MGSC-662-076 - Project Report

Group 3855 - 5

Identifying the Optimal Hub for Efficient Snow Removal in Montreal

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1. Introduction

Montreal, celebrated for its vibrant culture and picturesque landscapes, faces notable challenges in winter, particularly in managing the significant snowfall that blankets the city. Efficient snow removal is crucial to maintain safe and navigable urban spaces. As a reference, in 2021, the city of Montreal spent $179.7 million dollars to address the overall removal and disposal of snow. The purpose of our project is to minimize the operational cost of this endeavor by identifying the optimal location of the hub from where all removal units are going to leave.

The first stage of our model is cost minimization, where we analyze and optimize the routes from snow removal sectors to disposal sites, seeking to reduce expenses associated with transportation and handling. Subsequently, the second stage shifts focus to identifying an optimal hub location. This involves analyzing various configurations to find a strategically placed hub that minimizes operational costs. This comprehensive approach is not just about route optimization but also about reimagining the organization of snow collection sectors for future urban planning.

This particular challenge is integral to urban planning in a city where winter conditions are a defining aspect. Through this optimization project, we aim not only to realize significant cost savings but also to improve the city's functional efficiency during winter. This initiative aligns with Montreal's dedication to sustainable urban development, embodying a proactive response to the challenges of its winter climate.

2. Problem Description and Formulation

In the context of optimizing snow disposal operations in Montreal, our objective is to minimize the overall cost of transporting snow from each of the 106 pick-up (removal) sectors to each of the 26 disposal sites. We strive to minimize this cost by identifying an optimal hub, the point where the trucks that carry the snow return to after dumping the snow. Given the scarce availability of real time data, our model is assuming an unlimited number of trucks and no constraint for truck capacity, for a future phase these constraints could be incorporated.

For our analysis, we leveraged comprehensive data from the Montreal Open Data portal (https://donnees.montreal.ca/), encompassing information on the coordinates of snow removal and disposal sites, the disposal sites' capacities, the volume of snow that needs to be removed from each sector, among others. Our dataset is not only comprehensive but also robust, featuring detailed information about hundreds of coordinates and transactions. Additionally, we obtained data detailing the distances between removal sectors and the disposal sites. These distances were calculated using a MapBox API, factoring in the actual roads within the city, which adds a layer of practicality and precision to our calculations.

The optimization problem is designed to minimize total transportation costs, which are influenced by the distance to disposal sites and the volume of snow to be transported. Key constraints in the model include the capacity of disposal sites, the prioritization of snow pick-up based on sector proximity to the downtown, and the amount of snow expected to be removed in each sector. The model also introduces auxiliary variables and penalty factors to manage priorities among removal sites, adding complexity to the optimization process.

The solution of our model involves finding the optimal routes and the optimal hub that minimizes the overall cost of transportation, which aligns with the city's broader objectives of maintaining operational excellence in public service management, particularly during the challenging winter months.

Objective function

Minimize: $\sum_{ij}((disposal\ cost_{ij} + transportation\ cost_{ij}) \times Y_i \times X_{ij}))$

$$where: i \in removal\ sites,\ j \in disposal\ sites$$

Variables

- X_{ij}: A binary decision variable that equals 1 if snow from removal site *i* is transported to disposal site *j*, and 0 otherwise. $X_{ij} \in \{0, 1\}$
- Y_i: A continuous decision variable that represents the total amount of snow transported from removal site *i*.
- Z_{ik}: A binary variable indicating whether removal site *i* should have a higher priority than removal site *k*. $Z_{ik} \in \{0, 1\}$
- $capacity_j$**:** It is the capacity of snow in m^3 that each disposal site can store.
- $volume_i$**:** It is the amount of snow in m^3 required to be picked up from each removal site.

- $disposal\ cost_{ij}$ **:** It is the elimination cost of disposing snow ($\$/m^3$), being calculated based on the type of the disposal site j [3.1]

- $transportation\ cost_{ij}$: It is the transport cost per cubic meter of snow from street segment i to site j ($\$/m^3$). The cost is equal to the formula:

  $(\alpha\ *\ (total\ distance\ traveled)\ +\ \beta)\ where\ \alpha\ =\ 0.1395,\ and\ \beta\ =\ 0.513$ [3.1]

Constraints

- **Capacity of disposal sites constraints:**

  $\sum_i Y_i\ *\ X_{ij} \leq capacity_j$ where i represents all the removal sites and j represents the disposal sites.

- **Completeness of snow removal constraints:**

  $\sum_j X_{ij}\ =\ 1$ where i represents all the removal sites and j represents the disposal sites.

- **Volume of snow requires to be removed:**

  $\sum_j Y_i\ *\ X_{ij}\ =\ volume_i$ where i represents all the removal sites and j represents the disposal sites

- **Non-negativity constraints:** $Y_i \geq 0$

3. Numerical Implementation and Results

The snow disposal allocation problem has been formulated and solved using Gurobi, a optimization modeling tool in Python. The data for the model was sourced from City of Montreal's website and pre-processed for the purposes of this project. We had the following csv files (information about the columns and the data structure can be found in the appendix):

1. Snowdisposal: dataset about all disposal sites in Montreal.
2. Snowpickup: dataset about all snow removal sectors in Montreal.
3. Transactions_deneigement_saison_2022-2023: dataset about the transportation of snow, that contains information about historical volume of snow for each removal sector.

Stage 1:

Cost -based optimization

In the initial phase of our study, our primary objective was to minimize the overall transportation cost per cubic meter of snow. The cost calculation consisted of two parts - the snow elimination cost and the snow transportation cost.

1. The snow elimination cost was derived by considering each disposal center type, such as sewer chutes (0.29 $\$/m^3$), surface (0.58 $\$/m^3$) or quarry (0.34 $\$/m^3$). This involved a comprehensive analysis, drawing insights from the research paper titled "*The sector design and assignment problem for snow disposal operations"* [3.1], which served as a foundational reference for our cost computations.
2. The snow transportation cost was calculated based on the equation:

$$Cost_{transportation} = (\alpha * Distancee_{ij}) + \beta$$

where $transportation\ cost_{ij}$ is the transport cost per cubic meter of snow from street segment i to site j ($\$/m^3$), α = 0.1395, and β = 0.513. [3.1]

We contemplated the route in the following manner: a central hub serving as the base for all trucks, from which they would travel to designated removal sites to collect snow, dispose of the snow at designated locations, and then return to the central hub.

To determine the precise distances between removal sites and disposal sites, we leveraged the latitude and longitude coordinates provided in the datasets. With the aid of the MapBox API, we obtained the accurate distances, taking into account the city's configuration. This method ensured a granular and accurate assessment of the transportation distances, forming a crucial component of our comprehensive formulation to address the snow transportation optimization problem.

For the purpose of this project, we considered 3 initial scenarios: assigning the central hub to the closest removal site to the Downtown "VMA-109", to the furthest removal site "IBI-301", and to a middle point removal site "LAS-326".

Results

Scenario	Central Hub Location	Total Cost ($)	Variation from 2021 Expenditure (%)	Percentage Difference (from Closer Hub)
Closer Hub	VMA-109 (Ville-Marie)	**57,035,642.81**	-68.3%	-
Furthest Hub	IBI-301 (L'Île-Bizard–Sainte -Geneviève)	**121,770,460.70**	-32.2%	+113.5%
Middle Point Hub	LAS-326 (LaSalle)	**53,226,555.05**	-70.4%	-6.7%

Interpretation

- **Cost Variation:** There is a significant variation in total costs depending on the central hub location. The scenario with the hub located at the furthest removal site (IBI-301) incurs more than double the cost of the closer hub scenario.
- **Most Economical Option:** The middle point hub (LAS-326) emerges as the most cost-effective option, with a total cost approximately 6.7% lower than the closest hub to Downtown (VMA-109). This suggests that a centrally located hub can lead to more efficient routing and lower transportation costs.
- **Impact of Hub Location:** The furthest hub scenario's substantial increase in cost (over 113.5% higher than the closest hub) highlights the critical impact of hub location on operational costs. Longer distances from the central hub to removal and disposal sites significantly increase transportation costs.
- **Strategic Planning Implications:** These results underscore the importance of strategic hub placement in optimizing logistics and minimizing operational costs. The middle point hub, despite not being the closest to the high-priority downtown area, provides the best balance between accessibility and cost-efficiency.

Stage 2:

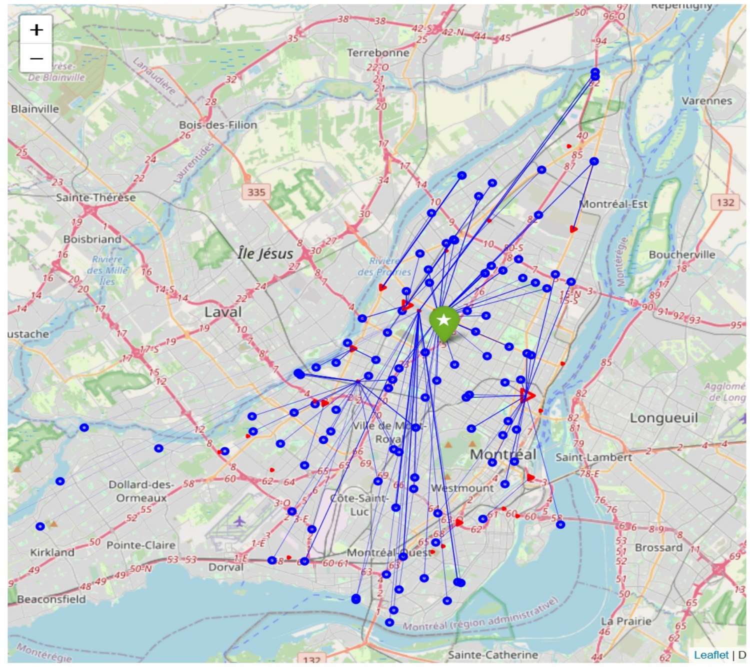
Locating the optimal Hub

In the previous phases, we conducted cost analyses by selecting the optimal hub as the nearest, farthest, and equidistant to Downtown. In this stage, our focus was on determining the optimal hub allocation based on the distance from Downtown to minimize costs. No new constraints were introduced, and the objective function remained unmodified. The addition of a "for" loop enabled us to systematically identify the hub allocation that would result in the least cost.

Results

Optimal Hub

- **Hub ID:** VSP-206
- **Borough:** Villeray–Saint-Michel–Parc Extension
- **Location:** Near mid-point between the farthest and closest sites to Downtown
- **Total Cost of Snow Removal:** $42,049,058.48

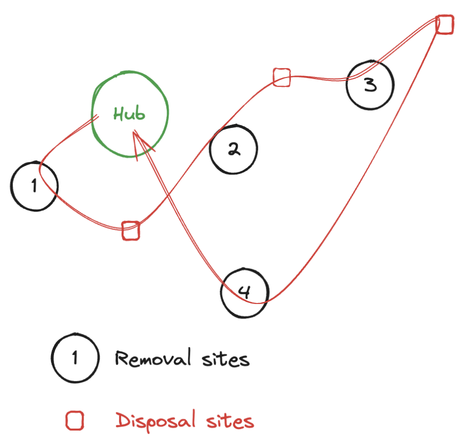


Interpretation

- **Cost Efficiency**: The selection of "VSP-206" as the hub resulted in a total cost of approximately $42.05 million, which is considerably lower than the scenarios where hubs were chosen based on being the closest or farthest from Downtown. With savings of $11,177,496 (20%) compared to Middle Point Hub solution.
- **Impact of Systematic Hub Selection:** Implementing a systematic approach to select the hub based on its distance from Downtown appears to have identified an optimal location that balances the removal site distances effectively, thereby reducing the overall costs.
- **Strategic Location of VSP-206:** The near mid-point location of "VSP-206" suggests that a central hub, equidistant from various sites, can potentially offer the best logistical balance. It reduces travel distances on average and optimizes the snow removal process.

4. Problem Extensions

1. **Prioritizing Pickup Sites:** We considered implementing the prioritizing constraint in our model to make the problem more realistic, by creating a binary variable Z_{ik} whose value is 1 if priority of site i $is\ greater\ than$ j. Nevertheless, this variable did not play a role in our current objective function, due to the assumption that the truck must return to the hub after disposing of the snow, and that the snow must be completely removed from all sites. So optimizing the problem with or without Z_{ik} variable would give the same objective value which is the minimum cost. However, we can further extend the problem by eliminating the constraint that requires the vehicles to return to the hub. For eg:



Example of sequential snow disposal

In the scenario depicted in the previous image, the truck can leave from the central hub to Removal site #1, and after dumping the snow it will continue to Removal site #2 instead of coming back to the central hub, which can be identified by minimizing the distance from Removal site 1 to Disposal site j to Removal site 2.

2. **Considering Budget Constraints:** To further refine our approach, the budget of the city should be taken into account. We can incorporate it as a constraint in our base model, ensuring that the snow removal plan aligns with financial considerations. This addition enhances the model's practicality by incorporating a crucial real-world constraint.
3. **Environmental Impact Assessment (Multi-Objective)**: To further enhance our project, we aim to broaden the optimization criteria by incorporating environmental considerations. This involves evaluating the varying environmental impacts associated with disposing of snow at different types of disposal sites, such as sewer sites.
4. **Exploring the Possibility of Multiple Hubs:** An enhancement to the current problem could involve segmenting the removal sites into 'n' distinct clusters and determining the optimal hub locations and costs for each cluster. By varying n we can also find the optimal value of n. This modification not only adds a layer of realism to the problem but also aligns with the practical understanding that utilizing multiple hubs can be more cost-effective for covering larger areas.
5. **Incorporating Salt-Based Snow Removal:** Expanding our project's scope, we could include ice-melting strategies using agents like Calcium chloride. This addition introduces a new dimension to the problem, as it involves different types of vehicles and strategic locations for salt distribution. Considering factors such as the environmental impact of salt, optimal distribution techniques, and timing for maximum efficiency.

5. Recommendations and Conclusions

As consultants on this project, we would recommend to the authorities in Montreal that significant cost savings can be achieved by optimizing the locations of hubs and routes for snow removal vehicles. We urge them to progress this project to stages where the results can be implemented in the real world, potentially realizing savings of over a million dollars.

From this project, we learned that accurate data is as crucial as optimizing the model, since incorrect data leads to flawed results regardless of the mathematical model's precision. We also realized the importance of a generalizable code and mathematical formulation, allowing for the incorporation of new constraints without needing to redevelop the problem entirely. Additionally, when optimal solutions are elusive, considering heuristics can yield good, if not perfect, results.

If undertaken again, we would suggest running initial models on smaller datasets to save time. Instead of addressing all 106 sites, optimizing a smaller cluster of 8-9 sites at a detailed level, considering factors like priority, truck, and budget constraints, would be more effective.

A major bottleneck was the compute time, particularly in calculating a 132 x 132 matrix of distances, which took 1.5 hours. The overall model required 2.5 hours each run. Another challenge was integrating real-world scenarios, such as prioritization, into the model. Also, the complexity of integrating various constraints, such as vehicle capacity and vehicle count into the model presented significant challenges.

6. References

1. Montreal Open Data portal (https://donnees.montreal.ca/)
    1.1. Contracts and transactions of snow removal: https://donnees.montreal.ca/dataset/contrats-transaction-deneigement
    1.2. Snow Removal Areas: https://donnees.montreal.ca/dataset/secteur-deneigement
    1.3. Disposal Sites: https://donnees.montreal.ca/dataset/depot-neige
2. Mapbox API: https://www.mapbox.com/matrix-api
3. Research Papers
    3.1. The sector design and assignment problem for snow disposal operations
    3.2. Snow plow route optimization: A constraint programming approach

7. Appendix

I. Overall Cost of Transportation for several hubs out of 106 potential hubs considered in the problem:

Hub Name	Total Cost ($)	Remarks
VSP-206	42,049,058.48	Most Optimal
VMA-109	57,035,642.81	Closest to Downtown
IBI-301	121,770,460.70	Farthest from Downtown
LAS-326	53,226,555.05	At Median from Downtown

II. Sample output : optimal routing between 106 removal sites and 26 disposal sites

```
Snow Transported for Each Route:
Removal site VMA-109 -> Disposal site Iberville (PMR): 93274.51 m³
Removal site VMA-307 -> Disposal site Iberville (PMR): 82691.13 m³
Removal site VMA-306 -> Disposal site Iberville (PMR): 96229.11 m³
Removal site VMA-111 -> Disposal site Iberville (PMR): 85847.51 m³
Removal site VMA-110 -> Disposal site Iberville (PMR): 127483.61 m³
Removal site PMR-101 -> Disposal site Iberville (PMR): 158592.4 m³
Removal site PMR-102 -> Disposal site Iberville (PMR): 144354.73 m³
Removal site S-O-104 -> Disposal site Iberville (PMR): 136883.4 m³
Removal site PMR-204 -> Disposal site Iberville (PMR): 80600.83 m³
Removal site MHM-109 -> Disposal site Iberville (PMR): 126720.19 m³
Removal site PMR-203 -> Disposal site Iberville (PMR): 97228.93 m³
Removal site RPP-201 -> Disposal site St-Michel - Robert (VSP): 116858.26 m³
Removal site MHM-209 -> Disposal site Iberville (PMR): 124186.67 m³
Removal site MHM-210 -> Disposal site Iberville (PMR): 156288.64 m³
Removal site RPP-204 -> Disposal site St-Michel - Robert (VSP): 123910.35 m³
Removal site RPP-101 -> Disposal site St-Michel - Robert (VSP): 100797.42 m³
Removal site RPP-102 -> Disposal site St-Michel - Robert (VSP): 95611.77 m³
Removal site OUT-101 -> Disposal site SauvÃ© (AHU): 170139.37 m³
Removal site RPP-104 -> Disposal site St-Michel - Robert (VSP): 152513.24 m³
Removal site VER-310B -> Disposal site Iberville (PMR): 91295.89 m³
Removal site VSP-107 -> Disposal site St-Michel - Robert (VSP): 125642.5 m³
Removal site CDN-111 -> Disposal site Iberville (PMR): 70225.35 m³
Removal site VSP-206 -> Disposal site St-Michel - Robert (VSP): 107770.34 m³
Removal site S-O-201B -> Disposal site Riverside (VMA): 107975.69 m³
Removal site RPP-205 -> Disposal site St-Michel - Robert (VSP): 133863.99 m³
Removal site AHU-107 -> Disposal site Millen (AHU): 165025.8 m³
Removal site RPP-103 -> Disposal site St-Michel - Robert (VSP): 113049.76 m³
```

III. Front End Interactive Interface

Snow Removal Optimization

Select a Hub

VSP-206

Total Cost for VSP-206: $42.05 M

Utilization of Disposal Sites:

	NomDepot	Capacity (M m^3)	Total Snow Disposed (m^3)	Utilization (%)
0	Iberville (PMR)	Unlimited	1,957,978.36	-
1	Jules-Poitras 2 (SLA)	Unlimited	81,596.87	-
2	Lafarge (sud) (MHM)	1.1	182,385.61	16.58
3	Lausanne (MTN)	Unlimited	506,842.21	-
4	Millen (AHU)	Unlimited	561,342.25	-
5	Riverside (VMA)	Unlimited	107,975.69	-
6	Saint-Pierre (LAC)	Unlimited	94,217.6	-
7	St-Michel - Charland (VSP	1.26	1,144,274.01	90.82
8	St-Michel - Robert (VSP)	3.78	3,779,977.67	100.0

IV. Interface for checking real time distance and timing between two sites:

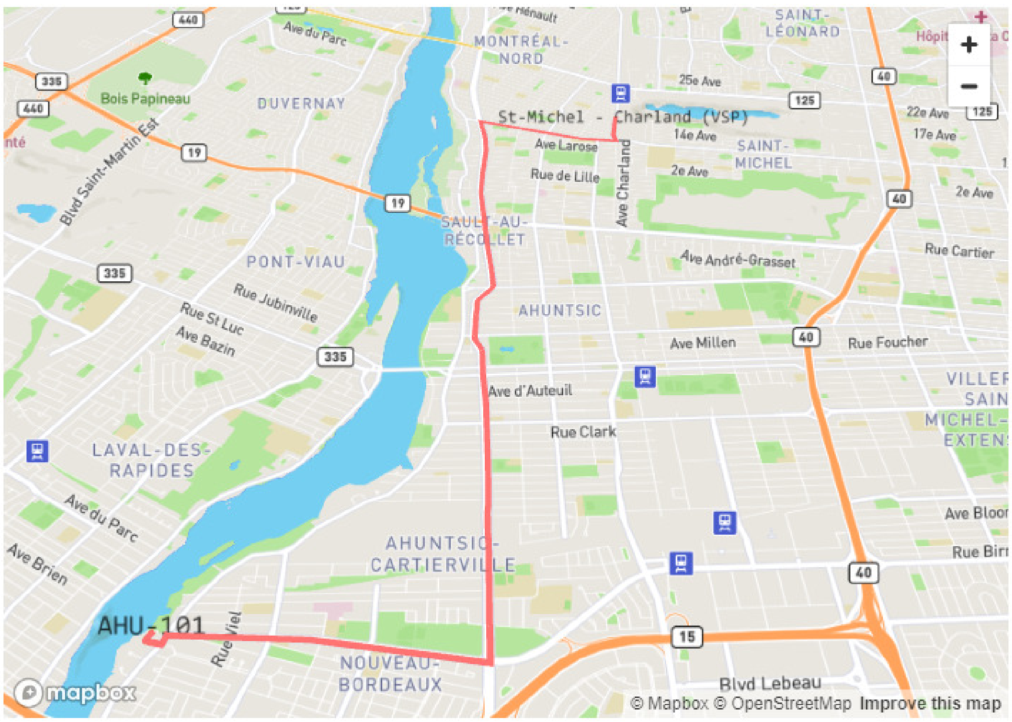
Sector-Deposit Site Routing with Names

Select a Route

AHU-101 to St-Michel - Charland (VSP)

Selected Route Distance: 10.20 km

Estimated Travel Time: 20.77 minutes



V. Code for calculating distance using Mapbox API:

```python
import requests
from itertools import product
import pandas as pd

def fetch_route_from_mapbox(start_coords, end_coords, mapbox_token):
    url = f"https://api.mapbox.com/directions/v5/mapbox/driving-traffic/{start_coords};{end_coords}"
    params = {
        "access_token": mapbox_token,
        "geometries": "geojson",
        "overview": "full",
        "annotations": "duration,distance,congestion"
    }
    response = requests.get(url, params=params)
    return response.json()

def main(start_coords, end_coords, mapbox_token):
    # Fetch the route
    route_response = fetch_route_from_mapbox(start_coords, end_coords, mapbox_token)

    if 'routes' in route_response and route_response['routes']:
        best_route = min(route_response["routes"], key=lambda r: r['duration'])
        distance = best_route["distance"] / 1000  # Convert to kilometers
        duration = best_route["duration"] / 60    # Convert to minutes

        return distance  # Optionally return the best route
    else:
        print("Failed to fetch the route. Please check your coordinates and Mapbox token.")
        return None
```

```python
if __name__ == "__main__":
    mapbox_token = "pk.eyJ1Ijoia3Jpc2hhbmd1cHRhMzMiLCJhIjoiY2xwOHNuZmIwMHluZzJqcXA2Y253ajhwNyJ9.AgLEDuvcdU7ocKc8tLumPQ"


    #read Removal Sectors i sheet from DataFrames.xlsx
    df_removal_sites = pd.read_excel('DataFrames.xlsx', sheet_name='Removal Sectors i')
    #read Disposal Sites j sheet from DataFrames.xlsx
    df_disposal_sites = pd.read_excel('DataFrames.xlsx', sheet_name='Disposal Sites j')

    removal_sites_longitudes=df_removal_sites['Longitude'].tolist()
    removal_sites_latitudes=df_removal_sites['Latitude'].tolist()

    disposal_sites_longitudes=df_disposal_sites['Longitude'].tolist()
    disposal_sites_latitudes=df_disposal_sites['Latitude'].tolist()

    final_df = pd.DataFrame(columns=['Removal Site', 'Disposal Site', 'Distance'])

    for i in range(len(removal_sites_longitudes)):
        for j in range(len(disposal_sites_longitudes)):
            start_location = f"{removal_sites_longitudes[i]},{removal_sites_latitudes[i]}"
            start_name=df_removal_sites['NomSecteur'][i]

            end_location = f"{disposal_sites_longitudes[j]},{disposal_sites_latitudes[j]}"
            end_name=df_disposal_sites['NomDepot'][j]

            distance=main(start_location, end_location, mapbox_token)
            print(f"Distance between {start_name} and {end_name} is {distance} km")
            new_row = {'Removal Site': start_name, 'Disposal Site': end_name, 'Distance': distance}
            new_row_df = pd.DataFrame([new_row])
            final_df = pd.concat([final_df, new_row_df], ignore_index=True)

    print(final_df)
    final_df.to_excel('Distance_output.xlsx',index=False)
```