A Proposed Air-land Distribution Network for Delivery of Emergency Supplies in Mexico

Ramon-Gabriel García-Martínez a, Tania-Lucero Reyes-Ortiz a, Gloria-Karina Herrera-Cortina b, Eduardo Belmonte-García b, Lizbeth Calihuá-Pacheco a and Santiago-Omar Caballero-Morales c*

a Tecnologico Nacional de Mexico – Instituto Tecnologico de Tehuacan, Libramiento Tecnológico S/N, A.P 247, Sta. María Coapan, 75770, Tehuacán, Puebla, Mexico.

b Instituto Tecnologico Superior de Perote, Carr. Federal México - Perote 140, 91270, Perote, Veracruz, Mexico.

c Universidad Popular Autonoma del Estado de Puebla A.C., C. 17 Sur 901, Barrio de Santiago, 72410, Puebla, Mexico.

Authors’ contributions
This work was carried out in collaboration among all authors. Author SOCM designed the study and coordinated the development activities. Authors RGGM, TLRO, GKHC, EBG and LCP performed the development activities and wrote the first draft of the manuscript. Author SOCM revised the final version of the manuscript. All authors read and approved the final manuscript.

Article Information
DOI: 10.9734/JERR/2022/v23i12770

ABSTRACT
Within logistics and the COVID-19 pandemic, the distribution of vaccines represented an important challenge as time was vital to attend the needs of the world population. This aspect involved an efficient the distribution chain between vaccine producers and consumers. For this purpose,
appropriate transportation infrastructure, analysis of demand rate, inventory planning, and vaccine distribution locations were needed. The present work proposes an air-land distribution network which can be adapted for the delivery of vaccines, or prompt delivery of other emergency resources. This network is aimed to decentralize the international reception of these goods through an alternative of main international airports which can connect to local airports to speed up their delivery. Then a land distribution network is designed to reach the final application centers. The results of the network on a test instance provided insights regarding the challenges and practical implications for a real implementation.

Keywords: Facility allocation; vehicle routing; distribution; supply chain management.

1. INTRODUCTION

A disturbing agent is defined as an aggressive and potentially harmful event, natural or derived from human activity, which can cause loss of life or injury, material damage, serious disruption of social and economic, life, or environmental degradation [1].

In 2020, the COVID-19 pandemic led to a global disturbing event which, as of 2022, caused 633,267,920 contagions and 6,602,669 deaths. The peak of deaths took place within the period of December 2020 and May 2021 [2]. The development and application of vaccines at the beginning of 2021 reduced the mortality rate of this infectious disease.

From the logistic point of view, the distribution of vaccines represented an important challenge as time was vital to attend the needs of the world population. To address this aspect, the distribution chain between producers to consumers requires efficient transportation infrastructure, analysis of demand rate and inventory planning, and the identification of suitable vaccine distribution locations [3].

This led to propose different supply chain models for the distribution of vaccines and reduce the mortality risk due to their untimely delivery to customers [4,5]. In this context, priority is a factor to define who should receive them first [6]. Extensive work has been reported on defining distribution schemes for vaccines. In [7] distribution planning considers the type of vaccines, allocation capacity within the vaccination center, and transportation between vaccination centers. In [8] a distribution model which considers locations, transportation modes and replenishment frequency is presented.

Hence, we contribute with an air-land distribution network which can be adapted for the delivery of vaccines, or prompt delivery of other emergency resources, in case of another disturbing event. The air-land proposal is aimed to decentralize the international reception of these goods through an alternative network of main international airports which can connect to local airports to speed up their delivery. Then, a land distribution can be performed to reach those locations aimed to their application (i.e., vaccine centers).

As such, the approach consists of the integration of two main logistic models:

a) An assignment model to identify which main airport is to connect to each local airport within a region;

b) A routing model to deliver the received goods to the application places.

2. METHODOLOGY

2.1 The Allocation Problem for the Airport Connections

First, it is important to define a priority metric to each destination within the considered region. In this case we considered Mexico and the statistics reported by its Federal Government for the three quarters (January to December) of 2020 regarding the percentage of infections for each state [9].

Between each quarter ($Q_1$, $Q_2$ and $Q_3$), we estimated the total growth rate $TGR$ as:

$$TGR = (Q_2 - Q_1) + (Q_3 - Q_2) + (Q_3 - Q_1)$$

(1)

We also computed the total percentage of cases $TC$ per state as:

$$TC = Q_1 + Q_2 + Q_3$$

(2)

Finally, we standardized the $TGR$ and $TC$ to determine which states have the highest growth...
rate and percentage of infections. These results are presented in Table 1.

As presented, the states of DISTRITO FEDERAL – CDMX, BAJA CALIFORNIA SUR, QUERETARO, DURANGO, SONORA and NUEVO LEON have the highest P. Coincidentally, in three of these states the vaccination started in January 2021. Also, in later research, CDMX, QUERETARO and NUEVO LEON were identified as the locations with the highest priority for distribution of COVID-19 vaccines [10].

By determining the priority P, we proceeded to identify the main airports in all 32 states. Particularly, the six states with highest P were considered as the main incoming points for vaccines, and thus, their airports were required to be international. For the remaining states, we did not consider this requirement as these are to be served by the main airports.

With this consideration, we proceeded to obtain the geographical coordinates of the most important airports for each of the 32 states in Mexico. This information is presented in Table 2 (where applicable, next to the state, the name of the airport is listed).

By obtaining the geographical coordinates, we computed the distances between the six main airports and the remaining secondary 26 airports. The distances were computed by considering the Euclidean distance:

\[ d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, \]

(3)

Where \( x_i \) and \( x_j \) are the x-coordinates (longitude) and \( y_i \) and \( y_j \) the y-coordinates (latitude) of the \( i \)-th main airport and the \( j \)-th secondary airports. These distances then were stored within a distance matrix which is presented in Table 3.

Table 1. % COVID-19 cases, growth rates, and priority metric each Mexican state in 2020

| State                              | 1Q  | 2Q  | 3Q  | TC     | TGR   | TC (St) | TGR (St) | P       |
|------------------------------------|-----|-----|-----|--------|-------|---------|----------|---------|
| DISTRITO FEDERAL - CDMX (Benito Juárez) | 0.10% | 1.11% | 2.70% | 3.91% | 5.20% | 0.1063 | 0.1352 | 0.2415 |
| BAJA CALIFORNIA SUR (Los Cabos)     | 0.04% | 0.94% | 1.28% | 2.26% | 2.48% | 0.0614 | 0.0645 | 0.1259 |
| QUERETARO                          | 0.01% | 0.29% | 1.17% | 1.47% | 2.32% | 0.0400 | 0.0603 | 0.1003 |
| DURANGO                            | 0.00% | 0.36% | 1.02% | 1.38% | 2.04% | 0.0375 | 0.0530 | 0.0906 |
| SONORA (Hermosillo)                | 0.01% | 1.01% | 0.80% | 1.82% | 1.58% | 0.0495 | 0.0411 | 0.0906 |
| NUEVO LEON (Monterrey)             | 0.01% | 0.54% | 0.96% | 1.51% | 1.90% | 0.0410 | 0.0494 | 0.0904 |
| COAHUILA (Torreón)                 | 0.01% | 0.69% | 0.89% | 1.59% | 1.76% | 0.0432 | 0.0458 | 0.0890 |
| ZACATECAS                          | 0.01% | 0.32% | 0.95% | 1.28% | 1.88% | 0.0348 | 0.0489 | 0.0837 |
| GUANAJUATO                          | 0.01% | 0.54% | 0.83% | 1.38% | 1.64% | 0.0375 | 0.0426 | 0.0802 |
| SAN LUIS POTOSI                    | 0.01% | 0.68% | 0.77% | 1.46% | 1.52% | 0.0397 | 0.0395 | 0.0792 |
| TABASCO                            | 0.05% | 1.08% | 0.62% | 1.75% | 1.14% | 0.0476 | 0.0296 | 0.0772 |
| AGUASCALIENTES                    | 0.02% | 0.39% | 0.80% | 1.21% | 1.56% | 0.0392 | 0.0406 | 0.0735 |
| CHIHUAHUA                          | 0.02% | 0.26% | 0.73% | 1.01% | 1.42% | 0.0275 | 0.0369 | 0.0644 |
| YUCATAN ( Mérida)                  | 0.03% | 0.66% | 0.51% | 1.20% | 0.96% | 0.0328 | 0.0250 | 0.0576 |
| COLOMBIA (Mar del Plata)           | 0.00% | 0.50% | 0.52% | 1.02% | 1.04% | 0.0277 | 0.0270 | 0.0548 |
| TAMAULIPAS (Tampico)               | 0.02% | 0.69% | 0.43% | 1.14% | 0.82% | 0.0310 | 0.0213 | 0.0523 |
| BAJA CALIFORNIA (Tijuana)          | 0.06% | 0.43% | 0.50% | 0.99% | 0.88% | 0.0269 | 0.0229 | 0.0498 |
| HIDALGO                            | 0.01% | 0.34% | 0.46% | 0.81% | 0.90% | 0.0220 | 0.0234 | 0.0454 |
| MEXICO (Toluca)                    | 0.03% | 0.40% | 0.44% | 0.87% | 0.82% | 0.0236 | 0.0213 | 0.0450 |
| TLAXCALA (Puebla)                  | 0.02% | 0.48% | 0.35% | 0.85% | 0.66% | 0.0231 | 0.0172 | 0.0403 |
| QUINTANA ROD (Cancún)              | 0.06% | 0.57% | 0.31% | 0.94% | 0.50% | 0.0256 | 0.0130 | 0.0386 |
| MICHOACAN                          | 0.01% | 0.33% | 0.57% | 0.71% | 0.72% | 0.0193 | 0.0187 | 0.0380 |
| OAXACA                             | 0.00% | 0.36% | 0.35% | 0.71% | 0.70% | 0.0193 | 0.0182 | 0.0375 |
| SINALOA (Culiacán)                 | 0.04% | 0.51% | 0.31% | 0.86% | 0.54% | 0.0234 | 0.0140 | 0.0374 |
| JALISCO (Guadalajara)              | 0.01% | 0.25% | 0.38% | 0.64% | 0.74% | 0.0174 | 0.0192 | 0.0366 |
| PUEBLA                             | 0.01% | 0.42% | 0.31% | 0.74% | 0.60% | 0.0201 | 0.0156 | 0.0357 |
| GUERRERO (Acapulco)                | 0.01% | 0.41% | 0.31% | 0.73% | 0.60% | 0.0198 | 0.0156 | 0.0354 |
| NAYARIT (Tepic)                    | 0.01% | 0.39% | 0.22% | 0.62% | 0.42% | 0.0169 | 0.0109 | 0.0278 |
| CAMPECHE                           | 0.01% | 0.57% | 0.15% | 0.73% | 0.28% | 0.0198 | 0.0073 | 0.0271 |
| MORELOS (Cuernavaca)               | 0.03% | 0.24% | 0.26% | 0.53% | 0.46% | 0.0144 | 0.0120 | 0.0264 |
| VERACRUZ                           | 0.01% | 0.34% | 0.17% | 0.52% | 0.32% | 0.0141 | 0.0083 | 0.0225 |
| CHIAPAS (Tapachula)                | 0.00% | 0.12% | 0.03% | 0.15% | 0.06% | 0.0041 | 0.0016 | 0.0056 |
Table 2. List of main airports for the air-land distribution network

| State                                      | P     | x               | y               |
|--------------------------------------------|-------|-----------------|-----------------|
| DISTRITO FEDERAL - CDMX (Benito Juárez)    | 0.2415| -102.315981     | 21.70119        |
| BAJA CALIFORNIA SUR (Los Cabos)            | 0.1259| -116.97206      | 32.54137        |
| QUERETARO                                  | 0.1003| -109.719407     | 23.13894        |
| DURANGO                                    | 0.0906| -90.501945      | 19.81352        |
| SONORA (Hermosillo)                        | 0.0906| -92.373484      | 14.78834        |
| NUEVO LEON (Monterrey)                     | 0.0904| -105.969346     | 28.70441        |
| COAHUILA (Torreón)                         | 0.0890| -103.399043     | 25.56329        |
| ZACATECAS                                  | 0.0837| -104.558423     | 19.14914        |
| GUANAJUATO                                  | 0.0802| -99.073493      | 19.43624        |
| SAN LUIS POTOSI                            | 0.0792| -104.533885     | 24.12657        |
| TABASCO                                    | 0.0772| -101.479376     | 20.99272        |
| AGUASCALIENTES                             | 0.0735| -99.755955      | 16.75895        |
| CHIHUAHUA                                  | 0.0644| -98.782594      | 20.07487        |
| YUCATAN (Mérida)                           | 0.0576| -103.307818     | 20.52583        |
| COLIMA (Manzanillo)                        | 0.0548| -99.570951      | 19.33933        |
| TAMAULIPAS (Tampico)                       | 0.0523| -101.028362     | 19.84584        |
| BAJA CALIFORNIA (Tijuana)                  | 0.0498| -99.261583      | 18.83282        |
| HIDALGO                                    | 0.0454| -104.839853     | 21.41645        |
| MEXICO (Toluca)                            | 0.0450| -100.108459     | 25.77745        |
| TLAXCALA (Puebla)                          | 0.0403| -96.7204        | 17.00071        |
| QUINTANA ROO (Cancún)                      | 0.0386| -98.375103      | 19.16574        |
| MICHOACAN                                  | 0.0380| -100.187243     | 20.62313        |
| OAXACA                                     | 0.0375| -86.874028      | 21.04154        |
| SINALOA (Cullacán)                         | 0.0374| -100.934258     | 22.25671        |
| JALISCO (Guadalajara)                      | 0.0366| -107.476645     | 24.76447        |
| PUEBLA                                     | 0.0357| -111.051778     | 29.08957        |
| GUERRERO (Acapulco)                        | 0.0354| -92.817644      | 17.9954         |
| NAYARIT (Tepic)                            | 0.0278| -97.869927      | 22.28986        |
| CAMPECHE                                   | 0.0271| -98.375103      | 19.16574        |
| MORELOS (Guemavaca)                        | 0.0264| -96.187044      | 19.14487        |
| VERACRUZ                                   | 0.0225| -99.660765      | 20.93386        |
| CHIAPAS (Tapachula)                        | 0.0056| -102.679613     | 22.90108        |

The distance matrix is used as source data for an allocation model which is to assign each of the secondary ports to its closest main port. This is to be solved with the following linear programming model:

\[
\text{Minimize} \sum_{i \in I} \sum_{j \in J} d_{ij} x_{ij}
\]

s.t.

\[
\sum_{i \in I} x_{ij} = 1, \quad \forall j \in J
\]

\[
x_{ij} \in \{0,1\} \quad \forall i \in I; \quad j \in J
\]

Where (4) represents the objective function which minimizes the total distance of assigning the main airports \(i\) to the secondary airports \(j\), (5) represents the constraint that each secondary airport must be assigned to only one main airport; and (6) defines the nature of the decision variable: \(x_{ij}\) is a non-negative binary variable, which is equal to "1" if the assignment is made between the main airport \(i\) and the secondary \(j\), and is equal to "0" otherwise.
Table 3. Distance matrix between the main and secondary airports for the air-land distribution network

|          | COA  | ZAC  | GUA  | SLP  | TAB  | AGU  | CHI  | YUC  | COL  | TAM  | BC   | HID  | MEX  | TLX  | QROO | MICH | OAX  | SIN  | JAL  | PUE  | GUER | NAY  | CAMP | MOR  | VER  | CHPS |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| DF-CDMX  | 4.01 | 3.40 | 3.96 | 3.29 | 1.10 | 5.57 | 3.89 | 1.54 | 3.62 | 2.26 | 4.19 | 2.54 | 4.64 | 7.31 | 4.69 | 2.39 | 15.46| 1.49 | 6.00 | 11.44| 10.20| 4.48 | 4.69 | 6.64 | 12.68| 1.25 |
| BJ SUR   | 15.26| 18.26| 22.18| 15.02| 19.32| 23.36| 22.05| 18.20| 21.84| 20.38| 22.40| 16.46| 18.17| 25.53| 22.91| 20.59| 32.22| 19.05| 12.27| 6.85 | 28.20| 21.68| 22.91| 24.73| 29.68| 17.24|
| QUER    | 6.77 | 6.52 | 11.27| 5.28 | 8.51 | 11.83| 11.36| 6.92 | 10.84| 9.29 | 11.31| 5.17 | 9.97 | 14.38| 12.02| 9.86 | 22.94| 8.83 | 2.77 | 6.10 | 17.67| 11.88| 12.02| 14.11| 20.18| 7.04 |
| DUR     | 14.12| 14.07| 8.58 | 14.68| 11.04| 9.75 | 8.28 | 12.83| 9.08 | 10.53| 8.81 | 14.43| 11.31| 6.83 | 7.90 | 9.72 | 3.83 | 10.71| 17.68| 22.55| 2.94 | 7.77 | 7.90 | 5.72 | 1.40 | 12.56|
| SON     | 15.42| 12.94| 8.15 | 15.33| 11.02| 7.64 | 8.31 | 12.35| 8.52 | 10.02| 7.99 | 14.12| 13.44| 4.88 | 7.43 | 9.75 | 3.33 | 11.36| 18.10| 23.52| 3.24 | 9.30 | 7.43 | 5.79 | 6.72 | 13.12|
| NL      | 4.06 | 9.66 | 11.55| 4.80 | 8.92 | 13.46| 11.23| 8.60 | 11.34| 10.14| 11.93| 7.37 | 6.55 | 14.92| 12.19| 9.94 | 20.58| 8.18 | 4.22 | 5.10 | 16.96| 10.33| 12.19| 13.68| 18.07| 6.67 |

Fig. 1. Lingo® code for the design of the land distribution routes between the airports and the application centers
While the model described by (4)-(6) is used to establish the airport connections, an extended version of the model can be used to define the allocation of vaccine locations to each main and secondary airport. Note that, in such case, demand and capacity data must be considered. To evaluate such scenario, we designed a test instance with 704 vaccination locations with homogeneous demand of 3000 doses. Regarding capacity, in January 2021, 550000 doses were received which were considered for distribution to five states [11]. This would lead to 110000 doses for each state which must be received at the main or secondary airport. This data also forms the basis for the next stage in the design of the distribution network which is explained in the next section.

### 2.2 The Routing Problem for Land Distribution

Once the capacity-restricted allocation between airports and vaccination points is achieved, we proceed to develop the land distribution planning. This is performed by vehicles of capacity = 30000 doses. In this case, the fleet may be dependent of the total number of doses required by the allocated vaccination points.

For solving the capacity-restricted route planning, the Vehicle Routing Problem (VRP) model provided by Lingo® was considered. The adapted code VROUTE is presented in Fig. 1. Note that all source data is stored in the Excel® file `databaseVRP.xlsx`. As presented in Fig. 2, the data associated to the locations for vaccine application, their demands, and the distance matrix are labelled to enable VROUTE to load and use them to design the routes of minimum distance.

### 3. RESULTS AND DISCUSSION

Solution of the model described by (4)-(6), the capacity-restricted allocation of airports to the 704 vaccination locations, and the capacity-restricted routing planning of vehicles to deliver the 3000 doses to these locations from the airports, were performed with different optimization tools.

Solution of the model described by (4)-(6), which consists of the airport connection between the main and the secondary airports, was obtained through the Solver tool of Excel® and the source data of Table 3. As presented in Table 4 and Fig. 3.

- The main airport of DF-CDMX connects the vaccine deliveries to 19 airports: Coahuila, Zacatecas, Guadalajara, San Luis Potosi, Tabasco, Aguascalientes, Chihuahua, Yucatán, Colima, Tamaulipas, Baja California, Hidalgo, Mexico, Quintana Roo, Michoacán, Sinaloa, Nayarit, Campeche and Chiapas;
- The main airport of Baja California Sur only receives vaccine deliveries for its own state;
- The main airport of Queretaro connects to the secondary airport of Jalisco;
- The main airport of Durango connects to Oaxaca, Guerrero, Morelos and Veracruz;
- The main airport of Sonora connects to Tlaxcala;
- The main airport of Nuevo Leon connects to Puebla.
Table 4. Allocation of secondary airports to main airports of the air distribution network

|      | COA | ZAC | GUA | SLP | TAB | AGU | CHI | YUC | COL | TAM | BC  | HID | MEX | TLX | QROO | MICH | OAX | SIN | JAL | PUE | GUER | NAY | CAMP | MOR | VER | CHPS |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|-----|-----|-----|-----|------|-----|------|-----|-----|------|
| DF-CDMX | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 0   | 1   | 0   | 1   | 0    | 0    | 1   | 1   | 0   | 1   | 1    | 0   | 0    | 1   |
| BJ SUR  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0   | 0   | 0   | 0   | 0    | 0   | 0    | 0   |
| QUER   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1    | 0    | 0   | 0   | 1   | 0   | 0    | 1   | 1    | 0   |
| DUR    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0    | 0    | 1   | 0   | 0   | 1   | 1    | 0   | 1    | 1   |
| SON    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1    | 0    | 0   | 0   | 0   | 0   | 0    | 0   | 0    | 0   |
| NL     | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0   | 1   | 0   | 0   | 0    | 0   | 0    | 0   |

Fig. 3. Visualization of the allocation of secondary airports to main airports of the air distribution network
### Table 5. Capacity-restricted allocation of application centers to all airports within the air distribution network

| DF-CDMX | 432 | 433 | 434 | 435 | 437 | 438 | 445 | 448 |
| BJ-SUR | 668 | 669 | 670 | 671 | 672 | 673 | 674 | 675 |
| QUER | 612 | 613 | 614 | 616 | 617 | 618 | 622 | 624 |
| DUR | 504 | 505 | 506 | 507 | 508 | 509 | 510 | 511 |
| SON | 21 | 22 | 24 | 25 | 26 | 27 | 28 | 29 |
| NL | 510 | 526 | 542 | 543 | 544 | 545 | 546 | 547 |
| COA | 252 | 253 | 256 | 264 | 350 | 360 | 382 | 363 |
| ZAC | 494 | 495 | 496 | 497 | 498 | 499 | 500 | 501 |
| GUA | 168 | 169 | 171 | 176 | 177 | 178 | 179 | 180 |
| SLP | 481 | 492 | 502 | 511 | 512 | 513 | 514 | 515 |
| TAB | 375 | 377 | 409 | 410 | 411 | 414 | 415 | 416 |
| AGU | 154 | 220 | 264 | 265 | |
| CHI | 88 | 91 | 92 | 99 | 109 | 117 | 152 | 157 |
| YUC | 431 | 439 | 446 | 450 | 451 | 455 | 456 | 457 |
| COL | 209 | 210 | 221 | 222 | 223 | 224 | 225 | 227 |
| TAM | 352 | 368 | 369 | 371 | 388 | 400 | 404 | 405 |
| BC | 173 | 175 | 207 | 213 | 216 | 230 | 232 | 241 |
| Hidalgo | 517 | 519 | 520 | 521 | 522 | 524 | 525 | 527 |
| MEX | 163 | 279 | 281 | 283 | 284 | 285 | 286 | 287 |
| TLX | 481 | 49 | 51 | 53 | 57 | 58 | 59 | 61 |
| ORO | 87 | 90 | 94 | 96 | 97 | 98 | 102 | 108 |
| Mich | 174 | 251 | 262 | 268 | 269 | 271 | 272 | 273 |
| OAX | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| SIN | 195 | 202 | 267 | 270 | 274 | 276 | 282 | 290 |
| JAL | 554 | 578 | 581 | 582 | 583 | 584 | 585 | 586 |
| PUE | 630 | 631 | 632 | 633 | 634 | 635 | 636 | 637 |
| GUER | 23 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
| NAY | 89 | 95 | 96 | 101 | 103 | 104 | 105 | 106 |
| CAMP | 47 | 50 | 52 | 54 | 55 | 56 | 60 | 62 |
| MOR | 47 | 50 | 52 | 54 | 55 | 56 | 60 | 62 |
| VER | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| CHPS | 358 | 359 | 373 | 376 | 378 | 380 | 385 | 386 |

130
| Airport | Route | Sequence of Vaccination Centers | Airport | Route | Sequence of Vaccination Centers |
|---------|-------|---------------------------------|---------|-------|---------------------------------|
| 1       | 1     | 433 435 437 434 432 438 448 445 1 | 19      | 19    | 279 289 287 283 286 288 284 183 19 |
| 1       | 2     | 668 674 676 673 681 685 689 688 683 682 2 | 2       | 19    | 281 292 325 318 319 317 307 313 308 298 19 |
| 2       | 1     | 672 696 699 704 700 697 702 701 703 698 2 | 3       | 19    | 285 316 314 323 315 321 324 320 302 301 19 |
| 3       | 2     | 675 677 679 678 671 670 669 2 | 4       | 19    | 297 304 306 305 300 299 293 296 294 19 |
| 4       | 1     | 680 687 686 692 690 694 695 693 691 684 2 | 5       | 20    | 48 67 66 70 59 64 65 58 53 51 20 |
| 3       | 3     | 617 618 616 613 614 612 3 | 6       | 20    | 49 115 113 112 111 110 100 84 71 68 20 |
| 3       | 4     | 624 625 622 627 628 629 669 661 662 3 | 7       | 20    | 64 63 57 20 |
| 4       | 1     | 5     | 21    | 22    | 24    | 26    | 28    | 29    | 43    | 27    | 25    | 5 |
| 5       | 1     | 526 544 543 546 551 552 550 545 542 6 |
| 6       | 2     | 547 549 548 576 577 596 596 580 565 6 |
| 7       | 3     | 555 572 567 573 575 574 571 561 562 553 6 |
| 8       | 4     | 558 562 563 569 559 560 558 510 6 |
| 9       | 5     | 284 420 419 418 417 422 403 374 367 7 |
| 10      | 6     | 270 488 490 483 491 493 479 475 476 470 7 |
| 11      | 7     | 393 384 370 360 362 363 256 253 252 7 |
| 12      | 8     | 497 505 506 507 509 501 8 |
| 13      | 4     | 499 500 498 496 495 494 8 |
| 13      | 9     | 168 177 179 181 185 192 187 217 221 212 9 |
| 13      | 10    | 171 178 189 191 190 186 184 169 9 |
| 14      | 11    | 176 182 188 193 201 211 200 197 194 9 |
| 15      | 12    | 180 215 199 203 198 218 219 214 208 204 9 |
| 16      | 13    | 280 377 424 425 429 428 421 416 415 11 |
| 17      | 14    | 409 410 411 11 |
| 18      | 15    | 125 220 264 265 12 |
| 19      | 16    | 128 91 92 170 165 167 164 163 157 117 109 13 |
| 20      | 17    | 166 196 206 205 226 247 245 248 152 193 12 |
| 21      | 18    | 143 451 456 460 458 467 478 468 476 463 14 |
| 22      | 19    | 143 459 465 486 487 503 504 455 450 446 14 |
| 23      | 20    | 147 459 466 472 482 484 485 471 464 462 14 |
| 24      | 21    | 210 224 250 257 258 254 243 15 |
| 25      | 22    | 223 235 234 240 244 239 237 231 229 221 15 |
| 26      | 23    | 225 249 260 259 261 263 266 280 275 255 15 |
| 27      | 24    | 238 228 236 242 233 222 227 208 15 |
| 28      | 25    | 352 371 388 400 408 397 369 16 |
| 29      | 26    | 407 413 412 440 442 441 430 427 404 368 16 |
| 30      | 27    | 173 207 213 234 232 230 246 216 175 17 |
| 31      | 28    | 18 528 529 527 536 534 533 531 532 530 28 18 |
| 32      | 29    | 18 528 529 527 536 534 533 531 532 530 28 18 |

García-Martínez et al., J. Eng. Res. Rep., vol. 23, no. 12, pp. 123-133, 2022; Article no.JERR.93947

| Airport | Route | Sequence of Vaccination Centers | Airport | Route | Sequence of Vaccination Centers |
|---------|-------|---------------------------------|---------|-------|---------------------------------|
| 33      | 1     | 30 47 60 72 75 78 79 80 81 82 86 30 |
| 34      | 2     | 30 50 54 56 30 |
| 35      | 1     | 69 62 85 83 77 74 76 73 55 52 30 |
| 36      | 2     | 31 19 31 |
| 37      | 1     | 32 376 380 389 387 386 385 378 373 359 358 32 |
| 38      | 2     | 32 401 402 398 397 395 396 390 391 394 392 32 |
| 39      | 1     | 32 423 444 449 447 443 436 32 |

131
Solution to the capacity-restricted allocation of airports to the 704 vaccination locations was obtained with Lingo®. For this case, all airports are considered to receive lots of 110,000 doses and each vaccination center is expected to require 3,000 doses. As presented in Table 5 and Fig. 4, there are two airports (the main airport of Durango, and the secondary airport of Campeche) which are not considered within the capacity-restricted allocation. Thus, these may be unnecessary international and connection airports within the proposed network.

Finally, solution to the capacity-restricted vehicle routing problem was obtained through the Lingo® code VROUTE described in Fig. 1. Note that this data was obtained from the solution of the capacity-restricted allocation of airports to the 704 vaccination locations (see Fig. 2). Table 6 presents the capacity-restricted routes (sequences of vaccination locations) for all airports.

4. CONCLUSION

As presented, the distribution of vital goods such as vaccines requires an integrated distribution network, which may need different transportation means (air, land). To achieve this, it is important to have different analysis tools, such as object-oriented programming and optimization software, operations research knowledge, and a multidisciplinary team.

The source data and results analysis required these multidisciplinary tools and skills for the development of the air-land distribution scheme. As first approach, there are opportunities for improvements, such as:

a) Integrate a forecast method to accurately define delivery times;
b) Provide more information to define the distribution costs;
c) Define the most suitable capacities for the airports according to the allocation results;
d) Improve the acquisition process of source data given the different elements of the supply chain;
e) Consider, within the last echelon of the supply chain, the personnel available to apply or deliver the received goods to the final customer.

ACKNOWLEDGEMENTS

The authors acknowledge the support received by Instituto Tecnologico de Tehuacan and its Department of Industrial Engineering and Logistics to develop the present work within the “Design of Distribution Networks” workshop at the 11th International Conference of Industrial Engineering and Logistics.

COMPETING INTERESTS

Authors have declared that no competing interests exist.
REFERENCES

1. Caballero-Morales SO, Barojas-Payan E, Sanchez-Partida D, Martinez-Flores JL. Extended GRASP-Capacitated K-Means Clustering Algorithm to Establish Humanitarian Support Centers in Large Regions at Risk in Mexico. Journal of Optimization. 2018;605298: 1-14.

2. Mathieu E, Ritchie H, Rodés-Guirao L, Appel C, Giattino C, Hasell J, Macdonald B, Dattani S, Beltekian D, Ortiz-Ospina E, Roser M. Coronavirus Pandemic (COVID-19). Our World in Data; 2022. Available: https://ourworldindata.org/coronavirus

3. Jacobson SH, Sewell EC, Proano RA. An analysis of the pediatric vaccine supply shortage problem. Health Care Management Science. 2006; 9(4):371–89.

4. Rastegar M, Tavana M, Meraj A, Mina H. An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic. Vaccine. 2021;39(3): 495-504.

5. Valizadeh J, Boloukifar S, Soltani S, Hooker EJ, Fouladi F, Rushchtc AA, Du B, Shen J. Designing an optimization model for the vaccine supply chain during the COVID-19 pandemic. Expert Systems with Applications. 2023; 214(119009):1-19.

6. Grauer J, Löwen H, Liebchen B. Strategic spatiotemporal vaccine distribution increases the survival rate in an infectious disease like Covid-19. Scientific Reports. 2020;10(21594): 1-10

7. Chen S, Norman BA, Rajgopal J, Assi TM, Lee BY, Brown ST. A planning model for the WHO-EPI vaccine distribution network in developing countries. IIE Transactions. 2014;46(8): 853-865.

8. Yang Y, Rajgopal J. An Iterative Cyclic Algorithm for Designing Vaccine Distribution Networks in Low and Middle-Income Countries. In Proc. of the International Joint Conference on Industrial Engineering and Operations Management-ABEPRO-ADINGOR-IIE-AIM-ASEM (IJCIEOM 2019). Novi Sad, Serbia, July 15-17, 2019.

9. GobMx. COVID-19 Tablero México - CONACYT - CentroGeo - GeoInt – DataLab. Gobierno de México - Información Covid-19 México, 2021. Accessed 18 February 2022. Available: https://datos.covid-19.conacyt.mx/#DownZCSV Spanish

10. Soria-Arguello I, Torres-Escobar R, Perez-Vicente HA, Perea-Rivera TG. A Proposal Mathematical Model for the Vaccine COVID-19 Distribution Network: A Case Study in Mexico. Mathematical Problems in Engineering. 2021;5484101: 1-11.

11. GobMx. Política Nacional Rectora de Vacunación contra el SARS-CoV-2 para la Prevención de la COVID-19 en México. Gobierno de México - Información Covid-19 México. Spanish; 2021.

© 2022 Garcia-Martinez et al.; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/93947