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Location of Vaccination Centers in the State of Puebla, Mexico by using the Gravity model

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Abstract. The location of vaccination centers exceeds the challenges imposed by the COVID-19 pandemic on academicians and practitioners. Given the importance of reducing population mobility during such a phenomenon, such a challenge arose. Specifically, centers in low-demand areas motivate people's mobility to get vaccinated, increasing contagion. In this document, we analyze the allocation of vaccination centers in Puebla, Mexico, to propose their relocation by closing some existing facilities in low-demand areas and opening new ones in regions with higher demand. To achieve this, we analyze different scenarios by considering uncertain changes in regions' vaccine demand. We apply the Gravity location model to relocate and minimize the distance between the region's population and its vaccination center.

Keywords: Facility Location Problem, Gravity Location Model, Euclidean Distance, Supply Chain, Vaccination Center.

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1 Introduction

According to Hongzhong et al. (2007), an important way to measure the effectiveness of facility placement is by evaluating the total average distance between demand points and facilities. When the total average distance decreases, the accessibility and efficiency of the facilities increase; this ratio applies to private and public facilities, such as supermarkets, post offices, and emergency service centers, for which proximity is desirable. During the COVID-19 pandemic, the problem arose of distributing the developed vaccines to hospitals and vaccination centers quickly and reliably. The supply chain in the health sector is paramount since it will help identify reducing the time and distance of transport for transferring vaccines and medicines (Guerrero, 2019). Vaccine distribution has become an important issue in this epidemic. The distribution centers' location significantly reduces or increases the population's mobility since vaccine demand changes from region to region (Desticioglu & Ozyoruk, 2022). The p-median problem (Hakimi, 1964), or continuous location-allocation problem (Love, 1988), searches for p-locations for facilities to minimize the total costs of transportation. Also, it can be applied to reduce traveled distances. In the last case, the objective function is the total sum of weighted distances from regions to the facilities. However, one of the disadvantages of the p-median model is that it is an NP-hard problem since it relies on searching the best nodes of a network, which means that the optimal solution of the model can be delayed (Daskin, 2015).

The Weber method is used in planning the location of facilities, such as vaccination centers, which was developed by Alfred Weber in the 19th century. This method is based on the principle that transportation costs are proportional to the distance that must be traveled between two points. Hence, the model aims to minimize transportation costs to find the most efficient locations (Tellier, 2010). Regarding the location of vaccination centers, policymakers and practitioners search to minimize the distance a population must travel to reach the nearest vaccination center. Hence, the Weber method can be applied to the previous problem since it uses a mathematical model that considers the location of potential users and the location of vaccination centers to determine the optimal location. Factors taken into account include the total population, population density, road accessibility, and population distribution in the area to be covered.

According to Gao (2020), many methods have been developed to determine the location of a single facility to cover the maximum number of demand points (Church & Velle, 1974; Hogan & ReVelle, 1986). Drezner (2014) reviews previous studies and points out the ones used to formulate single-facility location problems, which include the center of gravity method. Proposed by Ohsawa (1999), who considers the center of gravity of the demand points, this method computes the position of a facility by minimizing the mean square Euclidean distances from the facility to the demand points.

Consequently, the gravity location model simplifies the search of locations by considering previously used sites. Particularly, it focuses on finding the center point of a geographic area. So, it is used to find the places where the average distance to reach all patients is minimized (Alain Schärlig, 1973).

In this article, we use the Gravity location model to determine the best location for vaccination centers in the municipality of Puebla, Mexico. This model is based on population and distance to calculate vaccination demand and find the optimal location of vaccination centers. The main objective is to minimize the distance traveled by the area's inhabitants to guarantee accessibility and adequate availability of vaccination for the population. In other words, it provides an optimal solution in a context where other models require heuristics since their computational time increases exponentially. For example, the previous phenomenon arises when the P-median model is applied.

2 Literature Review

Distribution and transportation are key supply chain activities since they link the manufacturing site to the customer's location, commonly separated by long distances. Hence, a product's competitiveness relies on the supply chain's ability to cope with delivery times and care for the products' quality (Ballou, 2004). Nowadays, the ability to manage distribution networks is a component of competitive advantage that is very important for many industries (Pujawan & Mahendrawati, 2010). When determining a distribution route, companies must also consider the ability of the vehicle to pick up the products and the cost of the associated labor. With the optimal distribution route, companies minimize distribution costs and increase customer satisfaction with on-time delivery (Bahrampour, Safari & Taraghdari, 2016**).** In addition to the distribution route, the location of a strategic distribution center must also be considered in supply chain decision-making. In general, scheduling and delivery route determination issues can have several goals to achieve, such as minimizing delivery costs, delivery time, or distance.

The center of gravity method has been widely mentioned in the academic and commercial literature as an appropriate method for locating a fixed installation. According to Montgomery (2001)**,** an efficient way to find a single building is the center of gravity method, in which mode, median, geometric mean, and harmonic mean represent alternative location methods**.** All of these provide a unique value representing a complete series of values, just as the center of gravity gives a single coordinate location, the arithmetic mean. According to Ballou (1973), the center of gravity method is essentially a single-facility location procedure for determining the e coordinates of a warehouse to receive and distribute goods to several points. A grid is placed over the supply and demand points, and the calculations are coded at the grid coordinate locations of the points.

2 Description of the Problem

This article uses the gravity location model to determine the location of vaccination centers based on geographical-spatial distribution, minimizing their distance from the region's population center. Then, the location of the vaccination center is calculated by using the following expressions that correspond to the horizontal and vertical coordinates, denoted by $\overline{X}$ and $\overline{Y}$, respectively. Specifically, we have that

$$\bar{X} = \frac{\sum_i V_i R_i X_i}{\sum_i V_i R_i} \text{ and } \bar{Y} = \frac{\sum_i V_i R_i Y_i}{\sum_i V_i R_i}. \quad \textbf{(1)}$$

Where:
$\bar{X}$, $\bar{Y}$ = the coordinates facility locations.
X_i, Y_i = the grid coordinate locations of the supply and demand point.
V_i = the volume flowing to or from the point of supply or demand.
R_i = the transport fee to send to or from the point of supply or demand

We use the Lob-Hub Microsoft Excel Supply Chain Add-In extension to apply the gravity location model and gather data from INEGI (National Institute of Geography and Statistics, 2020). To determine the demand for each vaccination center, we consider the municipality of Puebla, Mexico, which includes 1,641,278 inhabitants divided into 497 regions called AGEBs (Geographic

Areas of Basic Statistics). Since each vaccination can cover the demand of a certain set of AGEBs, the gravity model minimizes the distance that inhabitants from each AGEB travel to get vaccinated in a center. Hence, we also consider the latitude and longitude of each region to calculate the demand. Table 1 exemplifies the data that we use for the model.

Table 1. Displays the content of AGEB coordinates and the amount of population. Own elaboration with data from INEGI.

No. AGEB	Latitude	Longitude	Population
2111400010126	19.0748986	-98.2063183	4450
2111400010130	19.0746755	-98.1994947	5861
2111400010198	19.0671609	-98.2347782	4662
2111400010338	19.0569595	-98.1535394	3320
2111400010361	19.0536333	-98.2269676	1500
2111402215127	18.961632	-98.15316474	2443

Through the previous discussion, we analyze the location of each vaccination center. We assume that $m \geq p$; that is to say, some sites have been pre-selected as locations where the population can be vaccinated. Once the health centers have been located, the inhabitants of each of the AGEBs will obtain their vaccines at the nearest health centers.
This model is used to determine the location of vaccination centers using the gravity location model, which is as follows:

Minimize:

$$\sum_i C_i Q_i d_i \tag{2}$$

Subject to:

$$d_i = \sqrt{(x_n - x_i)^2 + (y_n - y_i)^2} \tag{3}$$

$$x_n = \sum_i \frac{C_i Q_i X_i}{d_i} \left(\sum_i \frac{C_i Q_i}{d_i} \right)^{-1} \tag{4}$$

$$Y_n = \sum_i \frac{C_i Q_i Y_i}{d_i} \left(\sum_i \frac{C_i Q_i}{d_i} \right)^{-1} \tag{5}$$

Where:
i = place of distribution.
X_n = coordinate x new iteration of the vaccination center n.
Y_n = coordinate y new iteration of the vaccination center n.
X_i = coordinate x distribution of vaccination center i.
Y_i = coordinate y and location of vaccination center i.
Q_i = quantity of vaccination delivered to the vaccination center i.
C_i = cost of shipping vaccines to vaccination center i.

The model's objective is that gravity localization is represented in (2). Equations (4) and (5) are used to determine the iteration coordinate *n,* and then the coordinates are substituted into equation (3) to update the distance. The process continues until the location minimizes the traveled distance.

3 Discussion of Results

The first scenario analyzes the proposal of three vaccination centers with the objective of vaccinating the population of the city of Puebla. According to the results we get from minimizing the distance between AGEBs and vaccination centers, Table 2 shows the coordinates for the location of the vaccination centers and the number of inhabitants that each vaccination center must attend.

Table 2. Three vaccination centers cover the population. The location is provided by the gravity model's application.

Center	Latitude	Longitude	Population	Distance Km
Center 0	19.07377548	-98.213425	501580	1531.489185
Center 1	19.06235379	-98.14271804	464510	1761.670108
Center 2	18.98393969	-98.22363148	675188	1696.895125
TOTAL				4990.054419

In addition, Figure 1 shows the geographical location of the vaccination centers on a map of the city of Puebla.

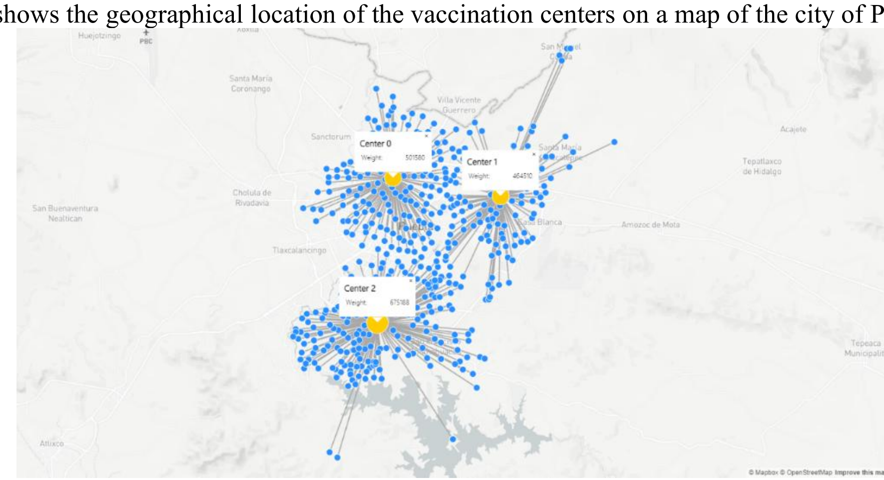

Fig. 1. Geographical location of three vaccination centers in Puebla.

The previous results show an almost homogeneous distribution of people among the three centers. However, vaccination center number 2 is the one that should attend to the largest population since there is no other center in the south of the city. Also, on average, centers are one and a half kilometers away from people's houses.

In a second analysis, we propose five vaccination centers to diminish walking distance and avoid center saturation. Table 3 shows the coordinates for the optimal location of the vaccination centers and the number of inhabitants they must attend. Figure 2 shows the location according to the results and the population each center must attend. Although the population attended diminishes in this scenario, most centers should attend more than 300,000 people, and the walking distance is larger than a kilometer.

Table 3. Five vaccination centers cover the population. The location is provided by the gravity model's application.

Center	Latitude	Longitude	Population	Distance Km
Center 0	18.97519406	-98.242716	405105	1136.265527
Center 1	19.08418673	-98.19041872	322303	1326.121426
Center 2	19.00314624	-98.19188917	336576	1347.834906
Center 3	19.06374447	-98.23471134	225384	1158.568672
Center 4	19.0642607	-98.13399308	351910	1354.936962
TOTAL				6323.727493

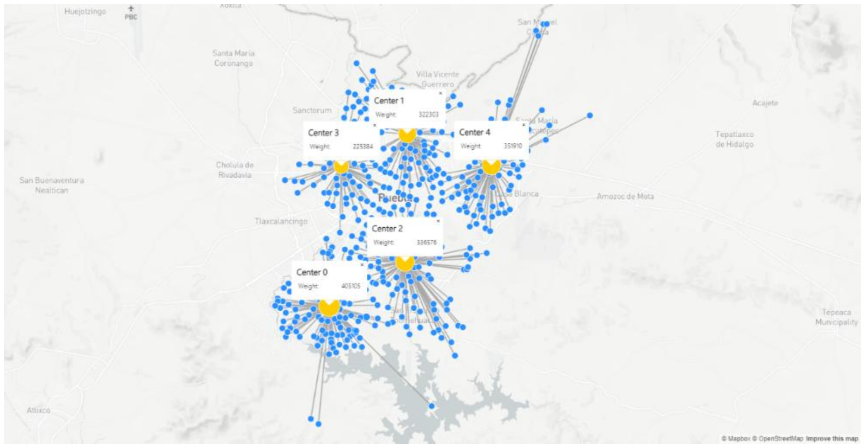

Fig. 2. Geographical location of five vaccination centers in Puebla.

As a third analysis scenario, we propose ten vaccination centers to vaccinate the population. The optimal location and population attended are shown in Table 4; as expected, the walking distance diminishes. Also, no vaccination center is attended by more than 250,000 people. In addition, Figure 3 shows the geographical location of the ten vaccination centers.

Table 4. The population is covered by ten vaccination centers. The location is provided by the gravity model's application.

Center	Latitude	Longitude	Population	Distance Km
Center 0	18.9756938	-98.26337939	118292	651.8997713
Center 1	19.06244774	-98.238314	184946	801.3039187
Center 2	18.95642877	-98.23585531	131347	750.0305218
Center 3	19.10077069	-98.20962697	136733	577.1923663
Center 4	19.02383334	-98.19315857	179738	777.185863
Center 5	18.97729449	-98.18160868	122078	840.0233366
Center 6	19.08768888	-98.1228663	139648	721.9685324
Center 7	18.9959853	-98.229605	210228	684.3019936
Center 8	19.07489355	-98.18073199	207038	926.111417
Center 9	19.04722473	-98.1407474	211230	832.6117226
TOTAL				7562.629443

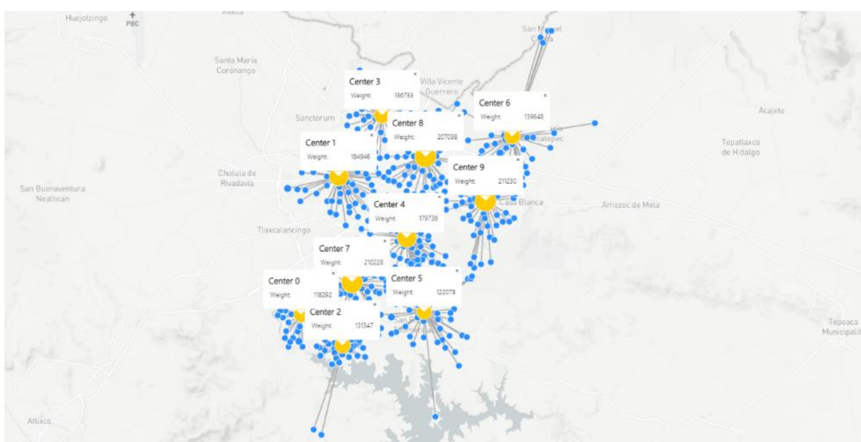

Fig. 3. Geographical location of ten vaccination centers in Puebla.

Now, we propose the establishment of 15 vaccination centers to serve the population and vaccinate it. Table 5 shows the results of the gravity model when we increase the number of centers to 15. In addition, Figure 4 shows the location according to the results. Note that walking distance is less than one kilometer, while vaccination centers now attend less than 200,000 people.

Table 5. The population is covered by 15 vaccination centers. The location is provided by the gravity model's application.

Center	Latitude	Longitude	Population	Distance Km
Center 0	19.06150408	-98.13469279	147601	690.3657847
Center 1	19.09964451	-98.2122551	133443	497.0221789
Center 2	19.08394364	-98.17861506	152221	768.2782124
Center 3	19.04829516	-98.17695161	102871	501.7957534
Center 4	18.9758368	-98.26270298	118572	554.0165204
Center 5	18.998694	-98.23416968	162294	581.8419004
Center 6	18.97925529	-98.21166841	119627	500.6491287
Center 7	19.06513226	-98.24769426	119070	681.8143053
Center 8	19.13847587	-98.09668551	18479	11.58425737
Center 9	19.03251025	-98.14212851	93245	649.654006
Center 10	18.96014421	-98.17002328	45950	669.5271999
Center 11	19.08572901	-98.1227333	74710	592.8969985
Center 12	18.9513197	-98.24165541	95018	644.5942659
Center 13	19.05192809	-98.21378371	111744	499.5110652
Center 14	19.01001084	-98.19053245	146433	641.4608433
TOTAL				8485.01242

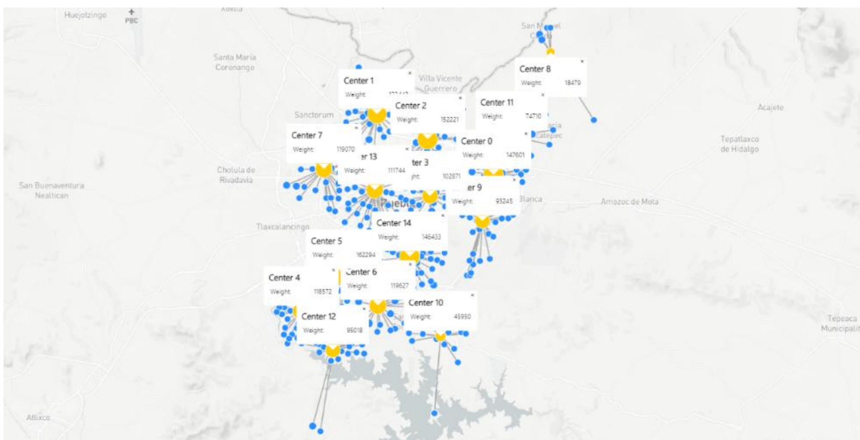

Fig. 4. Geographical location of 15 vaccination centers in Puebla.

In contrast to other facility location methods, the computational complexity of the gravity model does not represent a problem since it works with closed-form solutions to compute the optimal coordinates. Thus, we perform two additional analyses by considering 20 and 27 vaccination centers. Table 6 shows the results for the 20 centers, while Figure 5 shows their location.

Table 6. The population is covered by 20 vaccination centers. The location is provided by the gravity model's application.

Center	Latitude	Longitude	Population	Distance Km
Center 0	19.05516247	-98.15416617	81763	432.7591781
Center 1	19.0421184	-98.18319544	75505	425.9170365
Center 2	19.13847587	-98.09668551	18479	11.58425737
Center 3	18.98397029	-98.19966544	70947	490.3646931
Center 4	19.03422246	-98.21773957	77664	425.5492726
Center 5	19.06188434	-98.12963408	111026	527.7228905
Center 6	19.03077773	-98.14051372	76164	562.3949132
Center 7	18.95949647	-98.16926686	43873	574.658278
Center 8	18.90223992	-98.25318014	11692	0.655779645
Center 9	19.09354601	-98.17486388	85473	589.7904107
Center 10	19.07298361	-98.2281617	92593	378.5127096
Center 11	18.97333626	-98.26658391	91412	466.2924642

Center 12	19.07027458	-98.18865462	106274	416.0048383
Center 13	19.00946702	-98.18644707	110211	586.0410703
Center 14	18.99826481	-98.22307386	99861	447.2668756
Center 15	19.10257499	-98.21162839	108521	421.1445792
Center 16	19.08616673	-98.12423495	75069	509.5809226
Center 17	18.99260229	-98.24482623	102751	464.2946305
Center 18	19.06058823	-98.25449207	72339	513.6000529
Center 19	18.96284533	-98.23432001	129661	511.0014277
TOTAL				8755.136281

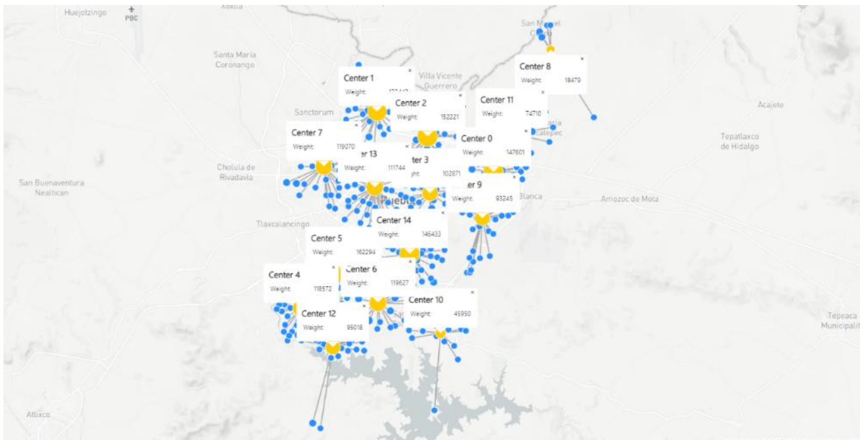

Fig. 5. Geographical location of 20 vaccination centers in Puebla.

The last scenario that we analyze considers 27 vaccination centers. In this case, some centers are located in the geographical center of an AGEB, which implies no walking distance. Moreover, the walking distance is no greater than 600 meters. Also, only two centers attend more than 100,000 people since they are located in the densest parts of the city. Table 7 and Figure 6 show the results for this last scenario.

Table 7. The population is covered by 27 vaccination centers. The location is provided by the gravity model's application.

Center	Latitude	Longitude	Population	Distance Km
Center 0	19.0339906	-98.14139546	87174	494.2264664
Center 1	19.08164234	-98.1053766	33596	440.4385875
Center 2	19.10525979	-98.22055614	60722	318.3598168
Center 3	19.07473894	-98.21030323	69220	342.2995226
Center 4	19.00226312	-98.18282792	74345	518.9285988
Center 5	19.09244602	-98.16953358	55648	519.9836187
Center 6	19.1481098	-98.10318944	15070	2.094344243
Center 7	18.99098124	-98.20666932	70154	434.4381035
Center 8	19.07504977	-98.24030658	73911	435.5403953
Center 9	18.9841725	-98.26566513	54499	416.4169195
Center 10	18.96494338	-98.26533284	48475	402.399479
Center 11	18.96575502	-98.17208488	46908	506.3877304
Center 12	19.04464085	-98.21499705	63672	372.079783
Center 13	18.98484778	-98.24111238	73074	337.3985623
Center 14	19.08575972	-98.1332136	59288	414.6488805
Center 15	18.91154629	-98.17403896	4224	0
Center 16	19.00221402	-98.23675633	72684	429.6739749
Center 17	18.9726927	-98.21839313	63590	357.0589702
Center 18	18.9581621	-98.23948649	80144	453.9601441
Center 19	19.01589089	-98.21525174	55941	358.6172961
Center 20	19.10258306	-98.19480262	55348	298.938309
Center 21	19.060092	-98.13432791	132836	529.7305179

Center 22	19.05073714	-98.17405378	77917	374.5367598
Center 23	19.05325894	-98.25463724	53735	477.3000967
Center 24	18.90223992	-98.25318014	11692	0.655779645
Center 25	19.07365275	-98.18276034	84542	382.9314815
Center 26	19.02540931	-98.1863098	62869	349.7604518
TOTAL				9968.80459

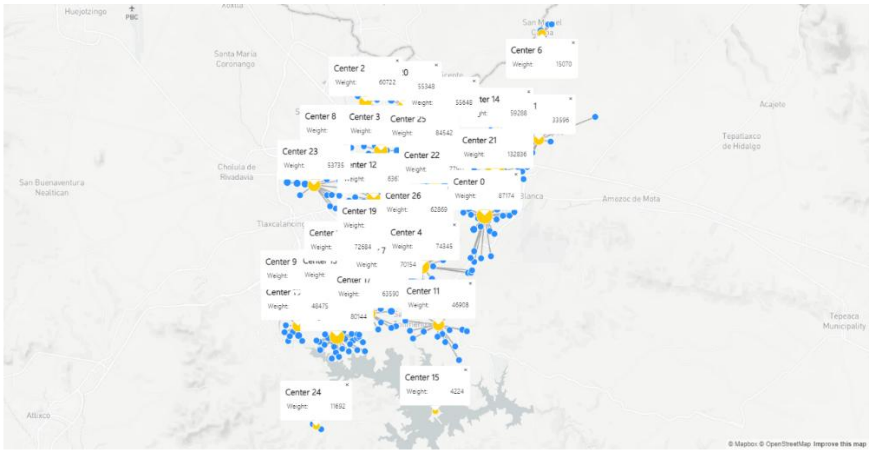

Fig. 6. Geographical location of 27 vaccination centers in Puebla.

4 Conclusions

The COVID-19 pandemic has highlighted the need for an adequate distribution of hospitals and vaccination centers in Puebla, Mexico. Particularly, in such a context, it is essential to consider the population and number of hospitals to expedite treatment and vaccination, as proper distribution can reduce time and costs. Despite the important work carried out by hospitals, obstacles such as a shortage of personnel and limited capacity in facilities have resulted in delays in immunizing the population.

This study recommends geographic locations for vaccination centers in Puebla using a model based on the gravity location principle. The results show that the scenario with three vaccination centers allows for the shortest total distance traveled, with locations near the Central de Autobuses de Pasajeros de la Ciudad de Puebla (CAPU), a residential area, and the Parque Centenario La Laguna de Chapulco. These locations can serve as a reference for relocating new vaccination centers and speeding up the immunization process for the population.

In conclusion, it is crucial to continue improving the distribution of hospitals and vaccination centers in the current context of the COVID-19 pandemic. Implementing adequate facility location strategies can improve accessibility and availability of medical services for the population, reducing social mobility, which is crucial during a phenomenon similar to the COVID-19 pandemic.

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