

# Optimization Model Applied to the Distribution of Covid-19 Vaccines in Lima and Callao



Juan Diego Guerra Vargas, Julio C. Quezada Rojas,  
and Eduardo J. Siuse Calixto

**Abstract** Currently, Peru has started a vaccination plan to face the crisis generated by Covid-19; however, it has not been the most efficient. The current study seeks to reduce vaccine distribution times and costs in Lima and Callao by applying a mathematical optimization model.

**Keywords** Optimization · Mathematical model · Supply chain · Covid-19

## 1 Introduction

As of August 01, 2021, the World Health Organization (WHO) has reported 210 million cases of COVID-19 globally; of which 39% has occurred only in America [1]. Particularly in Latin America, seeing the distant possibility of a rapid acquisition of vaccines, we opted for non-pharmaceutical interventions, such as mitigation and suppression, adapted to the capacity of each country [2]. In that area, the capacity of the Peru, although it has been increasing in recent years, continues to be low according to Dargent [3]. In Peru, since the first case was detected on March 6, 2020 until today, more than 2 million cases and more than 197 thousand deaths from this new disease have been confirmed [4]. In this context, vaccines came as the main solution, since they induce immunity against COVID-19, reducing symptoms and the risk of serious health consequences. This immunity generated by vaccines not only helps people to fight against this virus in case of infection, but also reduces the probability of infecting other people as well, therefore, indirectly reducing the transmission of the virus throughout the population [5, 6]. According to Fuentes [7], with the arrival of vaccines, the Peruvian economy is expected to increase from 7% to 12%, motivating people to consume products and services confidently as they are already vaccinated, thus reactivating businesses and promoting new jobs.

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J. D. Guerra Vargas (✉) · J. C. Quezada Rojas · E. J. Siuse Calixto  
Pontificia Universidad Católica del Perú, San Miguel, Perú  
e-mail: [jdguerra@pucp.edu.pe](mailto:jdguerra@pucp.edu.pe); [jcquezada@pucp.edu.pe](mailto:jcquezada@pucp.edu.pe); [eduardo.siuse@pucp.pe](mailto:eduardo.siuse@pucp.pe)

While vaccines remain a rare and coveted commodity in the world, Gooding et al. [8] demonstrated that it is important to improve the supply chain to achieve greater immunization in less time and face up frequently stockouts because of supply chain issues. In that sense, the type, quantity, allocation and distribution of the vaccine are considered the four main components of the vaccine supply chain, Rastegar et al. [9]. It is important to meet demand of vaccines in the period of high request, for that Peru follows a vaccination plan for age ranges and as Han et al. [10] mentioned, the mortality rate can be minimized by prioritizing vaccination for people who work in the health sector, followed by adults over 65 years old; then continue with people between 40 and 65 years old and thus to gradually decrease until the majority of the population is vaccinated.

As a result of improving the allocation and distribution of vaccines, Shakiba et al. [11] presented a mathematical optimization model for the optimal distribution of vaccines, which consists of dividing the population into different subgroups and distributing the vaccine in an equitable and justified manner to each. Recently, Georgiadis et al. [12] developed a mixed integer linear programming (MILP) model for optimal planning of the supply chain of COVID-19 vaccines in order to reduce costs related to the storage and transportation. To face up the stockouts, Sabouhi et al. [13] proposed a multi-objective optimization model which it uses clustering in order to improve the network design and supply in the regions. A similar study by Souto et al. [14] proposed a clustering methodology, and so they minimize costs and increase the flow of products demanded by customers through the installation of intermediate warehouses. Altabeeb et al. [15] carried out a research where she used a problem of generation of routes for trained vehicles (CVRP) with the objective of finding the routes of the vehicles minimizing the distances traveled; she was able to achieve far more promising results compared to other known methods. Further-more, Akhtar et al. [16] also used a CVRP and got the best routes in order to reduce the distances traveled, reduce transport costs and increase the efficiency of meeting demand for each point in their research case.

In this research, the improvement proposal will be presented to save distribution and storage costs in the supply chain of vaccines against COVID-19 for Lima and Callao. The proposal will consist of two stages. The first stage consists of a clustering process for the location and use of secondary warehouses, and the second stage, consists of a mathematical model applied to a vehicle routing problem for the optimal distribution of vaccines from secondary warehouses to vaccination points. Its proposed to determine and select the facilities of the secondary warehouses of the comprehensive health network for each zonal division of Lima and Callao. The health centers, communitary health posts, and the headquarters of the health directions and the vaccination centers will be part of the new proposed supply chain. In addition, logistical aspects such as storage capacity and transport capacity, the cost associated with transport, storage costs and implementation costs will be tackled as well. Lastly, all virtual aspects related to COVID-19 vaccination were considered, such as the monthly demand for vaccines, the segmentation of the population into age ranges, among others. Based on this, the current vaccination plan was analyzed, focusing on real data obtained in the North region of Lima. The objective of the

optimization proposal is to demonstrate the percentage of savings associated with costs and time in the distribution and storage of COVID-19 vaccines.

## 2 Methodology

### 2.1 Current Procedure

Presently, the vaccination system in Peru begins with the reception of vaccines from abroad, which are stored at the national supply addresses. Then, the vaccine is distributed to the different health directorates that are in charge of delivering the vaccines to the vaccination centers [17] in the areas assigned to them. There are five health directions that divide the capital into five zones: North Lima, East Lima, Central Lima, South Lima and Callao. Each of these is responsible for the distribution and storage of vaccines among the districts assigned to them. Figure 1 represents the vaccine supply chain for each area of Metropolitan Lima.

The current process has compromised the supply to meet the demand of each vaccination post, due to the limited response capacity and unplanned supply routes. According to the vaccination plan issued by the government [18], people from 12 to 39 years old, and those who are 40 years old or more laggards who were unable to vaccinate on the established dates, will be vaccinated between August and December this year. Therefore, the 18.7 million doses will be demanded and must be delivered during the respective periods to each of the vaccination points for each zone.

Figure 2 shows the monthly demand for each area. The demand reflects the population from 12 to 39 years old, information taken from CPI [19] where they estimate the number of people in Peru of this age group. On the other hand, the demand of the population aged 40 and over who had not received the first dose or the second dose was consider. The total population for the current year indicated by the INEI [20] for each district was use and the amount of doses applied in each of these was subtracted according to the government website [21].

With the current vaccination system, there are high costs for supplying vaccination centers. The demand from August to December will be up to 250% more than in the previous months. The cost of transportation is high because spacious units are required to be able to distribute from the Health Direction to all the vaccination

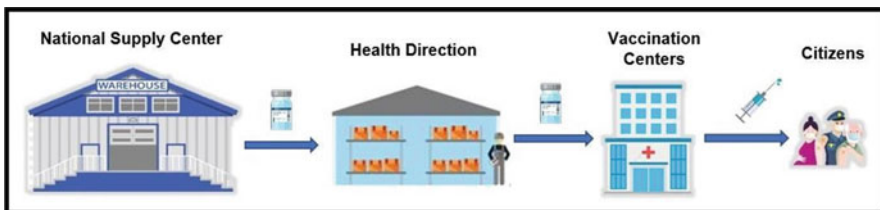


Fig. 1 Current Covid-19 Vaccine Supply Chain

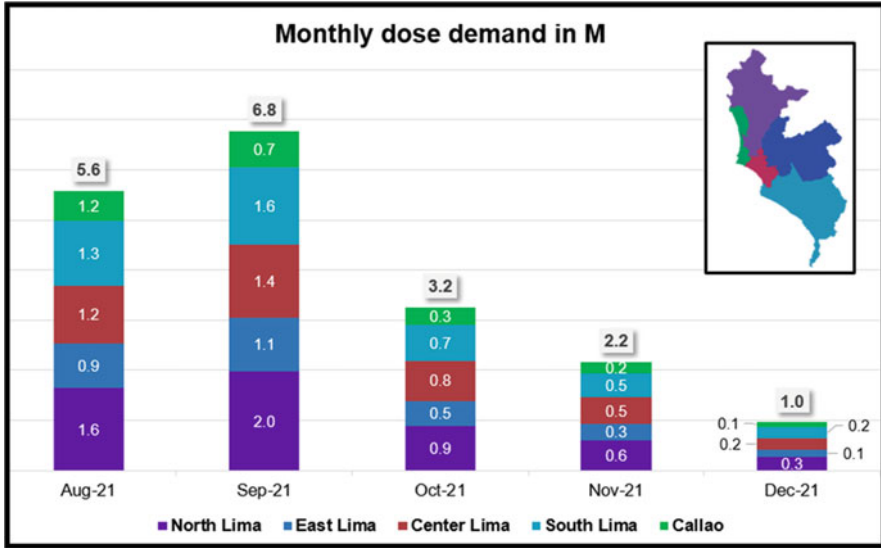


Fig. 2 Monthly dose demand

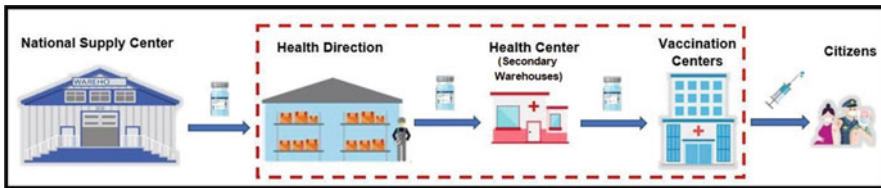


Fig. 3 Proposed supply chain for Covid-19 vaccines

points in each area, which leads to traveling for long stretches incurring cost overruns for not accelerating the rotation rate of the vaccinations and the cost of rescheduling trips to vaccination centers. The vaccination points demand a daily or inter-day supply and when evaluating a greater future demand there is a need to improve the vaccine distribution system in Metropolitan Lima.

### 2.2 Improvement Proposal

Based on the contributions of the referenced research and the analysis of the current situation, it was determined to include secondary warehouses in the supply chain, see Fig. 3.

For the optimal selection of secondary warehouses, the vaccination points were chosen to be in different areas of Metropolitan Lima, in order to find a geographic center. By applying the elbow method, performed in Python, it was possible to

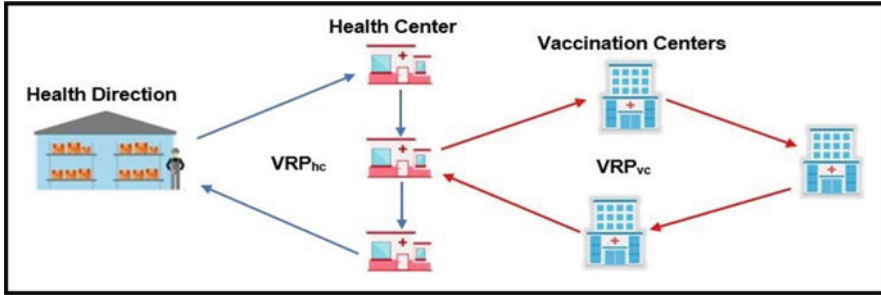


Fig. 4 Generic Net for CVRP application

determine the number of clusters needed for each zone and thus the number of centroids required. The health center or health post with the shortest distance from the centroid was chosen as the secondary warehouse. However, due to the dispersion of the vaccination points, there were some isolated cases from the rest of the points that were assigned to other clusters in order to determine the distribution network. As a result, two distribution networks are obtained: The main distribution network in which the Health Direction distributes to the secondary warehouses and the distribution network of the secondary warehouses to the vaccination points belong to the same cluster. The second stage focused on finding the optimal route to be followed by the vehicle. As shown in Fig. 4, there will be a route that the vehicle must follow through each secondary warehouse used and thus the minimum distribution cost will be obtained.

Currently, the cost of storing vaccines in health centers ( $c_2$ ) is much lower than the cost of storing in health directions ( $c_1$ ), because the spaces proposed are not being used and that these centers provide care outside the facilities to avoid using closed spaces when caring for patients and thus prevent contagion of Covid-19.

$$c_1 * t_1 - (c_1 * t_2 + c_2 * t_3) = Savings$$

On the other hand, the cost of storing a vaccine in the health directions ( $c_1$ ) multiplied by the time it remains in it ( $t_1$ ) gives as a result the total cost of storing a vaccine. In contrast, in the improvement proposal, the storage time in the health direction ( $t_2$ ) will decrease with the help of the secondary warehouses, in which they will be stored for the required time ( $t_3$ ). To find the total cost of storage in the improvement proposal, the storage cost in the health directions ( $c_1$ ) will be multiplied by the time the vaccines will remain in these ( $t_2$ ) and the result will be added with the storage cost in the secondary warehouse ( $c_2$ ) multiplied by the time it will remain in it ( $t_3$ ), thus producing considerable cost savings, as shown in Fig. 5.

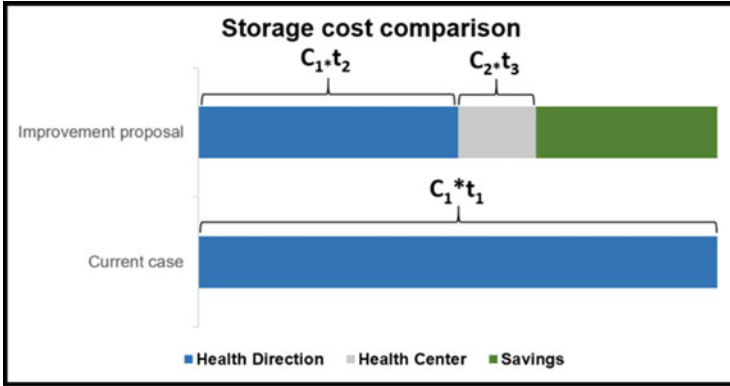


Fig. 5 Storage cost comparison

### 2.3 Mathematical Model

To optimize the use of the resources available to distribute vaccines, an optimization model is proposed in aims of minimizing costs of distribution and meet the demand of each vaccination center.

Below is each one of the parameters used in the optimization model:

- $x_{ij}$  is the binary decision variable defined to indicate if the vehicle traverses an arc  $(i, j)$
- $n$  is the number of vaccination centers
- $N$  is set of vaccination centers, with  $N = \{1, 2, \dots, n\}$
- $V$  is set of nodes, with  $V = \{0\} \cup N$
- $A$  is set of arcs, with  $A = \{(i, j) \in V^2 : i \neq j\}$
- $c_{ij}$  is cost of travel over arc  $(i, j) \in A$
- $Q$  is the vehicle capacity
- $q_i$  is the amount of vaccine cooler that has to be delivered to vaccination centers  $i \in N$

Based on the previously mentioned, the problem is presented by the following optimization model:

$$\text{Min } \sum_{i,j \in A} C_{ij} x_{ij} \tag{1}$$

Subject to:

$$\sum_{j \in V, j \neq i} x_{ij} = 1 \quad i \in N \tag{2}$$

$$\sum_{I \in V, i \neq j} x_{ij} = 1 \quad j \in N \tag{3}$$

$$\text{if } x_{ij} = 1 \rightarrow u_i + q_j = u_j \quad i, j \in A : j \neq 0, i \neq 0 \tag{4}$$

$$q_i \leq u_i \leq Q \quad i \in N \tag{5}$$

$$x_{ij} \in \{0, 1\} \quad i, j \in A \tag{6}$$

The objective function (1) minimizes the total costs for the routes chosen to meet the demand of the vaccination centers. The constraints (2) and (3) are the indegree and outdegree constraints for vaccination centers. Constraints (4) are the route continuity and sub-tour elimination constraints, ensuring that the solution contains no sub-tour disconnected from the depot, and that the vehicle load is a step function that accumulates the demand attended by the vaccination centers that are on the vehicle’s route. The constraints given in (5) are capacity bounding constraints that restrict the upper and lower bounds of  $u_i$  and constraints (6) are obligatory constraints.

### 3 Results

The results obtained by coding the elbow method in Python made it possible to determine the geographic locations of the secondary warehouses for each cluster. In this way, the cost of storage in each of these warehouses was calculated by using the estimated cost of these spaces and the amount of square meters that would be used to store the vaccines that will be distributed to each vaccination center.

The mathematical model was coded in CPLEX and supplemented with imported Python tools. Then, the cost of each arch between the nodes was estimated based on the average special cargo transportation rate, in dollars. Initially, the data from each vaccination point grouped in their respective clusters were evaluated, each one supplied by a secondary warehouse. Subsequently, the data from each secondary warehouse in each area was evaluated and the main headquarters of each Health Direction was taken as a reservoir. Both cases provided the costs associated with transportation and storage for each of the zones. In Callao, Central Lima, East Lima, North Lima and South Lima there were savings of 7.12%, 22.5%, 25.75%, 29.15% and 14.76% respectively. Figure 6 shows the monthly supply cost structure for Metropolitan Lima, showing the savings in dollars. Figure 7 shows the comparison of the current and proposed scenario for Central Lima, one of the areas that faces the greatest difficulty in terms of traffic and the time it takes to distribute the vaccines.

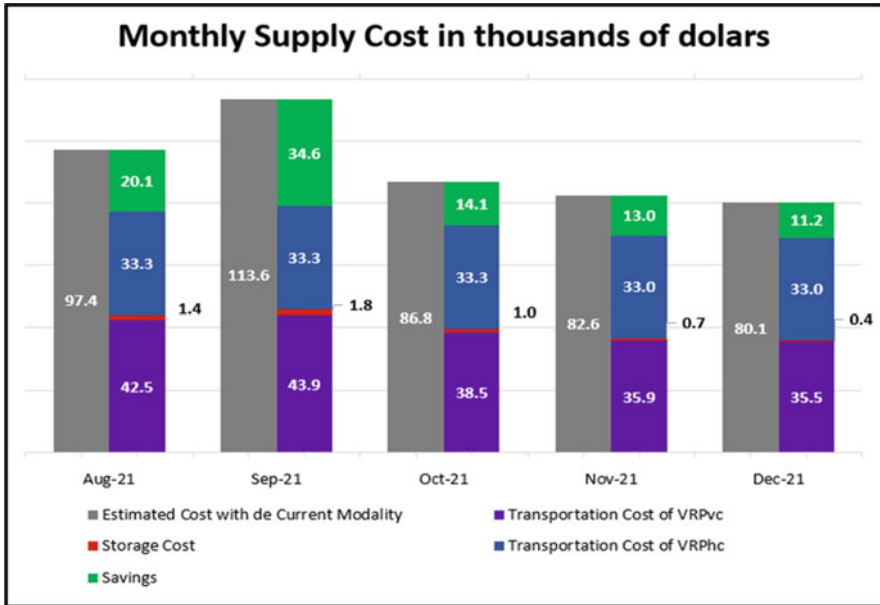


Fig. 6 Generic Net for CVRP application

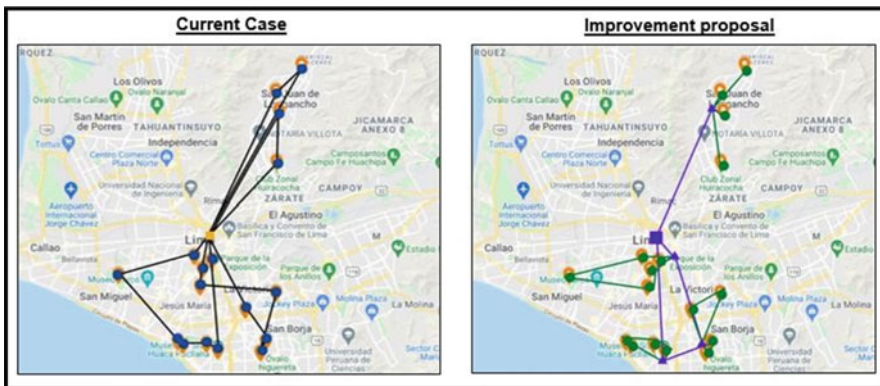


Fig. 7 Routing comparison in Central Lima

## 4 Conclusions

Based on the analysis, it can be concluded that the implementation of secondary warehouses in the Covid-19 vaccine supply chain in Metropolitan Lima increases response capacity and reduces costs associated with transportation and storage. This is the result of applying the elbow method to group vaccination sites and locate secondary warehouses in strategic geographic points; in addition to the application



of a vehicle routing problem model with limited capacity (CVRP) to determine the optimal route from each health direction to the final vaccination point of each cluster. The application of these two stages are operationally and economically feasible; However, it is important to note that if there are future variations due to the shortage of vaccines, the operational efficiency in the supply chain will have to be reorganized and re-evaluated. For future research, it would be relevant to analyze the variants of the proposed model in the face of atypical events and even develop a simulation model to control operational times and foresee a variation in time demands for the vaccination centers or a reduction in the number of vaccination centers.

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