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

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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.

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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,

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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:

$$TGR = (Q_2 - Q_1) + (Q_3 - Q_2) + (Q_3 - Q_1) \quad (1)$$

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

$$TC = Q_1 + Q_2 + Q_3 \quad (2)$$

Finally, we standardized the *TGR* and *TC* to compute a final priority value *P* = *TGR* + *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:

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

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

	Quarters 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%	0.0329	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

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

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:

$$Minimize\ \sum_{i\in I}\sum_{j\in J} d_{ij}x_{ij} \tag{4}$$

s.t.

$$\sum_{i\in I} x_{ij} = 1,\ \ \forall\, j \in J \tag{5}$$

$$x_{ij} \in \{0,1\}\ \ \forall i \in I;\ j \in J \tag{6}$$

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	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

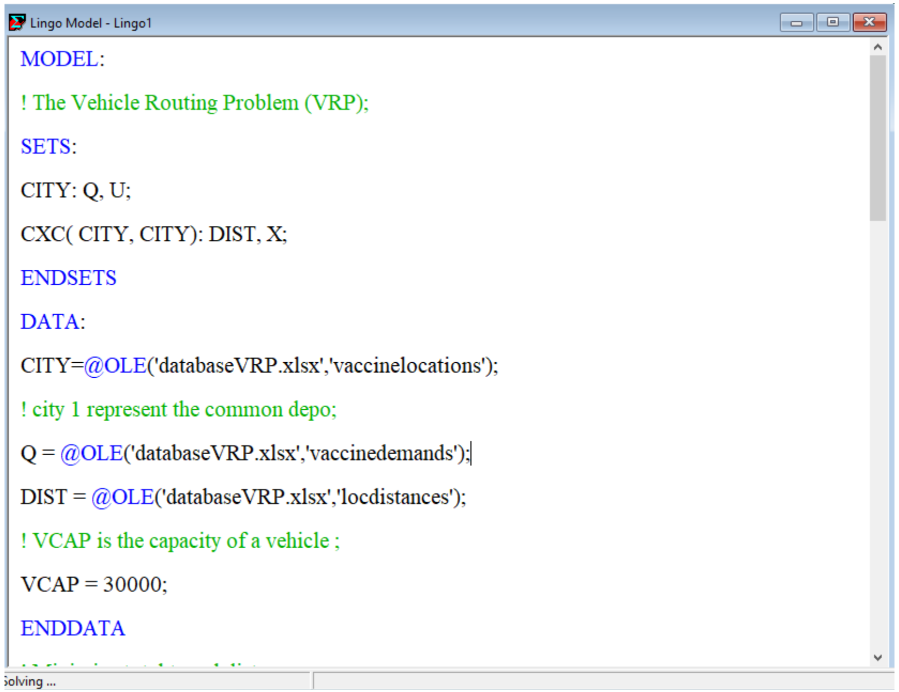
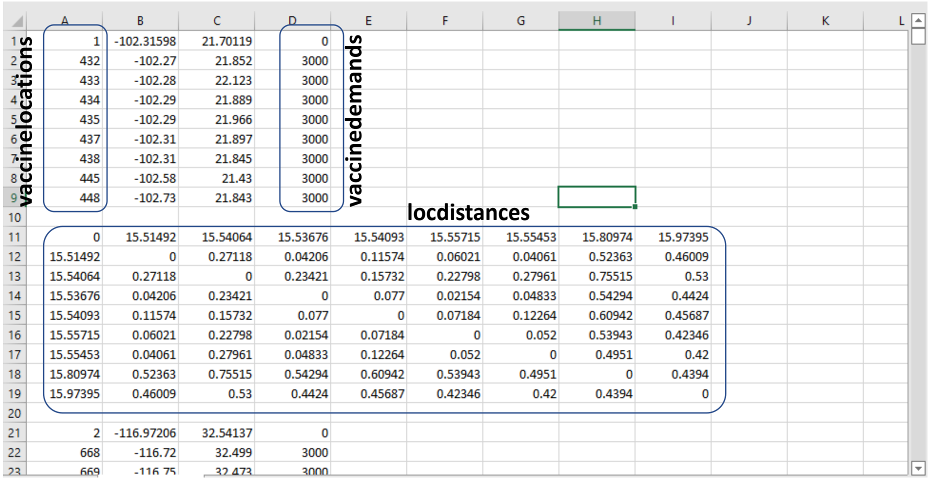


Fig. 1. Lingo® code for the design of the land distribution routes between the airports and the application centers



	A	B	C	D	E	F	G	H	I
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					

Fig. 2. Data labelling of the database for the Lingo® code

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	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	0	1	0	0	0	0	0	0

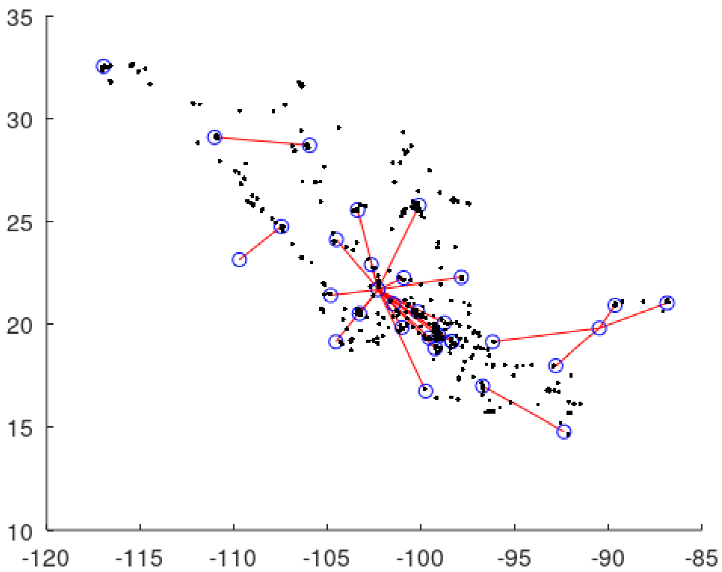


Fig. 3. Visualization of the allocation of secondary airports to main airports of the air distribution network

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	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	
QUER	612	613	614	616	617	618	622	624	625	627	628	629	661	662																								
DUR																																						
SON	21	22	24	25	26	27	28	29	43																													
NL	510	526	542	543	544	545	546	547	548	549	550	551	552	553	555	556	558	559	560	561	562	563	565	567	568	569	571	572	573	574	575	576	577	579	580	596	626	
COA	252	253	256	284	350	360	362	363	367	370	374	384	393	403	417	418	419	420	422	452	453	454	461	469	470	473	474	475	476	479	480	483	488	489	490	491	493	526
ZAC	494	495	496	497	498	499	500	501	505	506	507	508	509																									
GUA	168	169	171	176	177	178	179	180	181	182	184	185	186	187	188	189	190	191	192	193	194	197	198	199	200	201	203	204	208	211	212	214	215	217	218	219	221	
SLP	481	492	502	511	512	513	514	515	516	535	537	538	539	540	541	554	557	564	566	570																		
TAB	375	377	409	410	411	414	415	416	421	424	425	428	429																									
AGU	154	220	264	265																																		
CHI	88	91	92	99	109	117	152	157	163	164	165	166	167	170	196	205	206	226	245	247	248																	
YUC	431	439	446	450	451	455	456	457	458	459	460	462	463	464	465	466	467	468	471	472	477	478	482	484	485	486	487	503	504									
COL	209	210	221	222	223	224	225	227	228	229	231	233	234	235	236	237	238	239	240	242	243	244	249	250	254	255	257	258	259	260	261	263	266	275	280			
TAM	352	368	369	371	388	400	404	405	406	407	412	413	427	430	440	441	442																					
BC	173	175	207	213	216	230	232	241	246																													
HID	517	518	519	520	521	522	523	524	525	527	528	529	530	531	532	533	534	536																				
MEX	183	279	281	283	284	285	286	287	288	289	291	292	293	296	297	298	299	300	301	302	304	305	306	307	308	313	314	315	316	317	318	319	320	321	323	324	325	
TLX	48	49	51	53	57	58	59	61	63	64	65	66	67	68	70	71	84	100	110	111	112	113	115															
QROO	87	90	94	96	97	98	102	108	116	118	122	123	124	126	127	128	129	136	151	155	156	158	159	160	161	162												
MICH	174	251	262	268	269	271	272	273	277	278	295	303	311	329	335	336	337	338	339	340	342	343	344	345	347	348	351	353	361	365	366	372						
OAX	1	2	3	4	5	6	7	8	9																													
SIN	195	202	267	270	274	276	282	290	294	309	310	312	322	326	327	328	330	331	332	333	334	341	346	349	354	355	356	357	358	364	379	381	382	383	399	408	426	
JAL	554	578	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	615	619	620	621	623	
PUE	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	662	663	664	665	666	667	668
GUER	23	30	31	32	33	34	35	36	37	38	39	40	41	42	44	45	46																					
NAY	89	93	95	101	103	104	105	106	107	114	119	120	121	125	130	131	132	133	134	135	137	138	139	140	141	142	143	144	145	146	147	148	149	150	153	172	174	
CAMP																																						
MOR	47	50	52	54	55	56	60	62	69	72	73	74	75	76	77	78	79	80	81	82	83	85	86															
VER	10	11	12	13	14	15	16	17	18	19	20																											
CHPS	358	359	373	376	378	380	385	386	387	389	390	391	392	394	395	396	397	398	401	402	423	436	443	444	447	449												

Table 6. Capacity-restricted routes for all airports

Airport	Route	Sequence of Vaccination Centers											
1	1	1	433	435	437	434	432	438	448	445	1		
2	1	2	668	674	676	673	681	685	689	688	683	682	2
	2	2	672	696	699	704	700	697	702	701	703	698	2
	3	2	675	677	679	678	671	670	669	2			
	4	2	680	687	686	692	690	694	695	693	691	684	2
3	1	3	617	618	616	613	614	612	3				
	1	3	624	625	622	627	628	629	661	662	3		
4	[redacted]												
5	1	5	21	22	24	26	28	29	43	27	25	5	
6	1	6	526	544	543	546	551	552	550	545	542	6	
	2	6	547	549	548	576	577	579	626	596	580	565	6
	3	6	555	572	567	573	575	574	571	561	562	553	6
	4	6	556	568	563	569	559	560	558	510	6		
7	1	7	284	420	419	418	417	422	403	374	367	7	
	2	7	350	488	490	483	491	493	479	475	476	470	7
	3	7	393	384	370	360	362	363	256	253	252	7	
	4	7	469	489	474	480	473	454	452	453	461	526	7
8	1	8	497	505	506	507	508	509	501	8			
	2	8	499	500	498	496	495	494	8				
9	1	9	168	177	179	181	185	192	187	217	221	212	9
	2	9	171	178	189	191	190	186	184	169	9		
	3	9	176	182	188	193	201	211	200	197	194	9	
	4	9	180	215	199	203	198	218	219	214	208	204	9
10	1	10	537	540	538	539	554	535	516	513	502	492	10
	2	10	541	570	557	566	564	511	514	515	512	481	10
11	1	11	375	377	424	425	429	428	421	414	416	415	11
	2	11	409	410	411	11							
12	1	12	154	220	264	265	12						
13	1	13	88	13									
	2	13	91	92	170	165	167	164	163	157	117	109	13
	3	13	166	196	206	205	226	247	245	248	152	99	13
14	1	14	431	451	456	460	458	467	478	477	468	463	14
	2	14	439	465	486	487	503	504	455	450	446	14	
	3	14	457	459	466	472	482	484	485	471	464	462	14
15	1	15	210	224	250	257	258	254	243	15			
	2	15	223	235	234	240	244	239	237	231	229	221	15
	3	15	225	249	260	259	261	263	266	280	275	255	15
	4	15	238	228	236	242	233	222	227	209	15		
16	1	16	352	371	388	400	405	406	369	16			
	2	16	407	413	412	440	442	441	430	427	404	368	16
17	1	17	173	207	213	241	232	230	246	216	175	17	
18	1	18	518	521	524	523	522	519	520	517	18		
	2	18	525	529	527	536	534	533	531	532	530	528	18

Airport	Route	Sequence of Vaccination Centers											
19	1	19	279	289	287	283	286	288	284	183	19		
	2	19	281	292	325	318	319	317	307	313	308	298	19
	3	19	285	316	314	323	315	321	324	320	302	301	19
	4	19	297	304	306	305	300	299	293	296	291	19	
20	1	20	48	67	66	70	59	61	65	58	53	51	20
	2	20	49	115	113	112	111	110	100	84	71	68	20
	3	20	64	63	57	20							
21	1	21	90	94	116	156	160	158	155	136	127	87	21
	2	21	96	97	108	126	123	122	118	102	21		
	3	21	124	128	129	151	161	159	162	98	21		
22	1	22	174	251	22								
	2	22	269	295	337	338	278	277	272	271	273	262	22
	3	22	311	329	344	345	351	336	340	335	343	303	22
	4	22	342	347	348	353	372	366	365	361	339	268	22
23	1	23	9	6	5	4	3	2	1	7	23		
24	1	24	202	358	356	341	333	330	326	327	282	267	24
	2	24	270	309	322	312	310	294	274	195	24		
	3	24	276	364	382	381	399	426	408	383	379	24	
	4	24	355	357	354	349	346	334	331	332	328	290	24
25	1	25	581	582	585	586	588	587	584	25			
	2	25	583	607	602	605	603	610	620	621	619	554	25
	3	25	589	594	593	592	590	598	599	601	595	591	25
	4	25	597	600	615	623	604	609	606	608	611	578	25
26	1	26	631	632	634	635	637	636	633	630	26		
	2	26	638	642	641	646	650	647	659	653	655	645	26
	3	26	639	643	644	648	656	654	658	657	651	640	26
	4	26	664	662	665	667	663	666	660	668	652	649	26
27	1	27	23	34	33	35	36	44	46	45	31	27	30
		32	40	41	42	39	38	37	27				
28	1	28	130	135	138	139	134	141	142	143	120	172	28
	2	28	137	133	121	125	131	119	95	114	93	89	28
	3	28	153	149	148	147	132	140	146	150	145	144	28
	4	28	174	107	104	101	106	105	103	28			
29	[redacted]												
30	1	30	47	60	72	75	78	79	80	81	82	86	30
	2	30	50	54	56	30							
	3	30	69	62	85	83	77	74	76	73	55	52	30
31	1	31	19	31									
	2	31	20	17	15	14	18	16	10	13	11	12	31
32	1	32	376	380	389	387	386	385	378	373	359	358	32
	2	32	401	402	398	397	395	396	390	391	394	392	32
	3	32	423	444	449	447	443	436	32				

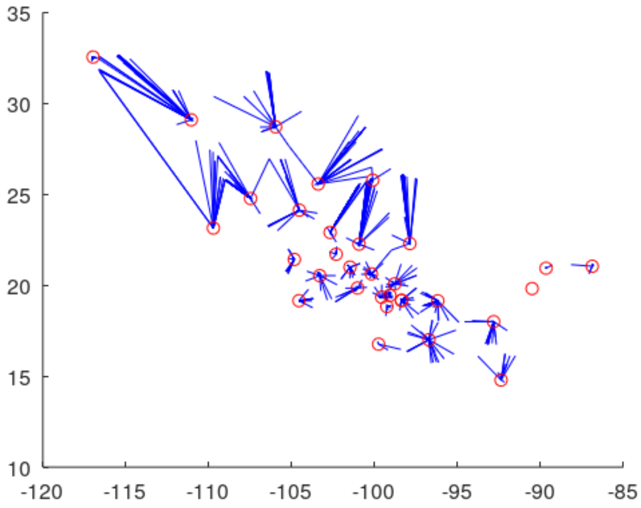


Fig. 4. Visualization of the capacity-restricted allocation of application centers to all airports within the air distribution network

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 110000 doses and each vaccination center is expected to require 3000 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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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