Third-Party COVID-19 Vaccine Distribution Management

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Abstract

The Covid-19 pandemic took the world by surprise, affecting millions of people and families in Paraguay and worldwide. We analyze the country's situation after the arrival of batches of anti-Covid-19 vaccines to formulate a mathematical model that allows efficient distribution of vaccines to citizens of the central department. Even more, maximizing the number of citizens in high-risk situations vaccinated with the help of a third-party company willing to lend its logistics fleet of trucks and drivers. We propose a Capacitated Vehicle Routing Problem (CVRP-type) mathematical model to find the optimal travel routes for fair distribution at the lowest possible cost. To solve the model, different parameters must be considered, such as the opening time of the vaccination centers, the drivers' working hours, and the vehicles' capacity, among others. In addition, in the case study, certain assumptions are considered to limit the initial situation before solving the model. One supposition is the demand, considered from July to September, when the country received the most significant number of vaccines. In this work, only the distribution of the Pfizer vaccine and all the care it requires was considered since it is the most widely available vaccine in the country. The proposed methodology is valid as a first instance to solve the distribution problem in the central department. It applies to other departments and vaccines for other diseases by changing the appropriate parameters.

Keywords
Logistics, Linear programming, CVRP, Vaccines, COVID-19

1. Introduction
Diseases are inherent to the human being, they have always been present over time, but technology has advanced with them, what nobody expected was that a pandemic would take the world by surprise and completely paralyze a disease that little is known about.

Technology is advancing rapidly again, and vaccines against COVID-19 are already available in producing and importing countries. As for Paraguay, it has companies dedicated to logistics distribution willing to lend their logistics infrastructure for the distribution of vaccines.

Based on these detected problems and opportunities, the research question was formulated to obtain a fair and equitable distribution management scheme for citizens, and that is useful for the outsourced company, using mathematical modeling as a support technique for decision-making. of decisions.

2. Vehicle Routing Problem
The Vehicle Routing Problem (VRP) is one of the most studied combinatorial optimization problems and deals with the optimal design of routes to be used by a fleet of vehicles to serve a set of customers.

The literature abounds with solution approaches for TSP (Traveling Salesman Problem) and VRP (Vehicle Routing Problem). These can be classified as follows:

• Mathematical modeling
With this approach, one is inclined to think that the model is capable of providing exact solutions. Unfortunately, even for a modestly sized TSP and VRP, it is computationally too complex to solve.
•Heuristics
Heuristics limit your exploration of the search space, but the goal is to produce a good solution in a reasonably short time.
• Metaheuristics
The most promising and effective solution methods for TSP and VRP are metaheuristics Gendreau et al. (2002), which are general-purpose mechanisms for solving difficult optimization problems. In metaheuristics, the emphasis is on deep exploration of the most promising regions of the solution space. These methods typically combine sophisticated neighborhood search rules, memory structures, and solution recombination. The quality of the solutions produced is usually much higher than those obtained by classical heuristics, however, the increase in computation time is a problem. Procedures are often context-dependent and require finely tuned parameters for efficient searching.
• Interactive approaches
These are simple approaches that can be adapted to a particular application. It can be based on intuition, simulation, preference or graphics to help the decision maker in a "what if" mode. This can be called as quick and dirty procedure. (Anbuudayasankarr et al., 2014)
• Hybrid approaches
Analysts have also tried hybrid approaches, combining two or more of those suggested above. Some of these are reported to have high potential to provide good solutions in low computational time. (Laporte et al., 2000)

2.1 Applications of mathematical models for product logistics management

Rodríguez Bedoya, (2014), presented a model of distribution and logistics of vaccines and related supplies, used for the District Secretary of Health of Bogotá, where a VRP routing problem was presented, which consists of the definition of efficient routes minimizing the time of each route, for each collection center in charge of one or more localities. For routing, they used the Clarke and Wright heuristic that designs the route through savings in route consolidation.

3. Third company´s information

- Fleet of drivers made available by the third company, presented in Table 1.

Table 1. Fleet of drivers made available by the third company

Job	Amount (People)
Distribution chief	1
Customer Service Assistant	6
Logistics Operations Assistant	1
Distribution Wizard	5

- Number and capacity of vehicles, data presented in the Table 2.

Table 2. Number and capacity of vehicles, data presented in the Table

Vehicle Capacity (Kg)	Number of Vehicule
10.000	4
1.000	38
15.000	1
2.000	37
3.500	35
5.000	32

8.000	16
Grand Total	**163**

- Table 3 shows the direct logistics costs.

Table 3. Direct logistics costs.

Costs	Account type	Average Cost 2021
Fixed Costs	Telephoness	Gs.11.854.545
Fixed Costs	Satellite tracking	Gs.14.818.167
Variable Costs	Freighters	Gs.385.220.618

- Distribution costs, presented below in the Table 4.

Table 4. Distribution costs.

Vehicle capacity (Tn)	Cost per km (Gs)
1	1.300
2	1.631
3,5	1.744
5	2.162
8	2.735
10	2.784
15	3.390
26	5.940

4. Information provided by the Ministry of Public Health and Social Welfare (MSPyBS).

- Geographical location of the distribution center, presented in the Table 5.

Table 5. Geographical location of the distribution center.

Distribution Center	Latitude	Longitude
National vaccine center (PAI)	-25,27621525	-57,59210824

5. Conceptual model design

The model that best fits our problem is the Capacitated Vehicle Routing Problem (CVRP). Next, Figure 1 shows a scheme of a solution of the type of CVRP model.

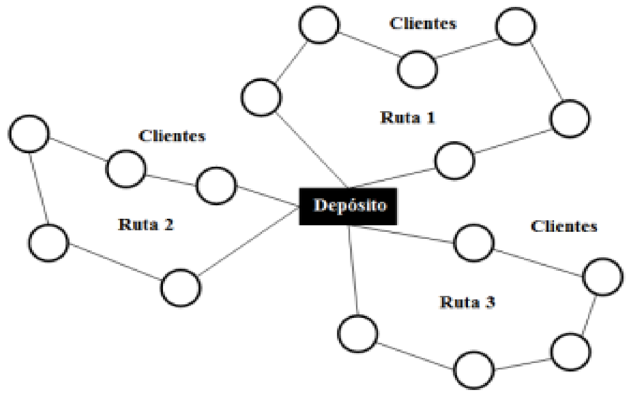

Figura 1: Schematic of a CVRP model solution. (Miguel et al., 2015)

6. Data collection and definition of parameters

6.1 Information collected for the description of the current situation

For the collection of information from the third company, the questionnaire method was used. In summary, the questions asked of the company were:

1. What operations does the company carry out? How many years have they been in the business?
2. How many cargo transportation vehicles does the company have? What is the load capacity of each?
3. How many of these vehicles and what cargo capacity will be available for the implementation of our project?
4. What is your available fleet of drivers?
5. What hours does your work activity include?
6. What costs do you incur to carry out your tasks?

To collect information from the Ministry of Public Health and Social Welfare (MSPyBS), its website was accessed in the Expanded Program on Immunizations (PAI) section. Likewise, data was requested from the public information portal of the MSPyBS through a questionnaire with the following questions:

1. What is the number of citizens enrolled in the national vaccination system?
2. What is the age range of the people enrolled?
3. In what geographical area are the registered people located?

6.2 Criteria for model resolution.

- Truck fleets (Units).
- Fleet of drivers (Man).
- Distribution capacity (Kg).
- Availability of time (Hours)
- The working hours of the third company extend from 06:00 a.m. to 06:00 p.m.
- Vaccination service hours extend from 7:00 a.m. to 5:00 p.m. for citizens, while from 6:00 a.m. to 6:00 p.m. there will be MSPyBS officials at the vaccination centers.
- Logistics Costs (Gs).
- Number of hospitals available for vaccination (Units).
- Geographic location of hospitals available for vaccination (Units).
- Number of citizens vaccinated by vaccination (People).
- Number of vaccines in Paraguay from 02/19/2021 to 12/31/2021

- Quantity of vaccines per box, dimensions, and volume of the Softbox, presented in Table 6.

Table 6. Number of vaccines per box, dimensions and volume of the box Softbox

Dose (un)	Size (cm)	Volume (m^3)
5.850	40x40x56	0,0896

- Number of vials per box of diluent, and dimensions of the box, which are presented in the Table 7.

Tablae 7. Number of vials per box of diluent, and dimensions of the box

Dose (un)	Size (cm)	Volume (m^3)
25	13.5x15x5,6	0.001134

- Volume occupied by vaccines and diluents presented in the Table 8.

Table 8. Volume occupied by vaccines and diluents.

Total space occupied by vaccine (5850) + diluent (m3)
0,097538

- Weight per box of vaccines and diluents, data presented in the Table 9.

Tabla 9. Weight per box of vaccines and diluents

Weight per box	Weight per box of vaccine Kg
Vaccines	36,5
Diluent	0,461953125
Total	36,96195313

- Capacity by volume (m3) and weight (Tn) of a truck of 1 (Tn) that is presented below in Table 10. It is worth mentioning that the dimensions of the truck are (mm) 2,415x1,465x1,290 and volume (m3) 4.56398775.

Table 10. Capacity by volume (m3) and weight (Tn) of a truck of 1 (Tn).

Measurement Unit	Vaccines Amount
m^3	273.732
Tn	154.270

6.3 Characteristics of the transport of vaccines

To ensure that the vaccines are kept in the cold conditions required during international transport and within the country, they are shipped in a special container or box used worldwide and called a SoftBox.

6.4 SoftBox Characteristics

- Capacity: Each container can hold up to five vaccine trays, with a total capacity of 5,850 doses. Each tray contains 195 vials, or a total of 1,170 doses per tray.
- Weight: Used at full capacity (five vaccine trays and a fresh load of dry ice), the vaccine container weighs 36.5 kg (81 lbs). To facilitate its transport, the container is provided with straps.
- Duration: With a full load of dry ice (20 kg), and if opened a maximum of 2 times per day for <5 min each time, the container will maintain extreme cold conditions for up to 8 days. However, it is recommended to renew the load of dry ice on arrival and every 5 days.

7. Mathematical model

The approach will focus on the creation of routes in the Central Department, defining a CVRP model with the objective function of minimizing the total time and distance traveled, respecting a number of restrictions, such as the maximum capacity per motorized vehicle and the demand for vaccines that must be satisfy.

7.1 Definitions

We have a graph$G(N, A)$, where N is the set of network nodes and A the set of arcs between each pair of nodes

7.2 Sets

N: Set of vaccination centers and Distribution Center.

V: Set of vaccinations.

$\{0\}$: We denote the Distribution Center (DC) as the zero node, within a set of a single element.

$N = V \cup \{0\} \qquad V = N \setminus \{0\}$

7.3 Parameters

c_{ij}: Cost of the shortest path starting at the node i and reaches the node j.

C: Vehicle capacity

d_i: Vaccination center demand i.

7.4 Decision variables.

x_{ij}: binary variable that takes value 1 if the arc (i, j) is at the optimal solution, zero otherwise.

u_i: is an additional continuous variable that represents the load of the vehicle after visiting the vaccine center i, $\forall\, i \in V$.

Objective Function

$$Min\ Z = \sum_{(i,j)\in A} c_{ij}.x_{ij} \qquad (1)$$

Subject to:

$$\sum_{i\in N} x_{ij} = 1 \ \ \forall\, j \in V \qquad (2)$$

$$\sum_{j\in N} x_{ij} = 1 \ \ \forall\, i \in V \qquad (3)$$

$$If\ \ x_{ij} = 1 \rightarrow u_j \geq u_i + d_j \ \ \forall\, (i, j) \in A\text{: } i \neq 0, j \neq 0 \qquad (4)$$

$$d_i \leq u_i \leq C \qquad \forall\, i \in V \qquad (5)$$

$$x_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in A \quad (6)$$

$$u_i \geq 0 \qquad \forall\, i \in V \qquad (7)$$

The objective function seeks to reduce the costs associated with transportation, that is, to reduce costs per route.
Constraint (2) is responsible for making the assignment of a vehicle to the route (i, j) mandatory.
Constraint (3) forces a single arc to start from an initial node to any other node.
Constraints (4) and (5) guarantee subtour breakages, that the number of vaccines delivered does not exceed capacity, and that demand is met.
Constraint (6) determines that the variable is binary.
Constraint (7) guarantees that the vehicle delivers vaccines at each point.

8. Assumptions considered for the realization of the model.

Demand: For purposes of practicality and to have more relevant data, the following are considered:

- Data from the three months in which the greatest number of vaccines were administered in the Central department, which were the months of July, August and September of the year 2021.
- Only the Pfizer vaccine and its characteristics, as it is the most widely available in Paraguay.
- A weekly demand, according to the characteristics of the "SoftBox" and the transport capacity of a large quantity of vaccines per truck, described in chapter 3.3.3.

Truck capacity: Three types of trucks with different capacities more in line with the weekly demand of all vaccination centers were considered.

Number of drivers: Considering the working hours of each driver, the duration of each trip and the number of drivers to be assigned for each trip will be calculated.

Truck speed: To determine the time of each trip, an average speed of each truck is assumed.
Service time: The service time is the time it takes for the delivery of the vaccines in each vaccination, which will be added to the total time of the trip to determine the total duration of a trip.

9. Model results

Next, the main results obtained when solving the designed mathematical model are described, using the Gurobi optimization software and the Python programming language. Different capacities were included for the trucks in the distribution of the vaccines, in order to obtain different results, compare them and make a decision considering aspects such as:

- Distance traveled
- Total time of the tours
- Necessary drivers
- Total cost

9.1 The results of the mathematical model with a vehicle with a capacity of 154,000 vaccines are presented in Table 11

The results of the mathematical model with a vehicle with a capacity of 154,000 vaccines are presented in Table 11.

Table 11. Summary of results of the mathematical model with a vehicle with a capacity of 154,000 vaccines.

Variable or parameter	Amount	Measurement Unit
Vaccines Delivered	86.772	vaccines
Used Vehicles	1	vehicles
Total Distance Traveled (km)	177.71	km
Drivers Used	3	drivers
Total Cost of the Tour	759.647	gs
Average speed	50	km/h
Average Service Time	15	min/vaccinatory
Total Travel Time	17,05	hours

Figure 2 shows the route graph made through the Gurobi optimization software with the Spyder Anaconda environment obtained because of the model with trucks with a capacity of 154,000 vaccines.

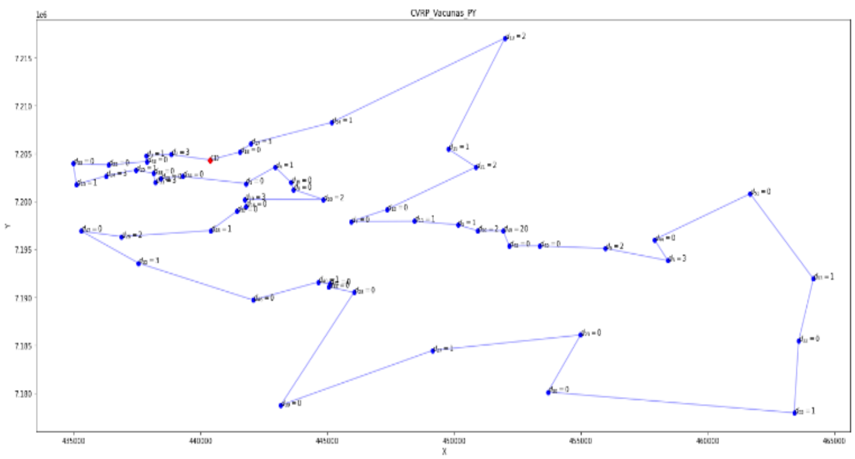

Figure 2: Route graph made using the Gurobi optimization software with the Spyder Anaconda environment for the solution with a vehicle loaded with 154,000 vaccines.

Figure 3 shows the route graph obtained because of the model with trucks with a capacity of 154,000 vaccines on google maps.

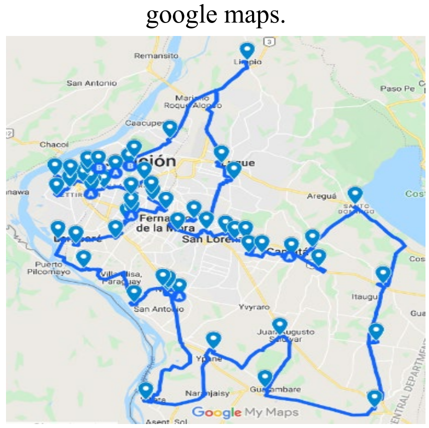

Figure 3: Route graph (Google Maps software) for the solution with a vehicle loaded with 154,000 vaccines.

9.2 Results of the mathematical model with a vehicle with a capacity of 75,000 Vaccines.

The results of the mathematical model with a vehicle with a capacity of 75,000 vaccines are presented in Table 12 and Table 13, summarizing the routes of vehicle 1 and vehicle 2, respectively.

Table 12. Summary of results with the vehicle with a capacity of 75,000 vaccines. Vehicle 1.

Variable or parameter	Amount	Measurement Unit
Vaccines Delivered	13.734	vaccines
Used Vehicles	1	vehicles
Total Distance Traveled (km)	16,35	km
drivers used	1	drivers
Total Cost of the Tour	164.011 ₲	gs
Average speed	50	km/h
Average Service Time	15	min/vaccinatory
Total Travel Time	3,33	hours

Table 13. Summary of results with the vehicle with a capacity of 75,000 vaccines. Vehicle 2.

Variable or parameter	Amount	Measurement Unit
Vaccines Delivered	73.038,3	vaccines
Used Vehicles	1	vehicles
Total Distance Traveled (km)	163,31	km
drivers used	2	drivers
Total Cost of the Tour	599.689 ₲	gs
Average speed	50	km/h
Average Service Time	15	min/vaccinatory
Total Travel Time	13,77	hours

Figure 4 shows the route graph made through the Gurobi optimization software with the Spyder Anaconda environment obtained because of the model with trucks with a capacity of 75,000 vaccines.

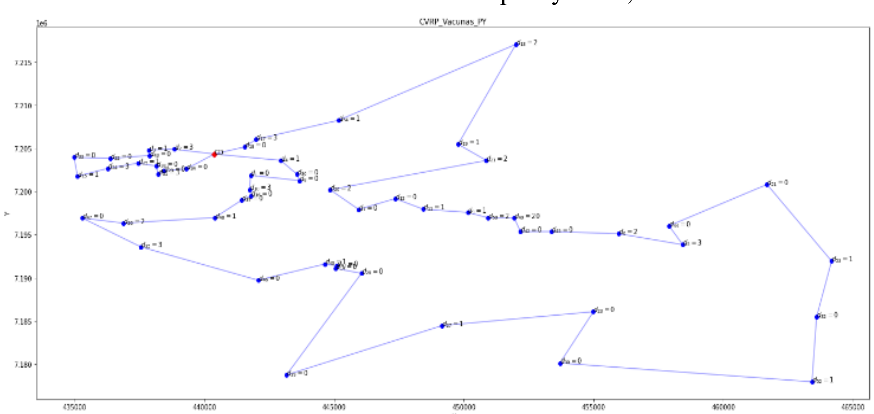

Figura 4: Route graph made using the Gurobi optimization software with the Spyder Anaconda environment for the solution with a vehicle loaded with 75,000 vaccines.

Figure 5 shows the route graph obtained because of the model with trucks with a capacity of 75,000 vaccines on google maps.

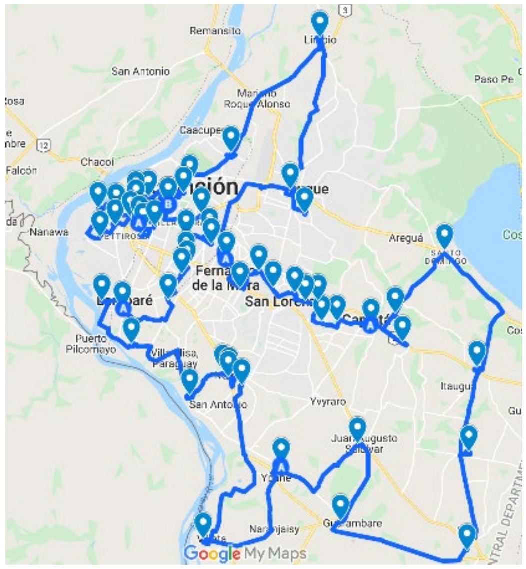

Figure 5: Route graph (Google Maps software) for the solution with a vehicle loaded with 75,000 vaccines.

9.3 Results of the mathematical model with a vehicle with a capacity of 65,000 Vaccines

The results of the mathematical model with a vehicle with a capacity of 65,000 vaccines are presented in Table 14 and Table 15, summarizing the routes of vehicle 1 and vehicle 2, respectively.

Table 14. Summary of results with the vehicle with a capacity of 65,000 vaccines. Vehicle 1.

Variable or parameter	Amount	Measurement Unit
Vaccines Delivered	26.460	vaccines
Used Vehicles	1	vehicles
Total Distance Traveled (km)	36,34	km
drivers used	1	drivers
Total Cost of the Tour	205.587 ₲	gs
Average speed	50	km/h
Average Service Time	15	min/vaccinatory
Total Travel Time	5,73	hours

Table 15. Summary of results with the vehicle with a capacity of 65,000 vaccines. Vehicle 2.

Variable or parameter	Amount	Measurement Unit
Vaccines Delivered	60.312	vaccines
Used Vehicles	1	vehicles
Total Distance Traveled (km)	145,42	km
drivers used	2	drivers
Total Cost of the Tour	562.481 ₲	gs

Average speed	50	km/h
Average Service Time	15	min/vaccinatory
Total Travel Time	11,41	hours

Figure 6 shows the route graph made through the Gurobi optimization software with the Spyder Anaconda environment obtained because of the model with trucks with a capacity of 65,000 Vaccines.

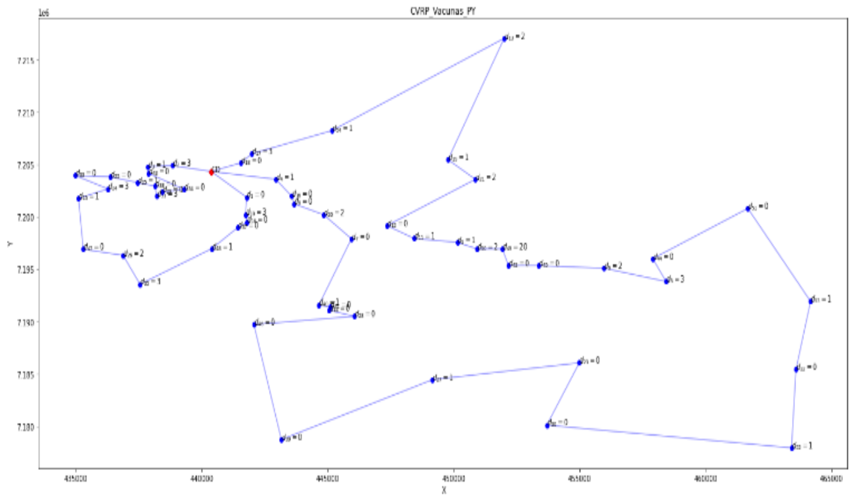

Figure 6: Route graph made using the Gurobi optimization software with the Spyder Anaconda environment for the solution with a vehicle loaded with 65,000 vaccines.

Figure 7 shows the route graph obtained because of the model with trucks with a capacity of 65,000 vaccines on google maps.

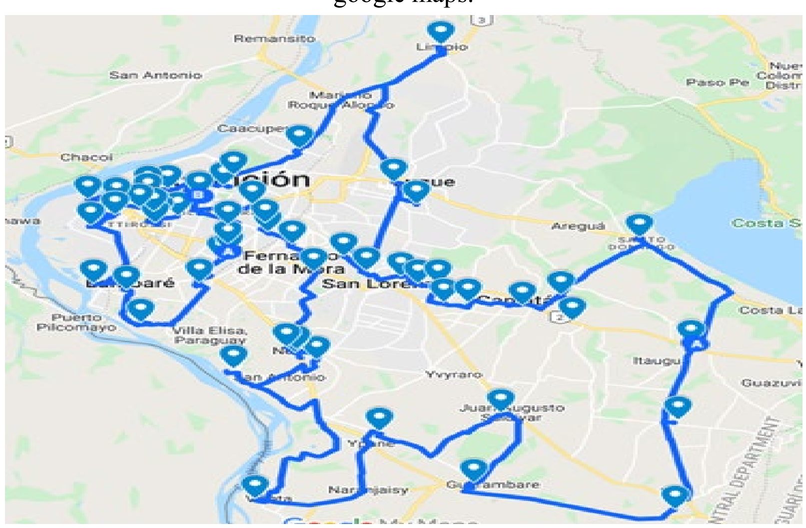

Figure 7: Route graph through Google Maps software for the solution with a vehicle loaded with 65,000 vaccines.

9.4 Results comparison

To make the comparison between the ways of loading the trucks, the following aspects are taken into account

- Trucks number
- Total cost of the tour

• Total travel time

The comparison of the results of the different resolutions of the model with different loads on the vehicles is presented in Table 16

Tabla 16. Results comparition

Capacity 154.000	Capacity 75.000	Capacity 65.000
Trucks Number		
1	2	2
Total Tour Cost		
759.647 ₲	763.700 ₲	768.059 ₲
Total Tour Time		
17,05 hs	13,77 hs	11,41 hs

9.5 Analysis of the results

Tables 11 to 15 summarize the results according to the capacity of the truck to be used. When analyzing the criterion of the number of trucks, when the truck is loaded with its full capacity, it is possible to distribute the demand for vaccines with a single truck, while with the other capacities, two trucks would be needed in each one.

In terms of the total cost of the trip, it is by distributing a maximum of 75,000 vaccines per truck that the lowest cost is achieved.

Considering the total time of the trip, distributing a maximum of 65,000 vaccines per truck will make the trip shorter. To decide, you must consider the schedule in which the vaccination clinics will have the capacity to receive the vaccines (6:00 a.m. to 6:00 p.m.) and the minimum distribution cost.

An important edge in our model and in decision-making is the fair and equal distribution at each vaccination point, prioritizing high-risk people, in order to comply with all Paraguayan citizens who, require vaccination and are in the study areas.

Therefore, option 3 is the one that meets all the requirements, with a vehicle with a capacity of 65,000 vaccines, since the distribution time falls within the range of twelve available hours. It is not the lowest cost solution, but we prioritize the distribution of vaccines in a single day to all vaccination centers.

By first solving the model with a minimization of costs, it is possible to meet all the weekly demand of the cities, so that with the model the social objective of satisfying the demand for vaccines of people in high-risk conditions and with priority is achieved. to be vaccinated

10. Conclusions and recommendations

10.1 Conclusions

It was possible to design a Linear Programming model, for the correct and fair distribution of vaccines against COVID - 19 to minimize total costs and distribute equitably to each city. The best solution is obtained using 2 trucks with a capacity of 65,000 vaccines and 3 drivers with a final total cost of 768,059 ₲.

The results are positive due to the speed with which the entire area can be supplied as well as the minimum costs that were achieved by using resources efficiently and complying with the limitations presented by the third company, which provides its distribution services. and logistics, to support the MSPyBS vaccine distribution management.

It is worth mentioning that currently the situation of Paraguayan citizens in the country to which the investigation is limited in terms of the need to distribute vaccines against COVID-19 is not in a state of emergency. However, this mathematical model could be used by the MSPyBS soon for the distribution of vaccines against other diseases, previously modifying the parameters to adapt the model to the new case study and obtain the resolution.

10.2 Recommendations

For the efficient distribution of vaccines, in a fair and equal manner, as well as at the lowest possible cost, we recommend weekly distribution in two trucks with a capacity of 65,000 vaccines each.

The model is detailed and given the future need for a massive distribution of vaccines, whether for COVID-19, its variations, or other diseases, we suggest pilot testing and application by the institutions that consider the proposed study and mathematical model necessary.

In order to obtain plans that adjust to the reality of the moment in which the implementation of the mathematical model is carried out, it is necessary that they have: the definition of the geographical scope of the distribution, the distribution requirements of the vaccine to be transported, definition of updated transportation costs, registration of historical data that may be relevant (population of the area, number of people affected by the disease, among others).

For future work that could be developed from the results obtained, it is recommended: Regarding the programming of the mathematical model, analyze the possibility of including in the design all the activities and costs associated with distribution without the collaboration of a third party company, extend the period of time to be considered, as well as the geographical area of study due to the differences that may be found (route conditions, number of vaccinations available) between the central department and the other departments of the country.

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Bibliography

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