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Identifying The Optimal Facility Location For Transporting And Distributing Vaccines

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Abstract

Efficient vaccine delivery is critical to ensuring accessibility while minimizing transportation costs. Identifying optimal regions for vaccine delivery within an existing geographical area is essential for reducing logistical expenses. Our system offers a user-friendly solution to identify single or multiple optimal facilities for vaccine delivery with minimal transportation costs through a website. The platform leverages the coordinates and vaccine demand at each supply point, provided by the user, to calculate the distance between locations. Using the Haversine formula, the tool computes distances accurately based on geographical coordinates. This calculation enables precise analysis of transportation costs and helps pinpoint cost-effective delivery facilities. Users can access the website to input data, such as coordinates and demand at various supply points, and obtain optimal solutions effortlessly. The platform supports decision-making for efficient vaccine distribution by minimizing transportation costs and optimizing facility locations. This tool is particularly useful for organizations involved in vaccine logistics, allowing them to streamline operations and focus resources effectively. By automating complex calculations, it eliminates manual efforts and provides actionable insights swiftly. With its ease of use and accuracy, the platform enhances supply chain efficiency, supporting equitable and timely vaccine distribution. This innovative solution bridges the gap between logistical challenges and efficient vaccine delivery, ensuring cost-effective, data-driven decision-making for public health initiatives.

Keywords
Facility Location, Transportation cost, P-Median Method, Haversine Method.

1. Introduction
Vaccination has been proven to be the most effective method to prevent various kinds of diseases. In Bangladesh, the EPI project formally launched on 7th April 1979, but the vaccination centers were few and located in urban healthcare

facilities. Especially in a remote area, there are no community clinics or kind of institutions, and for this reason, the immunization campaign's target is not fulfilled. The main objective of immunization is to provide vaccines for an actual number of people willing to get a vaccination. With the help of international organizations and new technological developments, many vaccines can now be obtained at low cost and in efficient quantities. However, shipping, storing, and delivering vaccines in a cost-efficient fashion while ensuring that vaccines are reliably available to end-users remains a major challenge. There are some barriers including population distribution, road network data, public transit data, and distribution of businesses, households, health centers, and other public facilities. These variables are assessed using mathematical location modeling techniques and geographic information systems (GIS) to choose the optimal solution while maximizing public access. Centralized immunization campaigns reduce patient travel distances, ensuring efficient vaccine distribution to the intended population group (Leithäuser1 2021).

A mathematical model optimizes COVID-19 vaccination coverage in Indonesia, minimizing travel distances and addressing locational analysis gaps (Rifai 2022). Location assignment problems for medical services can be efficiently solved using algorithms like Branch and Bound or heuristics for scalability (Akıra and C 2022). Healthcare location planning is vital amid population growth and challenges (Abdelkarim 2019). Location-allocation models optimize facility placement, addressing objectives like minimizing distances, maximizing coverage, or reducing maximum user-facility distance (Luo 2017). This study seeks to determine the facility location problem of vaccination with the help of the p-median method. We have built a website using the p-median method to find out the optimal facility locations and supply points. The distance from the facility location to the supply points will be minimized. This website can be used for delivering any type of vaccine in any region.

1.1 Objectives

The objectives are to find single and multiple health facility locations for the distribution of vaccines at different supply points and to minimize transportation costs.

2. Literature Review

Davari (2011) presented a fuzzy maximum coverage location problem (FMCLP), where the distance between any two nodes is seen as a fuzzy variable. Ushakov (2018) improved the known decomposition approach where a smaller p-median problem (PMP)s, related to the network components, can be solved instead of the initial large problem. The proposed method is structured in three stages and it combines Lagrangian relaxation-based techniques, variable fixing and reduction tests, and a dynamic programming algorithm. It drastically reduces the number and the dimensions of the p-median subproblems to be solved to optimality by a MILP solver and to be combined to determine the optimal solution of the original PMP by a multiple choice knapsack problem. Future research directions should focus on applying and adapting the suggested technique to various industrial applications and real-world issues where ODMP can be useful, particularly when it comes to solving choice problems where the trade-off between variety and redundancy emerges. Abdelkarim (2019) has integrated accessibility and location-allocation models into GIS to improve spatial planning and environmental sustainability of health services.

This integration provides a planning framework to check the efficiency of the spatial allocation of health services and to generate alternatives either by proposing an active service or improving an existing one. Setyorini (2019) addresses a multi-objective optimization facility location problem. Sari1(2020) developed the decision support system, Simple Additive Weighting (SAW), which was built and then combined with Google Maps API. The Haversine formula was used to get the radius, travel distance, and time value. The system was compared to another decision support system algorithm, TOPSIS, to understand the suitable method of this system. Tang (2020) solves the problem of logistics node location, using the P-median theory model, using a greedy take-away heuristic algorithm, the Jinan A fruit and vegetable company provides a precise algorithm on the location of the logistics node in Jinan. J. W. and Fan (2020) developed a three-index flow-based mixed integer formulation to solve a two-echelon location routing problem with simultaneous pickup and delivery. They solve such an NPhard problem by developing a multi-start hybrid heuristic with path relinking (MHH-PR). Alenezy (2020) addresses each demand point that can be supplied by more than one open facility. First, investigate a Lagrangian relaxation approach. Then, illustrate in the problem decomposition how to introduce tighter constraints, which solve the CFLP faster. M. A. and Zaferanieh (2021) investigated the bi-level programming model proposed by AZM, considering the incapacitated p-median facility location problem.

The lower level used the minimum information technique to determine the most likely allocation solution. Sbastian1 (2021) employed in this study is a feasibility analysis using the computation of Net Present Value, Payback Period, and IRR, as well as selecting the ideal location using the P-Median method and the Mixed Integer Linear Programming approach used concurrently. Qin (2021) designs an intelligent vaccine storage and transportation system based on Raspberry Pi. ROY (2021) presents a time-varying linear optimization-based approach, which incorporates epidemiological factors, such as population density, susceptible count, and infected ratio as well as transportation costs, to disseminate vaccines among zones. Rifai (2022) developed a mathematical model based on the maximal coverage location issue introduced and shown (MCLP). They try to optimize the coverage of the COVID-19 vaccine distribution. Sudari1 (2022) provides insights on maximizing vaccine distribution and raising community awareness about COVID-19 vaccination in rural regions with difficulty in transportation access, a lack of healthcare workers, and limited vaccine storage facilities. Fofou (2022) developed a strategy for determining location decisions for remanufacturing plants. The main objective is to obtain the capacity, number, and geographical locations for newly established remanufacturing facilities using a Capacitated Facility Location Problem (CFLP) approach. Redi (2022) investigated a multi-period maximal covering location problem with the design of various 9 types of facilities (MCLP). The proposed model can have applications such as locating disaster relief facilities, hospitals, and chain supermarkets.

3. Methods

In the case of vaccine delivery, efficient and low transportation cost delivery is very important. It is necessary to find out which region within the existing region will deliver the lowest cost. P- Median is one of the most efficient methods of locating facilities by which we can minimize the transport cost. The facility can be single or multiple. In this website, the user experience is improved and the user doesn't need any programming knowledge. A user needs to know the coordinates of the supply points and the number of unvaccinated populations.

Mathematical Notation

There are two methods that are used in making this website. They are P-median and Haversine.

The "p-median" problem is a distance-based optimization problem in which p facilities must be located and assigned to demand points such that each demand point is mapped to a single facility and the sum of all demand points and corresponding facilities is minimized (Akıra and C 2022).

Indices:

I=set of demand; J=set of facility

Where:

P = count of facilities to be located
hi = demand at node i ϵ i, divided by truck capacity.
dij = distance density of storage facilities
cij = cost per trip
Decision variable based from model:
Xj = 1, if facility was assigned as supplier; 0 if otherwise
Yij = 1, condition if selected receiver was covered by the assigned supplier; 0, otherwise

Objective function:

$$\text{Minimize} \sum i \sum j \, h_i \, d_{ij} \, c_{ij} \, X_j \, Y_{ij}$$

Constraints:

Equation 2: $\sum j \; Y_{ij} = 1 \; \forall i \epsilon i$
Equation 3: $Y_{ij} - X_j \leq 0 \; \forall i \epsilon i \; , \; \forall j \epsilon j$
Equation 4: $\sum j \; X_j = P$
Equation 5: $X_j \in \{0, 1\} \; \forall i \epsilon i$
Equation 6: $Y_{ij} \in \{0, 1\} \; \forall i \epsilon i$

The Haversine formula is primarily used to calculate geographical distances on Earth. This formula helps determine the great-circle distance between two points on a sphere based on their latitude and longitude. By inputting the coordinates of two locations, the distance between them can be calculated. The formula assumes the Earth is a perfect sphere, ignoring its slight elliptical shape. It is a specific application of spherical trigonometry's haversine law, which connects the sides and angles of spherical triangles. The Haversine formula is sufficiently accurate for identifying the nearest location based on given coordinates. Leithäuser1 (2021) uses the form of the formula of Haversine.

$$\Delta lat = lat1 - lat2$$

$\Delta long = long1 - long2$
$\alpha = sin2\ (\Delta lat\ 2) + cos(lat1\ ) \cdot cos(lat2\ ) \cdot sin2\ (\ \Delta lat\ 2\ )$
$c = 2a \cdot sin2\ (\sqrt{a}, \sqrt{1-a})$
$d = R \cdot c$

Where:

R = radius of the earth 6371(km)
Δlat = magnitude of the change in latitude
$\Delta long$ = magnitude of the change in longitude
c = calculation of the intersection of the axes
d = is the distance (km)

Making Website

The website is designed so that the user can easily locate the facility and demand points. There are three languages used for making this website. They are HTML, CSS, and JavaScript.

Steps of making the website

The processes that are involved in making the website are given step-by-step.
Step 1: Making a Homepage

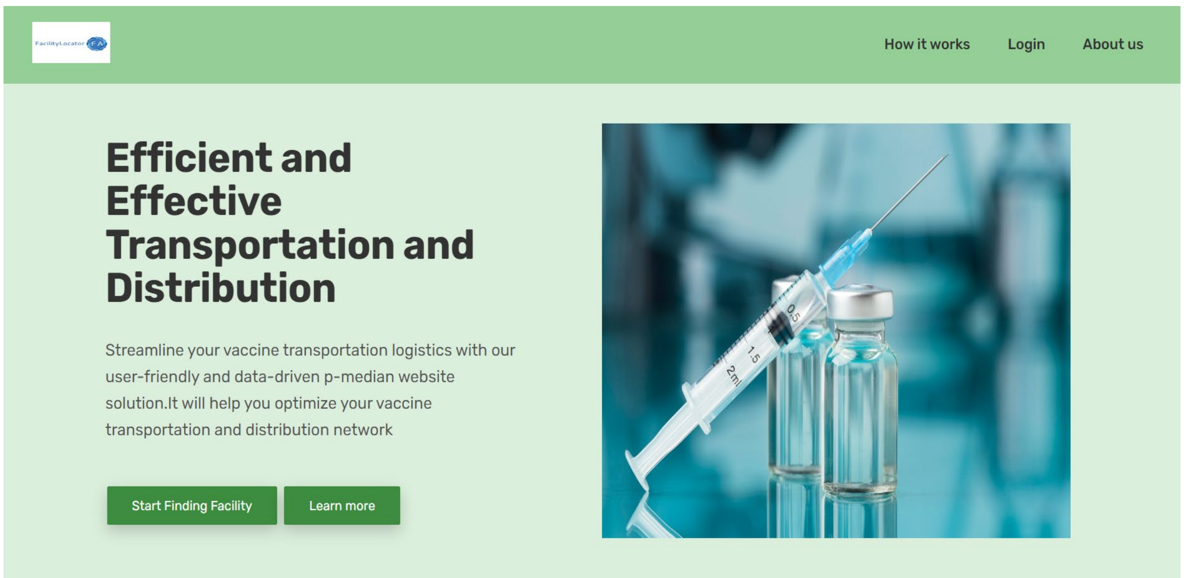

Figure 1. Homepage of the Webpage

Figure 1 shows the home page of our website. This is also called the start page of a website. This page will appear first when entering the website. We have added an icon in the left top corner of the header of the website. On the left side of the body of the homepage, we have given an overview of our website and added a picture on the right side. We tried to use proper font size, color, and layout to improve the user interface. This will attract the user's attention.

Step 2: Making Input Box

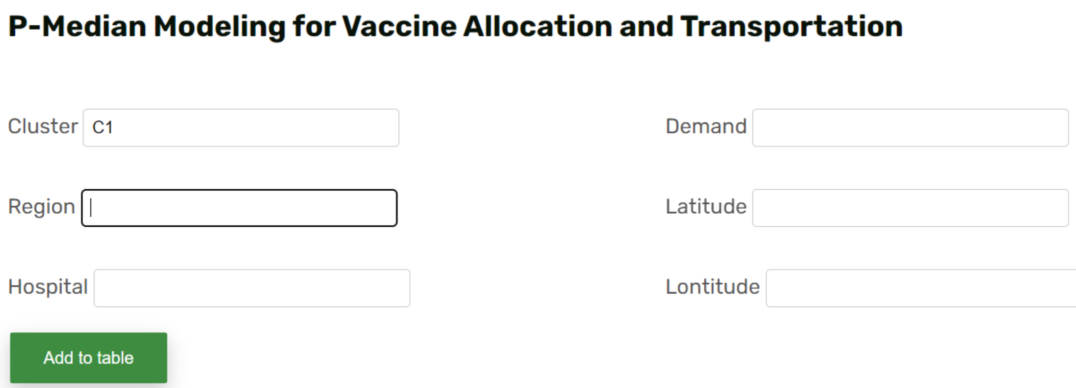

Figure 2. Input Box

Fig 2 shows the input box that will be used for taking the required value from the user. We have added 6 input boxes. They are Cluster, region, Hospital Name, Latitude, longitude, and demand. There is a button named 'Add to Table'. Among them latitude, longitude, and demand box will only accept numerical value, no text will not be allowed. When the button is pressed with the data in the six input boxes of the first supply point, a new table will appear and the data will be added to that table. That will be the first row of the table. A pop-up box will appear if the provided data of the input boxes are not correct and a new table will not be created. After the data is added to the table, the data in the input box will be deleted automatically. In this way, the user has to add the data of each supply point to the table.

Step 3: Add Distance matrix button
Adding a minimum of three supply points will automatically add a button named See Distance matrix below the table.

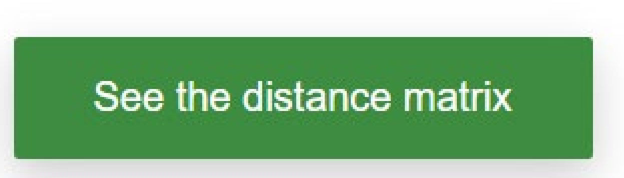

Figure 3. Distance matrix button

Figure 3 shows the distance matrix button. Clicking the button will show the distance between regions in another table.

Cluster	Region	Hospital	Latitude	Longitude	Unvaccined Population
C1	Ward-22	Munshipara	22.81	89.57	399
C2	Ward-28	Japan Bangladesh Society	22.8	89.56	658
C3	Ward-30	Nogor Sastho Kendro	22.83	89.53	509
C4	Ward-29	Nargis Memorial Hospital	22.82	89.58	480
C5	Ward	Tohmina kinder Garden	22.78	89.59	913

Figure 4. Information of given Supply points

Step 4: Distance measurement by Haversine formula

A function has been created using the Haversine formula. When the user presses the See the distance matrix button, the function will be called immediately and the latitude and longitude of the supply points will be passed through the function. To add these measured distances to the table, another function is used. After that, another section will be opened automatically after the distance matrix table.If such a user works with 5 supply points, the table will show the distance from supply point 1 to supply point 1,2,3,4,5. Supply points 2, 3, 4, and 5 will show the distance accordingly. Here is a sample of a distance matrix.

	C1	C2	C3	C4	C5
C1	0	1.51	4.66	1.51	3.92
C2	1.51	0	4.54	3.02	3.8
C3	4.66	4.54	0	5.24	8.29
C4	1.51	3.02	5.24	0	4.56
C5	3.92	3.8	8.29	4.56	0

Figure 5. Distance between all cluster

Step 5: Additional Information box created
In this section, there are 3 more input boxes. They are capable of a Capacity per delivery, unit cost, and Number of facilities to be located. Among them, a number of facilities indicate the facility locations that will be used for supplying the vaccine, and the remaining points will be used as a supply point.

Figure 6. Input box of Additional Information

Fig 6 shows the input box of additional Information. There are 3 options. If a user selects 1, the facility will be 1 and the remaining points will be supply points. If a user selects 3, the facility location will be 3 and the remaining points will be supply points. Unit cost input indicates the transportation cost from the facility location to all supply points. This is the drawback of this method. A very small error will occur. Truck capacity indicates the number of vaccines that can be delivered per trip to the supply point. There is a submit button below this section. On clicking the button another table will be added containing the number of trips in each cluster.

Delivery Trip

Cluster	Region	Hospital	Unvaccined Population	Number of Delivery Trips
C1	Ward-22	Munshipara	399	4
C2	Ward-28	Japan Bangladesh Society	658	7
C3	Ward-30	Nogor Sastho Kendro	509	6
C4	Ward-29	Nargis Memorial Hospital	480	5
C5	Ward-31	Tohmina Kilder Garden	913	10

Show the output

Figure 7. Number of Delivery trips to each cluster

Step 6: Creation of output button
There is a button below this table named Show the output. On clicking the show output button user will get the output immediately. In the output table, there are two columns. one is the Facility location and the other is the supply point. If the number of the facility is located in one, the facility location will be one and the remaining point will be the supply point. In the case of two facility locations, two rows will be created. The first row will show the supply points located at the first facility and less distance from it and the second row will show the supply points located at the second facility and less distance from it.

Faciliy and allocated supply point

Facility	Supply Point
C1	C1,C2,C3,C4,C5

Figure 8. Output of the system

4. Data Collection

We have collected data from BAVS CLINIC, KHULNA BRANCH for vaccine demand and location points. We took five healthcare locations and each location's coordinates from google Maps. This data is our main input for our website. This data is used for calculating the distance matrix for each demand point and the number of delivery trips.

Table 1. Information of the vaccine center

Cluster	Region	Center	Latitude	Longitude	Unvaccinated Population
C1	Ward-22	Munshipara	22.81	89.57	399
C2	Ward-28	Japan Bangladesh Society	22.8	89.56	658
C3	Ward-30	Nogor Sastho Kendro	22.83	89.53	509
C4	Ward-29	Nargis Memorial Hospital	22.82	89.58	480
C5	Ward-31	Tohmina Kilder Garden	22.78	89.59	913

Table 1 shows the information of the vaccine centers. Every ward has been considered as a cluster. This data is collected for EPI (Expanded Programme on Immunization) vaccine.

Data Analysis

Distance Matrix: The haversine formula uses coordinates for calculating distance. This formula is used for calculating the distance from each location to another location. This formula measures distance most accurately.

Table 2. Distance matrix

Cluster	C1	C2	C3	C4	C5
C1	0	1.51	4.66	1.51	3.92
C2	1.51	0	4.54	3.02	3.8
C3	4.66	4.54	0	5.24	8.29
C4	1.51	3.02	5.24	0	4.56
C5	3.92	3.8	8.29	4.56	0

This table 2 shows the distance matrix. From this table, we can measure the distance of each location to another. We have got this value from the website. A functionality is used for calculating the distance automatically.

Delivery Trip

The user gives the capacity number of vaccines per delivery. The number of delivery trips is computed by dividing the demand by the capacity number of vaccines per delivery.

Table 3**.** Delivery Trip

Cluster	Region	Hospital	Unvaccinated Population	Number of Delivery Trips
C1	Ward-22	Munshipara	399	4
C2	Ward-28	Japan Bangladesh Society	658	7
C3	Ward-30	Nogor Sastho Kendro	509	6
C4	Ward-29	Nargis Memorial Hospital	480	5
C5	Ward-31	Tohmina Kilder Garden	913	10

Table 3 shows the delivery trip that required for each ward.

5. Results and Discussion

Facilities are selected to supply vaccines to another demand point by using the p-median method. This method is used for single facilities to multiple supply points and also used for multi facilities for multiple supply points. By using the website, we have found that C1 is the optimal facility location for transporting the vaccine to single facility. When the number of facilities is two, C2 and C1 are the optimal facility locations for transporting the vaccine. C2, C1 and C4 are the optimal facility locations for transporting the vaccine when the number of facilities is three.

5.1 Numerical Results

Faciliy and allocated supply point

Facility	Supply Point
C2	C1,C2,C3,C4,C5

Figure 9. Number of Facility Locations one

Figure 9 shows that C1 is the optimal facility location for transporting the vaccine. Cluster C1 will meet up its demand and also supply the vaccine to the remaining demand points. We have got this output from our website.

Facility	Supply Point
C2	C2,C3,C5
C1	C1,C4

Figure 10. Number of Facility Locations two

Figure 10 shows that C2 and C1 are the optimal facility locations for transporting the vaccine. Cluster C2 will meet up its demand and also supply the vaccine to Cluster C3 and C5. Cluster C1 will meet up its demand and also supply the vaccine to Cluster C4.

Facility	Supply Point
C2	C2,C3,C5
C1	C1
C4	C4

Figure 11. Number of Facility Locations three

Fig 11 shows that C2, C1, and C4 are the optimal facility locations for transporting the vaccine. Cluster C2 will meet up its demand and also supply the vaccine to Cluster C3 and C5. The distance from Cluster C2 to Cluster C3 and Cluster C5 is minimum. So, transportation costs will be low.
Cluster C1 will only meet up its demand and Cluster C4 will only meet up its demand

6. Conclusion

We have built a personal website to find the optimal facility. A user will be able to find out single and multiple facilities to deliver the vaccine with minimum transportation costs. To check the validity of our website, we have selected five locations corresponding their unvaccinated population. From the google map, we have taken the coordinates of the five locations. The distance between each point is measured by the Haversine method. This method can result in an error of up to 0.5%. The optimal facility location can be single or multiple points which are measured using p-median method. This method is one of the most efficient methods of locating facilities by which we can minimize the transport cost. By using the website, an Optimal facility location can be found for any vaccine transportation. We have found the location for vaccine transportation. We have considered the vaccine reservation capability of each point to be vast. But This reservation capability can be limited. The future work of the study could be extended by taking the consideration of reservation capability.

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