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A proposed air-land distribution network for delivery of emergency supplies in Mexico

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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.

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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].

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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.

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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

35 infrastructure, analysis of demand rate and inventory planning, and the identification of
36 suitable vaccine distribution locations [3].

37 This led to propose different supply chain models for the distribution of vaccines and reduce
38 the mortality risk due to their untimely delivery to customers [3, 4]. In this context, priority is a
39 factor to define who should receive them first [5].

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

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

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

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

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51 **2. METHODOLOGY**

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53 **2.1 The Allocation Problem for the Airport Connections**

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55 First, it is important to define a priority metric to each destination within the considered region.
56 In this case we considered Mexico and the statistics reported by its Federal Government for
57 the three quarters (January to December) of 2020 regarding the percentage of infections for
58 each state [6].

59

60 Between each quarter (Q1, Q2 and Q3), we estimated the total growth rate TGR as:

$$61 \quad \text{TGR} = (Q2-Q1)+(Q3-Q2)+(Q3-Q1) \quad (1)$$

62

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

$$64 \quad \text{TC} = Q1 + Q2 + Q3 \quad (2)$$

65

66 Finally, we standardized the TGR and TC to compute a final priority value $P = \text{TGR} + \text{TC}$ to
67 determine which states have the highest growth rate and percentage of infections. These
68 results are presented in Table 1.

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70 As presented, the states of DISTRITO FEDERAL – CDMX, BAJA CALIFORNIA SUR,
71 QUERETARO, DURANGO, SONORA and NUEVO LEON have the highest P. Coincidentally,
72 in three of these states the vaccination started in January 2021.

73

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

78

79 With this consideration, we proceeded to obtain the geographical coordinates of the most
80 important airports for each of the 32 states in Mexico. This information is presented in Table
81 2 (where applicable, next to the state, the name of the airport is listed).

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

State	Quarters 2020							P
	1Q	2Q	3Q	TC	TGR	TC (St)	TGR (St)	
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%	0.0329	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%	0.0326	0.0250	0.0576
COLIMA (Manzanillo)	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 ROO (Cancún)	0.06%	0.57%	0.31%	0.94%	0.50%	0.0256	0.0130	0.0386
MICHOACAN	0.01%	0.33%	0.37%	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

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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 (Culiacán)	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 (Cuernavaca)	0.0264	-96.187044	19.14487
VERACRUZ	0.0225	-89.660765	20.93386
CHIAPAS (Tapachula)	0.0056	-102.679613	22.90108

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

$$90 \quad d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, \quad (3)$$

91
 92 Where x_i and x_j are the x -coordinates (longitude) and y_i and y_j the y -coordinates (latitude) of
 93 the i -th main airport and the j -th secondary airports. These distances then were stored within
 94 a distance matrix which is presented in Table 3.

95
 96 Table 3. Distance matrix between the main and secondary airports for the air-land distribution
 97 network

	COA	ZAC	GUA	SLP	TAB	AGU	CHI	YUC	COL	TAM	BC	HID	MEX	TLX	GROO	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	8.33	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

98
 99
 100 The distance matrix is used as source data for an allocation model which is to assign each of
 101 the secondary ports to its closest main port. This is to be solved with the following linear
 102 programming model:

$$103 \quad \text{Minimize } \sum_{i \in I} \sum_{j \in J} d_{ij} x_{ij} \quad (4)$$

104 s.t.

$$105 \quad \sum_{i \in I} x_{ij} = 1, \quad \forall j \in J \quad (5)$$

$$106 \quad x_{ij} \in \{0,1\} \quad \forall i \in I; j \in J \quad (6)$$

107
 108 Where (4) represents the objective function which minimizes the total distance of assigning
 109 the main airports i to the secondary airports j , (5) represents the constraint that each secondary
 110 airport must be assigned to only one main airport; and (6) defines the nature of the decision
 111 variable: x_{ij} is a non-negative binary variable, which is equal to "1" if the assignment is made
 112 between the main airport i and the secondary j , and is equal to "0" otherwise.

113
 114 While the model described by (4)-(6) is used to establish the airport connections, an extended
 115 version of the model can be used to define the allocation of vaccine locations to each main
 116 and secondary airport. Note that, in such case, demand and capacity data must be considered.
 117 To evaluate such scenario, we designed a test instance with 704 vaccination locations with
 118 homogeneous demand of 3000 doses. Regarding capacity, in January 2021, 550000 doses
 119 were received which were considered for distribution to five states [7]. This would lead to
 120 110000 doses for each state which must be received at the main or secondary airport. This
 121 data also forms the basis for the next stage in the design of the distribution network which is
 122 explained in the next section.

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 124

125 2.2 The Routing Problem for Land Distribution

126

127 Once the capacity-restricted allocation between airports and vaccination points is achieved,
 128 we proceed to develop the land distribution planning. This is performed by vehicles of capacity
 129 = 30000 doses. In this case, the fleet may be dependent of the total number of doses required
 130 by the allocated vaccination points.

131

132 For solving the capacity-restricted route planning, the Vehicle Routing Problem (VRP) model
 133 provided by Lingo® was considered. The adapted code VROUTE is presented in Figure 1.
 134 Note that all source data is stored in the Excel® file 'databaseVRP.xlsx'. As presented in

135 Figure 2, the data associated to the locations for vaccine application, their demands, and the
 136 distance matrix are labelled to enable VROUTE to load and use them to design the routes of
 137 minimum distance.
 138

```

Lingo Model - Lingo1
MODEL:
! The Vehicle Routing Problem (VRP);
SETS:
CITY: Q, U;
CXC( CITY, CITY): DIST, X;
ENDSETS
DATA:
CITY=@OLE('databaseVRP.xlsx','vaccinelocations');
! city 1 represent the common depo;
Q = @OLE('databaseVRP.xlsx','vaccinedemands');
DIST = @OLE('databaseVRP.xlsx','locdistances');
! VCAP is the capacity of a vehicle ;
VCAP = 30000;
ENDDATA
    
```

139
 140 Figure 1. Lingo® code for the design of the land distribution routes between the airports and
 141 the application centers.
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	A	B	C	D	E	F	G	H	I	J	K	L
1	1	-102.31598	21.70119	0								
2	432	-102.27	21.852	3000								
3	433	-102.28	22.123	3000								
4	434	-102.29	21.889	3000								
5	435	-102.29	21.966	3000								
6	437	-102.31	21.897	3000								
7	438	-102.31	21.845	3000								
8	445	-102.58	21.43	3000								
9	448	-102.73	21.843	3000								
10												
11	0	15.51492	15.54064	15.53676	15.54093	15.55715	15.55453	15.80974	15.97395			
12	15.51492	0	0.27118	0.04206	0.11574	0.06021	0.04061	0.52363	0.46009			
13	15.54064	0.27118	0	0.23421	0.15732	0.22798	0.27961	0.75515	0.53			
14	15.53676	0.04206	0.23421	0	0.077	0.02154	0.04833	0.54294	0.4424			
15	15.54093	0.11574	0.15732	0.077	0	0.07184	0.12264	0.60942	0.45687			
16	15.55715	0.06021	0.22798	0.02154	0.07184	0	0.052	0.53943	0.42346			
17	15.55453	0.04061	0.27961	0.04833	0.12264	0.052	0	0.4951	0.42			
18	15.80974	0.52363	0.75515	0.54294	0.60942	0.53943	0.4951	0	0.4394			
19	15.97395	0.46009	0.53	0.4424	0.45687	0.42346	0.42	0.4394	0			
20												
21	2	-116.97206	32.54137	0								
22	668	-116.72	32.499	3000								
23	669	-116.75	32.473	3000								

144
 145
 146 Figure 2. Data labelling of the database for the Lingo® code.
 147
 148

149 **3. RESULTS AND DISCUSSION**

150
 151 Solution of the model described by (4)-(6), the capacity-restricted allocation of airports to the
 152 704 vaccination locations, and the capacity-restricted routing planning of vehicles to deliver
 153 the 3000 doses to these locations from the airports, were performed with different optimization
 154 tools.

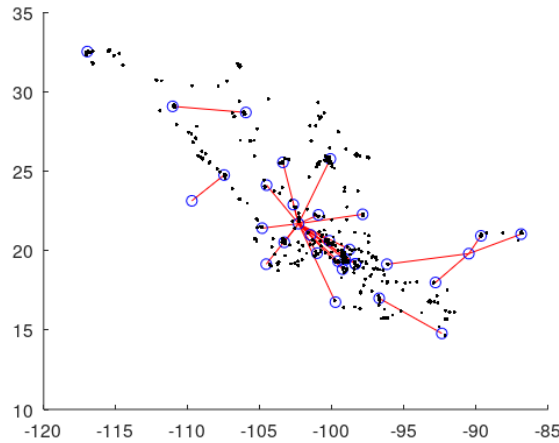
155 Solution of the model described by (4)-(6), which consists of the airport connection between
 156 the main and the secondary airports, was obtained through the Solver tool of Excel® and the
 157 source data of Table 3. As presented in Table 4 and Figure 3:

- 158 • the main airport of DF-CDMX connects the vaccine deliveries to 19 airports: Coahuila,
 159 Zacatecas, Guadalajara, San Luis Potosi, Tabasco, Aguascalientes, Chihuahua,
 160 Yucatán, Colima, Tamaulipas, Baja California, Hidalgo, Mexico, Quintana Roo,
 161 Michoacán, Sinaloa, Nayarit, Campeche and Chiapas;
- 162 • the main airport of Baja California Sur only receives vaccine deliveries for its own
 163 state;
- 164 • the main airport of Queretaro connects to the secondary airport of Jalisco;
- 165 • the main airport of Durango connects to Oaxaca, Guerrero, Morelos and Veracruz;
- 166 • the main airport of Sonora connects to Tlaxcala;
- 167 • the main airport of Nuevo Leon connects to Puebla.

168
 169 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	GROO	MICH	OAX	SIN	JAL	PUE	GUER	NAY	CAMP	MOR	VER	CHPS
DF-CDMX	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	0	0	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	0	0
QUER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
DUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	0
SON	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	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	0	1	0	0	0	0	0	0	0

170

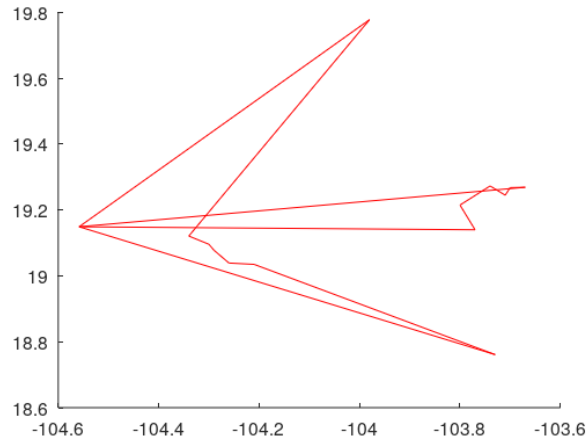


171
 172 Figure 3. Visualization of the allocation of secondary airports to main airports of the air
 173 distribution network.

174
 175 Solution to the capacity-restricted allocation of airports to the 704 vaccination locations was
 176 obtained with Lingo®. For this case, all airports are considered to receive lots of 110000 doses
 177 and each vaccination center is expected to require 3000 doses. As presented in Table 5 and
 178 Figure 4, there are two airports (the main airport of Durango, and the secondary airport of
 179 Campeche) which are not considered within the capacity-restricted allocation. Thus, these
 180 may be unnecessary international and connection airports within the proposed network.

181
 182 Finally, solution to the capacity-restricted vehicle routing problem was obtained through the
 183 Lingo® code VROUTE described in Figure 1. Note that this data was obtained from the
 184 solution of the capacity-restricted allocation of airports to the 704 vaccination locations (see
 185 Figure 2). For illustration purposes, Table 6 and Figure 5 presents the two routes obtained for
 186 the Zacatecas airport (8).

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Figure 5. Visualization of the capacity-restricted routes for the airport of Zacatecas (No. 8).

- 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.

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