the garbage carrying capacity of the trucks. The model is an example of the Arc Routing Problem that has been modified according to the use-case, using each neighborhood as a cluster of households. The model assumes that the frequency of garbage pickup is daily for all the 21 neighborhoods.

While formulating the model, we initially planned on solving the model as the Traveling Salesman Problem. However, as we researched about the business aspects of the waste management problem, we identified that it can be better solved as a Vehicle Routing Problem (or its modified version, Arc Routing). The project was interesting to solve since it relates to the real word closely and aims towards creating sustainable environment-friendly solutions for minimizing the distances traveled, leading to fuel usage minimization. This is also a major area of focus for several large multinational companies. Apart from that, the project helped us learn about creating the problem and implementing its solution theoretically and on Gurobi independently.

If we were to recreate the problem solution, we would have further refined the model by adding a greater degree of complexity to it. Creating clusters out of individual addresses rather than neighborhoods would result in a greater degree of accuracy to real-world data and applications. Secondly, all the trucks return to the depot once their garbage carrying capacity is exhausted. We could have added the trucks' ability to take multiple trips from the depot, thereby increasing the management's flexibility in using trucks of varying capacities.

We initially planned on running the Arc Routing model for multiple sub-neighborhoods, to make the model closer to the real-world scenario. However, while attempting to run the model for about 1000 locations (i.e., > 25 locations), Gurobi failed to optimize the model due to its Academic License limitations. Creating a high number of location nodes resulted in an exponential increase in the number of potential paths, thereby increasing the number of decision variables and constraints significantly. Therefore, we decided to use clustered data instead of actual addresses in terms of neighborhoods.

The problem was created using real data available on the internet. Actual distances between the Montreal neighborhoods were calculated while solving the problem, and the garbage carrying capacity was taken for the most common type of truck used by garbage disposal companies. The model demonstrates a practical scalable solution to the routing problem that can easily be incorporated into any company optimizing vehicle routes (like Canada Post). The results produced are comprehensive, visual, and easily interpretable as well, which is a testament to the complex, yet simplistic nature of the model produced.

Appendix

Appendix 1

Below is the format for the distance matrix that has been computed using the actual distances between all the 22 points (that is, 21 neighborhoods, and 1 garbage disposal center):

Locations	Montreal Junk and Gar	Ahuntsic-Cartierville	Anjou	Cote-des-Neiges–Notre	Lachine	LaSalle	Le Plateau-Mont-R
Montreal Junk and Garbage Removal	0	6.8	20.3	14.5	12.2	16.7	
Ahuntsic-Cartierville	6.9	0	13.4	15.6	16.6	21.1	
Anjou	20.4	13.9	0	24.3	25.7	30.4	
Cote-des-Neiges–Notre-Dame-de-Grace	14.9	14.8	24.7	0	5.9	4.6	
Lachine	12.4	18.7	30.4	6.3	0	6.7	
LaSalle	17.1	18.6	27.7	3.8	5.2	0	
Le Plateau-Mont-Royal	14	7.5	14.3	10.4	18.2	16	
Le Sud-Ouest	15.9	14.1	23.2	4.9	9.5	7.9	
L'Ile-Bizard–Sainte-Genevieve	15.6	24.5	36.7	28	22.4	27	
Mercier–Hochelaga-Maisonneuve	18.7	12.2	7.1	19.4	24.1	22.2	
Montreal-Nord	14.9	8.7	5.6	22.7	24.1	28.8	
Outremont	11.7	7	16.9	9	15.7	15.9	
Pierrefonds-Roxboro	14.6	21.7	35.3	24.4	18.8	23.4	
Riviere-des-Prairies–Pointe-aux-Trembles	26.1	19.6	5.7	30	31.4	36.1	
Rosemont–La Petite-Patrie	15.2	8.7	11	16.2	21.2	19	
Saint-Laurent	3.5	10.1	24.8	14.8	10.7	15.2	
Saint-Leonard	16.8	10.3	4.6	20.7	22.1	26.8	
Verdun	16.2	16	25.2	7.2	12.1	6.1	
Ville-Marie	20.1	9.8	16	10.1	16.1	13.3	
Villeray–Saint-Michel–Parc-Extension	11.8	4.6	11.2	13.2	17.1	21.6	
West Island	14	13.9	23.8	1.2	6.8	5.9	
Westmount	13.6	13.4	23.4	4.3	13	10.8	

Below is the dataset containing the randomized number of households within each neighborhood, along with the actual coordinates of each neighborhood:

Locations	latitude	longitude	Number of Households
Montreal Junk and Garbage Removal	45.51301395	-73.72782343	0
Ahuntsic-Cartierville	45.54529556	-73.66656599	76
Anjou	45.61535257	-73.56476363	141
Côte-des-Neiges–Notre-Dame-de-Grâce	45.45922476	-73.63865556	160
Lachine	45.43791516	-73.69249152	65
LaSalle	45.43141962	-73.63605234	132
Le Plateau-Mont-Royal	45.5247773	-73.58876237	249
Le Sud-Ouest	45.47361772	-73.58826334	202
L'Île-Bizard–Sainte-Geneviève	45.48926296	-73.8808497	109
Mercier–Hochelaga-Maisonneuve	45.57269465	-73.54756383	216
Montréal-Nord	45.60629182	-73.61670944	223
Outremont	45.51649422	-73.61220533	148
Pierrefonds-Roxboro	45.47270452	-73.86613933	105
Rivière-des-Prairies–Pointe-aux-Trembles	45.64889758	-73.57914029	55
Rosemont–La Petite-Patrie	45.54383572	-73.57881314	58
Saint-Laurent	45.49838798	-73.75130436	55
Saint-Leonard	45.59265206	-73.59223489	160
Verdun	45.45465065	-73.5802559	60
Ville-Marie	45.50778746	-73.56199659	206
Villeray–Saint-Michel–Parc-Extension	45.54149218	-73.61960363	90
West Island	45.46357752	-73.62887816	109
Westmount	45.48725177	-73.60328138	144

The dataset used for the model has been attached here:

Garbage Collection Optimization Datasets

Appendix 2

Below are the potential model extension ideas for future learnings:

- Trucks' ability to go back for garbage collection after dumping the collected garbage to the disposal center. In some scenarios, the trucks might be returning to the garbage disposal center due to capacity constraint. In such scenarios, if the truck is still left with a significant amount of time, we can formulate a problem that enables the same truck to restart its journey on the same day for garbage collection. This would lead to enhanced fare optimization, as fuel would be utilized more efficiently due to a lesser number of trucks. Also, lesser trucks mean lesser manpower requirements for driver and helper staff.

- Similar to the extension solution 1 mentioned above, we can deploy a mixed variety of trucks for garbage collection. This can be achieved by identifying trucks which are not utilizing their garbage carrying capacity (below a particular set threshold). Further, these large trucks would be suited to be replaced with smaller trucks wherever needed. This would lead to reduction in fuel costs and time (since larger trucks usually take more time than smaller trucks to travel the same distance).

- Currently, the objective function of the model is to minimize the distance. This can be updated to minimize the costs. Costs would include fuel costs and labor costs. The labor costs (like driver’s salaries) would be proportional to the number of trucks (which depends on the distance). The model hence already considers the labor cost reduction to some extent. However, for fuel costs calculations, the model can be updated to include fuel usage of trucks inside the neighborhoods, depending on the number of households in each neighborhood.

- The model can also be modified to identify the optimal location for setting up a new garbage disposal center. If the government considers the current solutions to be inefficient and approves the formation of a new center for dumping garbage, the model can be built using some of the existing constraints. New constraints like land availability, distance optimization, and budget, would enable in building the model. The addition of a garbage disposal center would result in increased time and fuel efficiencies.

- In the current model, the truck staff (like the driver and the helper) are working continuously after the truck leaves the garbage disposal center. They do not have any break times before the truck reaches back to the garbage disposal center. The continuous time spent by the staff could go up to 7 hours at a stretch. This situation is not realistic and ideal. We can enhance the model to include breaks after a continuous service of 3 to 4 hours. The breaks would be scheduled in a way that the truck is not inside a neighborhood during the break time.