MSCI 332 Project Part 2

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Table of Contents

Executive Summary

This report aims to present the formulation and results of different heuristic techniques that determine the optimal potential network of charging stations throughout key locations in Canada to help address the country's lack of electric vehicle support. More specifically, the study at hand focuses on finding the location and capacity for these electric vehicle charging stations that optimizes the cost of installation and customer usability. The problem definition provides a detailed insight into the problem being solutioned in the report. The following section details the formulation and implementation of two heuristic methods that determine a possible solution to the problem at hand. The construction heuristic is presented initially, followed by the simulated annealing metaheuristic with descriptions of the pseudocode and algorithms being detailed for both. The last section presents numerical testing for both heuristic methods by using instances to derive solutions. An analysis of the performance of each algorithm is then presented, determining the computational time and performance of each solution.

Problem Definition

With developments in technology and a growing concern for the environment, the need to adapt to alternative energy is more relevant than ever. The main concern surrounding the shift into an electric vehicle dominant market is the lack of infrastructure in Canada to support the users of such devices. Currently, the number of gas stations is more than double that of electric charging stations in the major provinces of Canada. This deficiency in charging stations around Canada proves to be a challenge for longer trips across the provinces and country for those who own electric vehicles. A reason for this lack of support is the exorbitant costs associated with the planning and installation of such stations, deterring companies from investing in the infrastructure. The aim of this project is to model the installation of electric vehicle charging stations throughout key locations in Canada, in an effort to minimize the overall cost of building charging stations within a network. The requirement for our system is to find the optimal location for an EV charging station, and the number of chargers to place at the site. This will essentially be a transportation model/graph with edges and vertices. The value at the edge will be the number of charging stations, and the vertex will be the distance from one station to another. The location of the charging stations should be determined through the capabilities of the standard EV and of an electric charging station. The number of chargers at a station can be determined by the frequency and connections at the node. This means that if a charging station has a lot of connections with it, we will place more chargers there as the assumption is that more connections would mean that more EV users will use that location.

Construction Heuristic

Description

The construction heuristic aims to build a solution based on the shortest paths between each node in the network, the range of the vehicle, the distance between adjacent nodes, and the number of chargers placed at a station. The algorithm will go through each possible route and find the shortest possible routes between the nodes in the network. The function to find the paths using Dijkstra's algorithm is **all_pairs_dijkstra_path**(2022, NetworkX Developers). This function will find all the possible routes within the network and output the shortest paths between all nodes. Each route within the list will be iterated through in order to find the solution for all paths. Within each route, the algorithm will iterate through the arcs(path between two adjacent nodes) and update the remaining charge, total distance traveled, and the number of chargers built. The algorithm will place a charger at a node if the remaining range is less than the arc length/ distance. The resulting number of chargers placed and the list of nodes where chargers are placed will be returned. Finally, the cost function will be based on the number of stations, number of chargers, and the total distance traveled in the route. Please refer to ***Appendix B*** to find the **pseudocode** for the construction heuristic.

Simulated Annealing Metaheuristic

Description

The simulated annealing metaheuristic aims to build on the solution found from the construction heuristic. The algorithm sorts the nodes with stations in an ascending order by the number of chargers they contain. The first node in the list is replaced by a neighboring node which results in a neighboring network. Each route that had a charging station at the replaced node is iterated through to check if the new route is a feasible solution. The algorithm will return a new candidate solution with an updated list of feasible chargers. The cost function will still be based on the number of stations, number of chargers, and the total distance traveled in the route. Please refer to ***Appendix C*** to find the **pseudocode** for the simulated annealing metaheuristic.

Since some charging stations are removed in the metaheuristic and the chargers are moved to different charging stations, the routes taken by the EVs may not be the shortest direct path from the start to the destination. This is accounted for in the objective function by adding the trip cost per km for the total distance all EVs travel across the network.

Numerical Testing

We tested our heuristics on Network 1, 2 and 3 (instances). For Network 1 that has 8 nodes, and arc lengths between 80 km and 200 km, and probability of nodes being connected of 0.25. Network 2 has 10 nodes with the same information as Network 1 with the exception of the different random number used for generating the network. Network 3 has 12 nodes with probability of nodes being connected of 0.2.

Construction Heuristic Results

The results from the implementation of the construction heuristic over three different networks are shown below. The basic feasible solution for network 1 in ***Figure 1,*** provides a model with 3 chargers at intersection 2, 1 charger at intersection 4, 5 chargers at intersection 5, and 1 charger at intersection 0 with an overall cost of $925,331. From predetermined logic and initial inspection, a ratio of 4 charging locations within a network of 8 nodes is evidently sub-optimal. The same conclusion can be made for Network 3 shown in ***Figure 3*** which provides a solution of 7 chargers within a network of 12 nodes and an overall cost of $1,560,825. Both networks derive an excessive amount of chargers compared to the number of possible nodes while having costs far exceeding initial expectations. In comparison, the solution for network 2 in ***Figure 2*** provides a more optimized model with 1 charger at intersection 8, 2 chargers at intersection 1 and 1 charger at intersection 0 and an overall cost of $640,519. From the results of the three networks, network 2 seemingly provides the most cost effective and optimal solution with 3 charging locations within 10 possible nodes.

Simulated Annealing Metaheuristic Results

The initial results of the construction heuristic provided solutions that were evidently excessive in the number of charging stations and associated total cost. Through the formulation and implementation of a simulated annealing metaheuristic, further potential solutions were derived**.** The results of the solution to network 1 seen in ***Figure 4*** presents a model with 2 charging stations within a network of 8 nodes with 7 chargers at intersection 5 and 3 chargers at intersection 2. The overall cost was found to be $500,335. The implementation of the metaheuristic on network 2 provided the solution seen in ***Figure 5*** determines that 7 chargers be placed in intersection 5 and 3 chargers placed in intersection 2 with an overall cost of $440,558. Lastly, the solution for network 3 shown in ***Figure 6,*** provides a network with 7 chargers at intersection 7, 8 chargers in intersection 2, and 1 charger in intersection 4 with a total cost of $823,217.

Comparison Between the Two Heuristic Methods

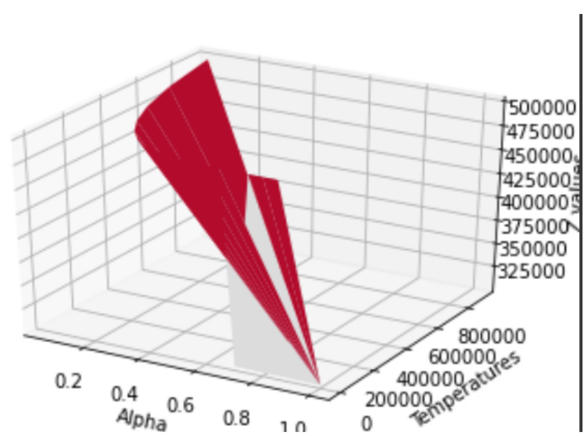
From examination of the results from the construction heuristic and simulated annealing metaheuristic, it is apparent that the simulated metaheuristic provided more efficient and effective results in terms of both cost and number of charging stations required to meet the specified requirements. Comparing the total costs across each network, the simulated annealing metaheuristic provided solutions that were cheaper for each of the 3 networks. The costs for network 1 using the CH was found to be $925,331 while the figure was $500,335 for the SMH, a significant decrease. Similarly, solutions to network 2 showed a decrease in cost with the CH having a cost of $640,519 and the SMH having a cost of $440,558. Solutions to network 3 had an even more significant cost difference with a figure of $1,560,825 for the CH and $823,217 for SMH respectively. Furthermore, the number of charging stations also saw a decrease for all three networks using the SMH solution. The CH provided a solution with 4 stations out of 8 nodes for network 1, 3 stations out of 10 nodes for network 2 and 7 stations out of 12 nodes for network 3. The SMH solutions saw chagrin station numbers of 2 for network 1, 2 for network 2, and only 3 for network 3. From these results we can conclude with confidence that the SMH method provided more optimal solutions for the problem at hand.

Testing Simulated Annealing over Range of alpha and temperature values

Testing is essential for determining the validity and accuracy of a model/heuristic. We decided that we will generate three different random networks (as mentioned earlier). We will then use Alpha and Temperature values to test and find the optimal value. Alpha values will range from 0.05 to 1. Temperature parameters will start from 1 and be divided by 1.5 every iteration. The temperature will then be obtained by multiplying the temperature parameter by the Optimal Cost.

Once feeding in all the temperature and alpha values into our Simulated Annealing Heuristic for Network 1 and we found the following 3-d graph.

Graph 1: 3-d plot for different temperature and alpha values



As seen in the Graph 1 above, x axis is Alpha, Y axis is Temperatures and Z axis is the Cost function values. The optimal location for Network 1 is 10 chargers at node 5 at temperature 2056.050149 and alpha 0.05 at cost $300,338.12. ***Figure 7*** in the **Appendix A** shows the solution for the optimal cost value for Network 1 based on testing over alpha and temperature parameter values.

Analysis of Algorithms

Our Construction heuristic was fairly efficient (running at O(n^2)). As mentioned earlier, figures 1, 2, and 3 in the Appendix illustrate a solution that looks feasible.

Based on the results of the previously stated algorithm, our Simulated Annealing heuristic is seemingly computational (running at O(n^4)). However, we have implemented several breaks in our loops in case they violate any of our conditions. These conditions include candidate solutions being accepted, reaching max iterations, and more. Due to these conditions, we found that the heuristic did not exceed the expected computational time, rather it showed a decrease.

Figure 8 shows the solution for the updated Optimal Solution for Network 1 using Gurobi Solver. The optimal value we found was $512,698. This number is smaller than our Construction Heuristic, $900,331, but larger than our Simulated Annealing, $300,338, (optimal across different Alphas and Temperatures). These values are logical since the Construction Heuristic is supposed to be the basic feasible solution and the Simulated Annealing is an intended improvement. Furthermore, the simulated annealing outperforms the Gurobi Solver because we no longer have predefined shortest path routes but instead the shortest path from the charger to the end node. Last but not the least, the optimal solution was found by testing across different Alpha and Temperature parameters.

References

CBC/Radio Canada. (2022, June 23). How accessible are EV charging stations across Canada? — CBC News. CBCnews. Retrieved October 21, 2022, from https://www.cbc.ca/news/canada/ask-electric-vehicles-faq-1.6451121 Costs Associated With Non-Residential Electric Vehicle Supply Equipment. (n.d.). Retrieved October 21, 2022, from https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf Electric cars, hybrids and beyond. GreenCars. (n.d.). Retrieved October 21, 2022, from https://www.greencars.com/?fbclid=IwAR1Lg6G58a4_p-QKY89BeyIRqL5DVX_FwIdEUmhEKdkmjPbuXeaj_Gh6Ang Energy consumption of full electric vehicles. EV Database. (n.d.). Retrieved October 21, 2022, from https://ev-database.org/cheatsheet/energy-consumption-electric-car Garza, F. (n.d.). Msci 332 Tutorial 2. Tutorial. Range of full electric vehicles. EV Database. (n.d.). Retrieved October 21, 2022, from https://ev-database.org/cheatsheet/range-electric-car Rylan Urban. (2021, December 26). Electricity prices in Canada 2021. energyhub.org. Retrieved October 21, 2022, from https://www.energyhub.org/electricity-prices/

All_pairs_dijkstra_path#. all_pairs_dijkstra_path - NetworkX 2.8.8 documentation. (n.d.). Retrieved December 2, 2022, from https://networkx.org/documentation/stable/reference/algorithms/generated/networkx.algorithms.shortest_paths.weighted.all_pairs_dijkstra_path.html#networkx.algorithms.shortest_paths.weighted.all_pairs_dijkstra_path

Appendix A: Results

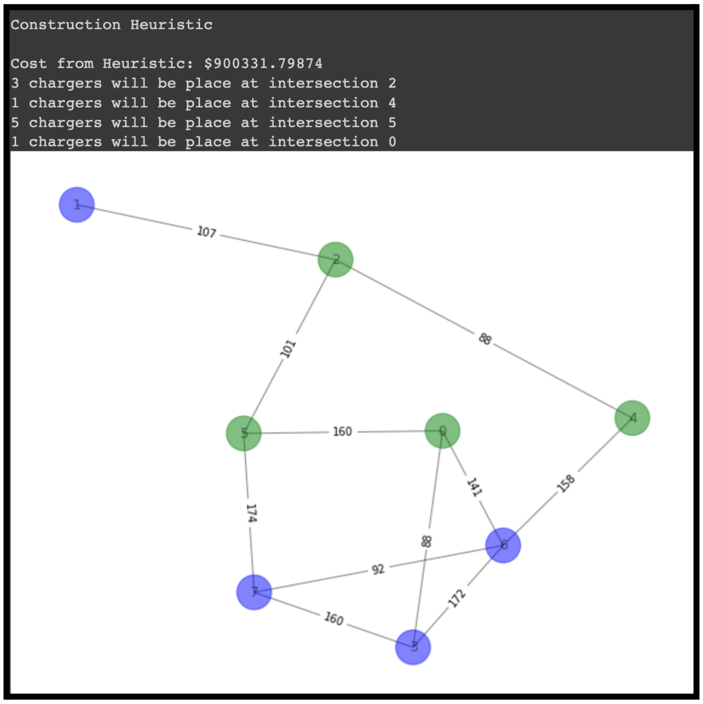


Figure 1: Construction Heuristic Results for Network 1

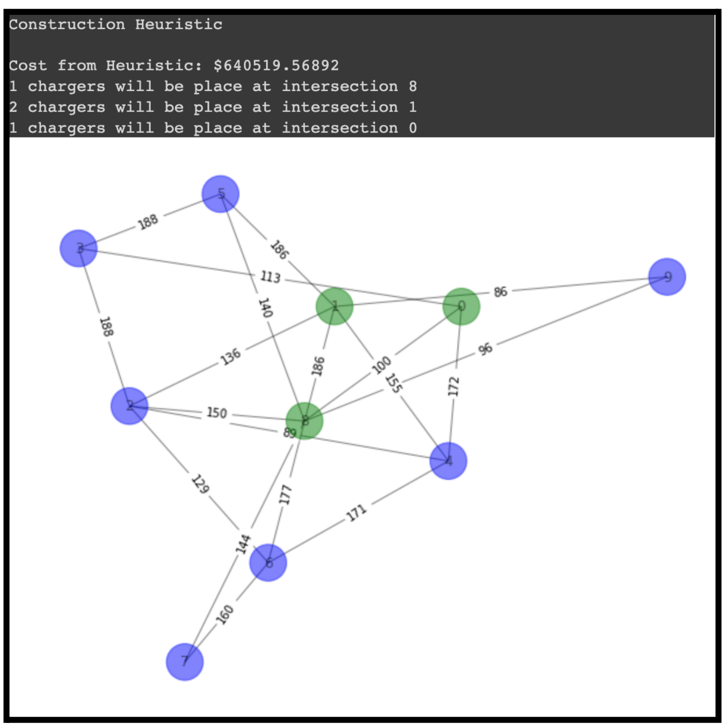


Figure 2: Construction Heuristic Results for Network 2

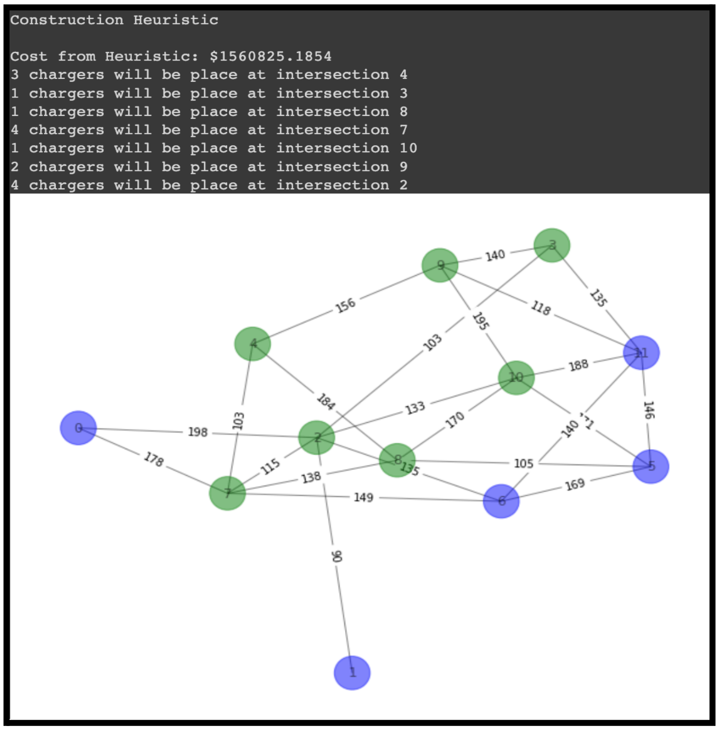


Figure 3: Construction Heuristic Results for Network 1

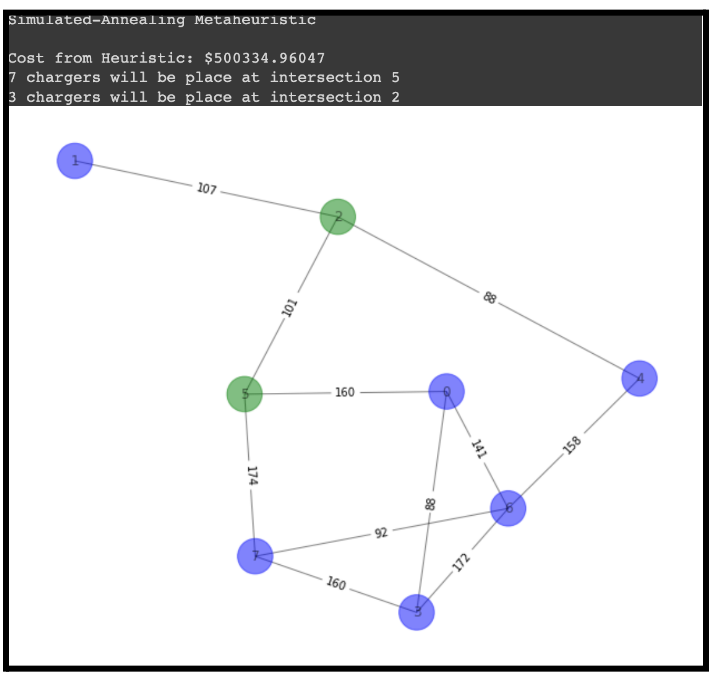


Figure 4: Simulated Annealing Metaheuristic Results for Network 1

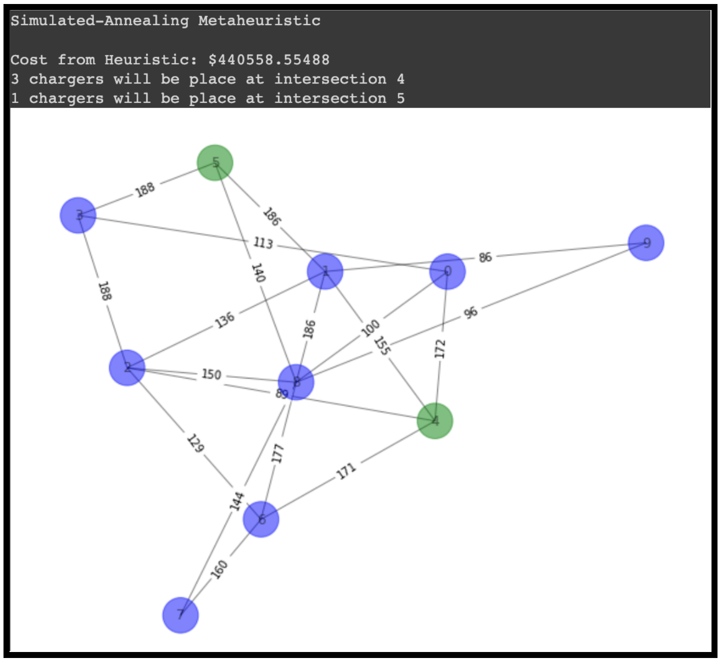


Figure 5: Simulated Annealing Metaheuristic Results for Network 2

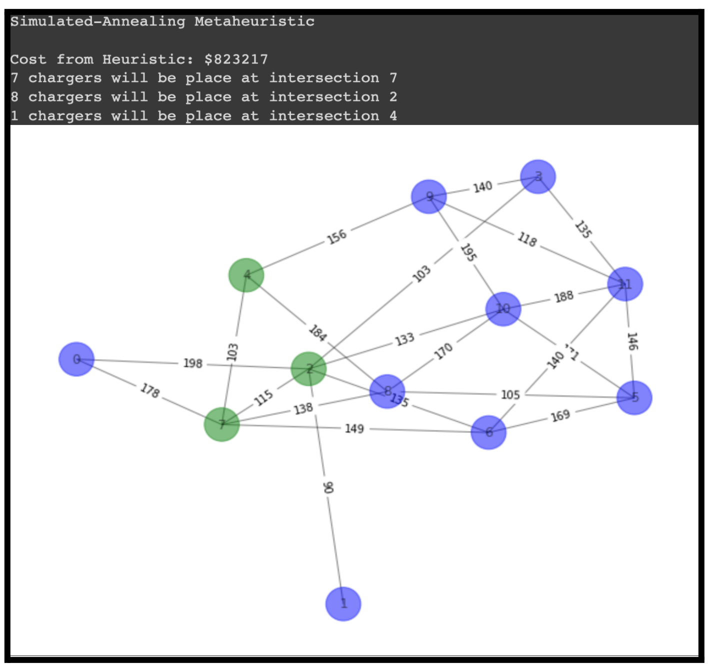


Figure 6: Simulated Annealing Metaheuristic Results for Network 3

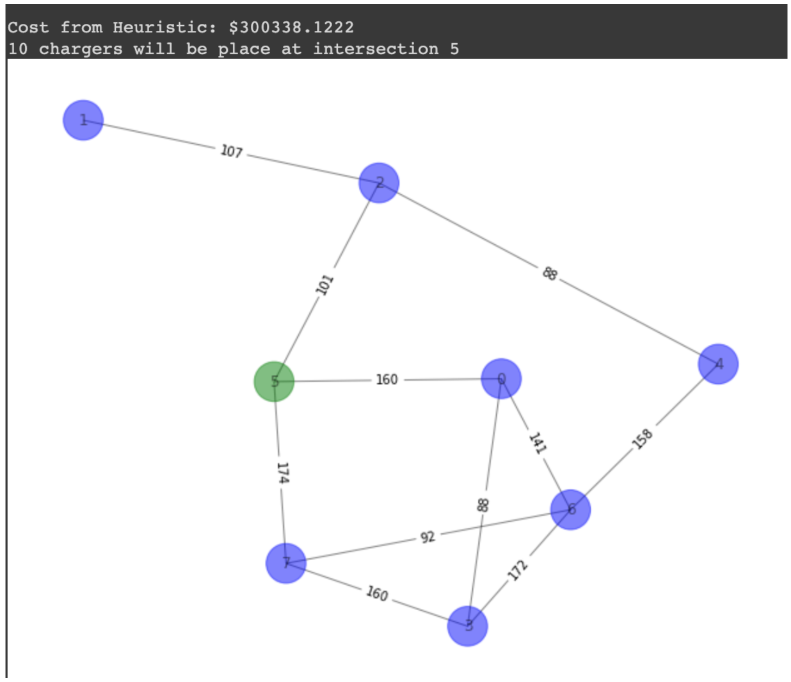


Figure 7: Simulated Annealing Metaheuristic Results for Network 1 with alpha and temperature values that give the optimal Heuristic Cost

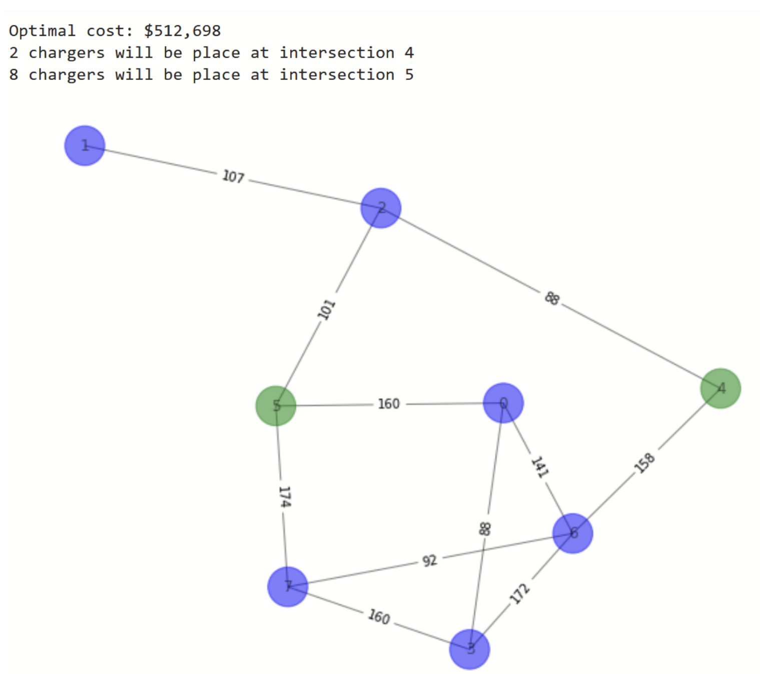


Figure 8: Network 1 solution using Gurobi Solver

Appendix B: Construction Heuristic Pseudocode

Initialize:

List of all shortest paths in the network between all nodes(**from Dijkstra's algorithm**): SP

Shortest path between nodes: $route$

Path between two adjacent nodes: arc

Distance of the path between two adjacent nodes: arc_length

Matrix with the distances between each adjacent node: arc_matrix

Vehicle range is full, Remaining charge: $RC = C = 360$

Total distance of the path: $total\_length$

Number of chargers placed at charging stations: $chargers\_placed$

List of nodes where chargers are placed: $chargers\_list$

Number of charging stations at a node: $stations\_placed$

Number of nodes where a charger was placed: $num\_stations$

Total cost of installing chargers and charging stations: $cost$

Iterate:

For each shortest path, split the path into pairs of nodes SP
    For each $route$ in SP
        Set $RC = 360$

        For each arc in $route$
            Check the arc_matrix to find the arc_length
            Update $RC = RC - arc\_length$
            Update $total\_length = total\_length + arc\_length$

            If $RC < 0$
              If $stations\_placed$ at first node = 0
                  Update $stations\_placed = stations\_placed + 1$
                  Update $num\_stations = num\_stations + 1$
              else
                  If $chargers\_placed$ at first node in arc <= 10
                      Update $chargers\_placed = chargers\_placed + 1$
                      Update $chargers\_list$ to include first node in arc

Set $RC = 360$

Return $chargers\_placed$ and $chargers\_list$

$cost$ = $num\_stations$ * 200,000 + $chargers\_placed$ * 10,000 + $total\_length$ * *0.02613*

Appendix C: Simulated Annealing Metaheuristic Pseudocode

Initialize:

Let Z_c be the current objective cost.

Let Z_n be the cost of the current iteration.

Start by setting the current solution and Z_c to be the solution and objective cost returned by the construction heuristic.

Set the temperature T to be the initial temperature chosen from parameter calibration.

Set A to the alpha value chosen from parameter calibration.

Iterate:

Sort all the nodes with charging stations in ascending order by the number of chargers they contain.

Loop over this sorted list of nodes with chargers (loop 1):

- Find the neighbors of the current node and loop over them (loop 2):
  - Update list of nodes with charging stations in the network by removing the current node and adding the neighbor node.
  - For each node with charging stations in the neighbor network (loop 3):
    - For each route that used to charge at the node from which the charger was removed (loop 4):
      - Find the distance using the Dijkstra's shortest path length from the starting node to the current node with charging stations.
      - Distance the EV can travel = range of EV × number of chargers between the starting node and the current node with charging stations + 1, not including the first and last nodes.
      - Remaining distance = distance the EV can travel - shortest path distance calculated earlier.
      - If remaining distance < 0, then this route is infeasible, skip to the next neighbor in loop 2.
      - Find the distance using the Dijkstra's shortest path length from the current node with charging stations to the destination node.

Distance the EV can travel = remaining range from the previous step + range of EV × number of chargers between the current node with charging stations and the destination node, not including the first and last nodes.

remaining distance = distance the EV can travel - shortest path distance calculated earlier.

If remaining distance < 0, then this route is infeasible, skip to the next neighbor in loop 2.

Return the sum of the shortest path distances from the starting node to the current node with charging stations, and from the current node with charging stations to the destination node.

Select the node with charging stations with the minimum shortest path distances to the start and destination nodes, and add a charger to this node with charging stations.

New candidate solution charging station placement includes an updated list of feasible chargers calculated in the previous step. No charging station can exist with 0 chargers.

Calculate Z_n =

\$200,000 × number of charging stations which are built

+ \$10,000 × total number of chargers placed across the network

+ \$0.02613 × total distance traveled by all EVs in all possible routes

For a minimization problem, we check if $Z_n <= Z_c$:

Accept this new solution, set $Z_c = Z_n$

Else if $Z_n > Z_c$:

P(accept) = $exp\left(\frac{Z_c - Z_n}{T}\right)$

Update T for next iteration = A × T

Repeat for up to 20 iterations, or if the new candidate charger placement is different from the previous current solution.

Appendix D: Additional Calculations

Cost of charging EV to increase range by 1 km:

Average energy consumption - 201Wh/km (2022, EV Database))
Average total cost of electricity in Ontario, based on a monthly consumption of 1,000kWh - 13¢/kWh (2020, Rylan Urban)

$$201\ Wh/km\ =\ 0.201\ kWh/\ km$$
$$13¢/\ kWh\ =\ \$0.13/\ kWh$$

$$0.201\ \frac{kWh}{km}\ \times\ \frac{\$0.13}{kWh} =\ \$0.02613/km$$