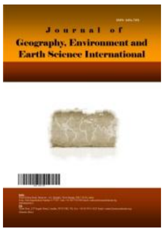

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Strategy for the Location of Shelters in Communities of High Seismic Risk in the Central-South Zone of Mexico

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Authors' contributions

This work was carried out in collaboration between both authors. Authors DSP and SOCM designed the study, performed the data analysis, developed the programming code for the two-stage solving approach and wrote the first draft of the manuscript. Author SOCM revised the final draft of the manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

Earthquakes cause diverse damages on human settlements, from disruption of services, collapse and destabilization of buildings, to the rise of diseases and death of people. Mexico is one of the countries with the highest risk of earthquakes given its location in the so-called "Ring of Fire" which registers the majority of telluric movements worldwide. In particular, the central-southern zone of Mexico has been severely affected by recent earthquakes. Since the greatest impact has been the immediate loss of housing and basic service infrastructure, a strategy is imperative to locate shelters that cover these needs during and after the seismic event until the affected housing and services are restored. Similarly, these shelters must have the capacity to receive the majority of the long-term affected population. Therefore, this paper develops a logistics strategy to locate these centers for the state of Puebla, which has been severely affected by these events. The strategy makes use of Weber's multiple location model which is solved using a nearest neighbor heuristic and mixed programming. The results provide coverage for high-risk areas that can be implemented in other regions of the country.

Keywords: Humanitarian logistics; facility location; weber problem; heuristics; natural disasters.

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1. INTRODUCTION

Due to its geographical location, climatic, orographic and hydrological characteristics, as well as its volcanic and seismic activity, Mexico is prone to the impact of a wide variety of natural phenomena with the potential to cause disasters. The negative consequences of these events are increased by the poor social and economic conditions that exist in large sectors of the population, which generates high levels of vulnerability in many regions of the country [1].

Natural disasters are measured by the economic and social impacts they generate, such as: injured people and deaths, houses, schools and hospitals damaged, among others. Frequently, the greatest effects are found in the most vulnerable and highly marginalized communities [2].

One of the most devastating events was the 1985 earthquake of 8.0 magnitude which caused nearly 5,000 – 45000 deaths, 3000 injuries and economic losses of more than 4.1 billion dollars. In 2017, another earthquake of 7.1 magnitude caused 369 deaths, 6000 injuries and losses of 3.3 billion dollars [2-4].

After the earthquake event, it is important to have an effective shelter infrastructure to reduce further damages to injured people and survivors. Note that this kind of infrastructure is nearly inexistent in most of the affected communities. Thus, research has been performed on shelter planning by using facility location models which are frequently used in logistics [5,6].

In this context, the present work contributes with a logistics strategy to locate these shelters in the state of Puebla, which has been severely affected by these events [4]. The strategy makes use of Weber's multiple location model which is solved using a nearest neighbor heuristic and mixed programming. The results provide coverage for high-risk areas that can be implemented in other regions of the country.

The paper is structured as follows: in Section 2 we extend on the seismic events in Mexico and the region under study; then, in Section 3 we review the features of the shelters; in Section 4 we present the details of our shelter location strategy, including data acquisition and the two-phase solution method; the results regarding shelter location and allocation of communities are presented and analyzed in Section 5; finally, our conclusions and future work are discussed in Section 6.

2. SEISMIC RISK IN MEXICO

Earthquakes are phenomena caused by movements of the Earth's crust which produce vibrations that can spread in various directions. Earthquakes in Mexico are mainly due to two types of movements:

- Subduction, which occurs when two plates collide at a convergent boundary and one plate is driven beneath the other, back into the Earth's interior. This happens along the coastal portion of the states of Jalisco and Chiapas;
- Transform fault, which occurs when two plates slide past each other, horizontally. This happens between the Pacific and North American plates through a lateral sliding movement [7].

The country is located in one of the most active seismic zones in the world, the Pacific "Ring of Fire", whose name is due to the high degree of seismicity resulting from the mobility of four tectonic plates: North American, Cocos, Rivera and the Pacific. In the last 200 years in Mexico there have been 75 relevant earthquakes due to the damages or losses they generated, of these, 60 had a magnitude greater than 7.0 [3,4,8].

In the state of Puebla, three regions of seismic risk have been identified (see Fig. 1) [8]:

- High Risk (113 municipalities): the epicenters are frequent and include communities such as Tehuacan, Acatlan, and Izucar de Matamoros.
- Medium Risk (53 municipalities): epicenters are less frequent and include communities such as San Martin Texmelucan, Cholula, Puebla, Oriental, Lara Grajales, Ciudad Serdan, Tecamachalco, Acatzingo and Atlixco.
- Low Risk (51 municipalities): epicenters are rare, such as Sierra Norte and Nororiental, Cuetzalan region, Teziutlan and Zacatlan.

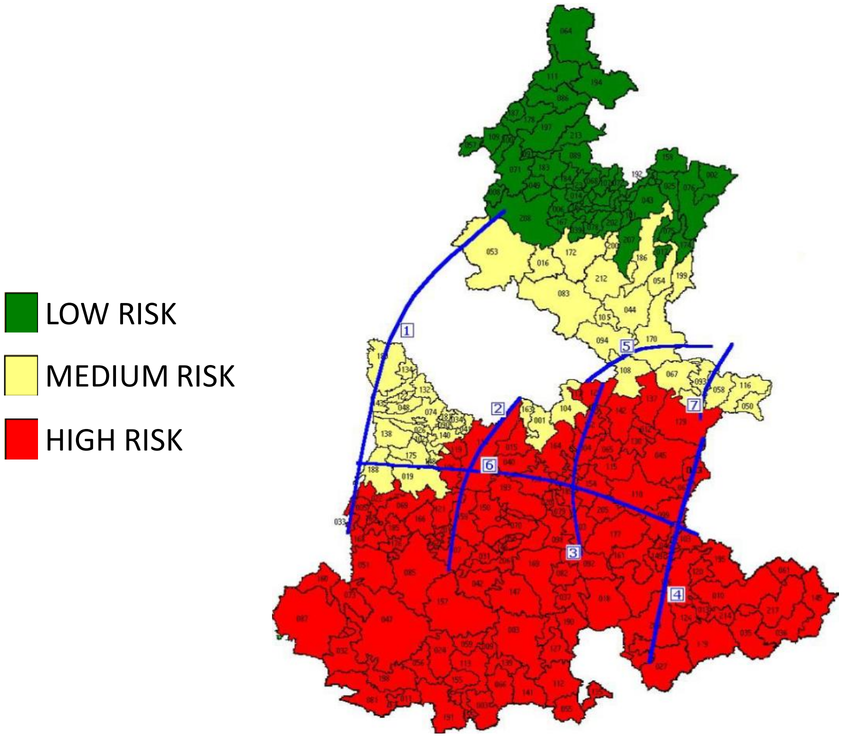

Fig. 1. Seismic Risks in the State of Puebla: Green – Low Risk, Yellow – Medium Risk, Red – High Risk (adapted from [8])

3. CHARACTERISTICS OF TEMPORARY SHELTERS

In Mexico, the term "Temporary Shelter" refers to the physical installation enabled to temporarily provide protection and well-being to people who do not have immediate possibilities of access to a safe room in case of imminent risk, an emergency or disaster [9].

One of the strategies established by the Ministry of the Interior, through the National Civil Protection System, consists of the installation of temporary shelters to provide shelter from inclement weather for the population when an emergency or disaster has occurred. These sites should be considered of great interest in terms of public health, because diseases are more prone to disseminate in reduced spaces with high population density [9].

The World Health Organization (WHO) recommends that ventilated and easily accessible spaces with a dimension of 3.5 m^2 or 10.0 m^3 per person should be guaranteed for emergency accommodation. Similarly, it must have infrastructure for food preparation, storage, collection, hygiene, and recreation, with the following supplies: drinking water, garbage dumps, cleaning material, non-perishable food, clothing and diapers, and medicines for infections [9].

4. SHELTER LOCATION STRATEGY

4.1 Analysis of Data

The first step in designing the strategy for the location of the shelters in the areas of greatest seismic risk is to collect the geographic and population information of the same. For this, public information available by the National Institute of Statistics and Geography (INEGI) was consulted regarding the number and name of the municipalities or communities in the state of Puebla and the most updated number of inhabitants in each of them [10]. The second step consists of identifying the geographical location of each municipality. To do this, the *Google Maps* © geolocation tool was used. Table 1 and Table 2 present this information for the municipalities in the areas of low/medium and high seismic risk respectively. As presented, the state capital Puebla is in the high-risk region, so are the municipalities of Tehuacan, Amozoc, Tepeaca and Izucar de Matamoros.

Table 1. Geographic location and population density in the low and medium risk zones of puebla [10]

Low Risk

#	Code	Community	Latitude	Longitude	Inhabitants
1	2	ACATENO	20.0845	-97.2570	9170
2	6	AHUACATLÁN	20.0069	-97.8550	14542
3	8	AHUAZOTEPEC	20.0448	-98.1620	11439
4	14	AMIXTLÁN	20.0494	-97.7991	4812
5	25	AYOTOXCO_DE_GUERRERO	20.0945	-97.4097	8208
6	28	CAMOCUAUTLA	20.0376	-97.7573	2758
7	29	CAXHUACAN	20.0662	-97.6112	3811
8	30	COATEPEC	19.4539	-96.9595	772
9	39	CUAUTEMPAN	19.9097	-97.7936	9837
10	43	CUETZALAN_DEL_PROGRESO	20.0179	-97.5251	49864
11	49	CHICONCUAUTLA	20.0923	-97.9392	17382
12	57	HONEY	20.2377	-98.2140	6687
13	64	FRANCISCO_Z._MENA	20.7301	-97.8496	17824
14	68	HERMENEGILDO_GALEANA	20.1203	-97.7421	7011
15	71	HUAUCHINANGO	20.1734	-98.0545	103946
16	72	HUEHUETLA	20.1051	-97.6256	17082
17	75	HUEYAPAN	19.8878	-97.4442	13080
18	76	HUEYTAMALCO	19.9413	-97.2894	27600
19	77	HUEYTLALPAN	20.0277	-97.6960	5951
20	78	HUITZILAN_DE_SERDÁN	19.9637	-97.6941	15928
21	80	ATLEQUIZAYAN	20.0129	-97.6252	2633
22	84	IXTEPEC	20.0234	-97.6460	6950
23	86	JALPAN	20.4766	-97.9427	12050
24	88	JONOTLA	20.0296	-97.5755	4457
25	89	JOPALA	20.1626	-97.6923	12131
26	91	JUAN_GALINDO	20.2163	-97.9946	9828
27	100	NAUPAN	20.2316	-98.1075	9310
28	101	NAUZONTLA	19.9608	-97.6018	3317
29	107	OLINTLA	20.1045	-97.6795	11993
30	109	PAHUATLÁN	20.2777	-98.1497	20274
31	111	PANTEPEC	20.5564	-97.8639	18528
32	123	SAN_FELIPE_TEPATLÁN	20.0908	-97.7963	3793
33	158	TENAMPULCO	20.1703	-97.4057	6743
34	162	TEPANGO_DE_RODRÍGUEZ	20.0041	-97.7972	4155
35	167	TEPETZINTLA	19.9677	-97.8411	10373
36	174	TEZIUTLÁN	19.8188	-97.3608	103583
37	178	TLACUILOTEPEC	20.3236	-98.0679	15977
38	183	TLAOLA	20.1366	-97.9246	20433
39	184	TLAPACOYA	20.1222	-97.8507	6422
40	187	TLAXCO	20.4224	-98.0303	4934
41	192	TUZAMAPAN_DE_GALEANA	20.0659	-97.5760	5924
42	194	VENUSTIANO_CARRANZA	20.5061	-97.6738	28395
43	197	XICOTEPEC	20.2817	-97.9498	80591
44	202	XOCHITLÁN_DE_VICENTE_SUÁREZ	19.9699	-97.6297	13025
45	204	YAONÁHUAC	19.8901	-97.4627	7926
46	207	ZACAPOAXTLA	19.8769	-97.5872	57887
47	208	ZACATLÁN	19.9409	-97.9581	87361
48	210	ZAPOTITLÁN_DE_MÉNDEZ	20.0035	-97.7161	5675
49	213	ZIHUATEUTLA	20.2523	-97.8877	11967
50	215	ZONGOZOTLA	19.9791	-97.7292	4539
51	216	ZOQUIAPAN	20.0062	-97.5954	2452

Medium Risk

#	Code	Community	Latitude	Longitude	Inhabitants
1	1	ACAJETE	19.1089	-97.9479	72894
2	4	ACATZINGO	18.9853	-97.7791	63743
3	16	AQUIXTLA	19.7953	-97.9363	9021
4	17	ATEMPAN	19.8368	-97.4572	29742
5	19	ATLIXCO	18.9075	-98.4370	141793
6	26	CALPAN	19.1033	-98.4616	15271
7	34	CORONANGO	19.1351	-98.2879	46836
8	38	CUAPIAXTLA	18.9149	-97.8254	10542
9	41	CUAUTLANCINGO	19.1110	-98.2561	137435
10	44	CUYOACO	19.6014	-97.6213	17139
11	48	CHIAUTZINGO	19.2073	-98.4787	22039
12	50	CHICHIQUILA	19.1995	-97.0663	26928
13	53	CHIGNAHUAPAN	19.8370	-98.0326	66464
14	54	CHIGNAUTLA	19.8135	-97.3891	35223
15	58	CHILCHOTLA	19.2535	-97.1840	21002
16	60	DOMINGO_ARENAS	19.1388	-98.4515	7982
17	67	GUADALUPE_VICTORIA	19.2810	-97.3406	18784
18	74	HUEJOTZINGO	19.1477	-98.4065	90794
19	83	IXTACAMAXTITLÁN	19.6233	-97.8146	25319
20	90	JUAN_C._BONILLA	19.1182	-98.3480	23783
21	93	LAFRAGUA	19.2887	-97.3044	7650
22	94	LIBRES	19.4626	-97.6914	37257
23	96	MAZAPILTEPEC_DE_JUÁREZ	19.1176	-97.7010	3176
24	102	NEALTICAN	19.0549	-98.4324	14075
25	104	NOPALUCAN	19.1990	-97.8100	32772
26	105	OCOTEPEC	19.5533	-97.6542	5077
27	108	ORIENTAL	19.3705	-97.6176	19903
28	116	QUIMIXTLÁN	19.2537	-97.1366	22855
29	117	RAFAEL_LARA_GRAJALES	19.2257	-97.8022	15952
30	119	SAN_ANDRÉS_CHOLULA	19.0445	-98.3023	154448
31	122	SAN_FELIPE_TEOTLALCINGO	19.2323	-98.5047	11063
32	125	SAN_GREGORIO_ATZOMPA	19.0100	-98.3422	9671
33	126	SAN_JERÓNIMO_TECUANIPAN	19.0150	-98.4006	6597
34	132	SAN_MARTÍN_TEXMELUCAN	19.2851	-98.4399	155738
35	134	SAN_MATÍAS_TLALANCALECA	19.3213	-98.5023	20974
36	136	SAN_MIGUEL_XOXTLA	19.1683	-98.3085	12461
37	138	SAN_NICOLÁS_DE_LOS_RANCHOS	19.0711	-98.4851	11780
38	140	SAN_PEDRO_CHOLULA	19.0733	-98.3275	138433
39	143	SAN_SALVADOR_EL_VERDE	19.2677	-98.5148	34880
40	148	SANTA_ISABEL_CHOLULA	18.9901	-98.3797	11498
41	163	TEPATLAXCO_DE_HIDALGO	19.0789	-97.9717	18854
42	170	TEPEYAHUALCO	19.4892	-97.4906	19200
43	172	TETELA_DE_OCAMPO	19.8166	-97.8062	27216
44	173	TETELES_DE_AVILA_CASTILLO	19.8561	-97.4544	6653
45	175	TIANGUISMANALCO	18.9775	-98.4459	14432
46	180	TLAHUAPAN	19.3388	-98.5738	41547
47	181	TLALTENANGO	19.1707	-98.3418	7425
48	186	TLATLAUQUITEPEC	19.7458	-97.5233	55576
49	188	TOCHIMILCO	18.8894	-98.5717	19315
50	199	XIUTETELCO	19.7914	-97.3239	42943
51	200	XOCHIAPULCO	19.8167	-97.6559	3443
52	211	ZARAGOZA	19.7685	-97.5520	16752
53	212	ZAUTLA	19.7198	-97.6886	20717

4.2 Analysis with Logistical Approach

Depending on the set of clients in an area of interest, it may be that a single facility or center does not have the capacity to cover them for a specific service. In this case, it is advisable to open a greater number of facilities or centers. In this context, this logistics scenario can be addressed using the multi-facility location model which has the following mixed programming model [11]:

$$\text{minimize } Z = \sum_{j=1}^{P} F_j y_j + \sum_{j=1}^{P} \sum_{i=1}^{N} c_{ij} x_{ij} \quad (1)$$

Subject to:

$$\sum_{i=1}^{N} d_i x_{ij} \le b_j,\ j = 1,\dots, P \quad (2)$$

$$\sum_{j=1}^{P} x_{ij} = 1,\ i = 1,\dots, N \quad (3)$$

$$x_{ij} \le y_j,\ i = 1,\dots, N \text{ and } j = 1,\dots, P \quad (4)$$

$$x_{ij}, y_j \in \{0,1\},\ i = 1,\dots,N \text{ and } j = 1,\dots, P \quad (5)$$

Table 2. Geographic location and population density in the high risk zone of Puebla [10]

#	Code	Community	Latitude	Longitude	Inhabitants
1	3	ACATLÁN	18.1943	-98.0438	37955
2	5	ACTEOPAN	18.7643	-98.7118	3070
3	7	AHUATLÁN	18.5673	-98.2563	3162
4	9	AHUEHUETITLA	18.2135	-98.2201	2207
5	10	AJALPAN	18.3785	-97.2690	74768
6	11	ALBINO_ZERTUCHE	18.0157	-98.5397	1885
7	12	ALJOJUCA	19.0971	-97.5321	6591
8	13	ALTEPEXI	18.3645	-97.2957	22629
9	15	AMOZOC	19.0477	-98.0680	125876
10	18	ATEXCAL	18.4009	-97.7342	3859
11	20	ATOYATEMPAN	18.8203	-97.9156	7704
12	21	ATZALA	18.5455	-98.5522	1512
13	22	ATZITZIHUACÁN	18.8201	-98.5809	12857
14	23	ATZITZINTLA	18.8964	-97.3265	9051
15	24	AXUTLA	18.1885	-98.3899	976
16	27	CALTEPEC	18.1821	-97.4800	4128
17	31	COATZINGO	18.6107	-98.1729	2820
18	32	COHETZALA	18.1942	-98.8069	1382
19	33	COHUECAN	18.7835	-98.7212	5403
20	35	COXCATLÁN	18.2595	-97.1548	20653
21	36	COYOMEAPAN	18.2844	-96.9910	14806
22	37	COYOTEPEC	18.4007	-97.8276	2334
23	40	CUAUTINCHÁN	18.9550	-98.0169	12340
24	42	CUAYUCA_DE_ANDRADE	18.4825	-98.1778	3315
25	45	CHALCHICOMULA_DE_SESMA	18.9776	-97.4465	47410
26	46	CHAPULCO	18.6092	-97.4114	8193
27	47	CHIAUTLA	18.3001	-98.6022	21699
28	51	CHIETLA	18.5176	-98.5754	37030
29	52	CHIGMECATITLÁN	18.6447	-98.0749	1215
30	55	CHILA	17.9734	-97.8665	5082
31	56	CHILA_DE_LA_SAL	18.1077	-98.4846	1317
32	59	CHINANTLA	18.2060	-98.2617	2846
33	61	ELOXOCHITLÁN	18.5023	-96.9545	14461
34	62	EPATLÁN	18.6450	-98.3724	4943
35	63	ESPERANZA	18.8576	-97.3740	14766
36	65	GRAL._FELIPE_ANGELES	18.9918	-97.7011	22694
37	66	GUADALUPE	18.0864	-98.1206	6451
38	69	HUAQUECHULA	18.7705	-98.5444	29233
39	70	HUATLATLAUCA	18.6760	-98.0507	6111
40	73	HUEHUETLÁN_EL_CHICO	18.3741	-98.6902	9760
41	79	SANTA_CLARA_HUITZILTEPEC	18.7675	-97.8822	5782
42	81	IXCAMILPA_DE_GUERRERO	18.0314	-98.6989	4065
43	82	IXCAQUIXTLA	18.4605	-97.8309	8804
44	85	IZÚCAR_DE_MATAMOROS	18.6002	-98.4652	82809
45	87	JOLALPAN	18.3234	-98.8442	13308
46	92	JUAN_N._MÉNDEZ	18.5194	-97.7220	5293
47	95	LA_M._TLATLAQUILOTEPEC	19.8462	-97.4962	650
48	97	MIXTLA	18.9086	-97.8918	2668
49	98	MOLCAXAC	18.7475	-97.9135	6668
50	99	CAÑADA_MORELOS	18.7379	-97.4205	20659
51	103	NICOLÁS_BRAVO	18.6146	-97.3047	6644
52	106	OCOYUCAN	18.9757	-98.2971	42669
53	110	PALMAR_DE_BRAVO	18.8356	-97.5472	50226
54	112	PETLALCINGO	18.0879	-97.9147	9350
55	113	PIAXTLA	18.1968	-98.2562	4627
56	114	PUEBLA	19.0387	-98.2019	1692181
57	115	QUECHOLAC	18.9544	-97.6611	57992
58	118	LOS_REYES_DE_JUÁREZ	18.9433	-97.8049	30021
59	120	SAN_ANTONIO_CAÑADA	18.4988	-97.2857	5938
60	121	SAN_DIEGO_LA_MESA_TOCHIMILTZINGO	18.8112	-98.3306	1270
61	124	SAN_GABRIEL_CHILAC	18.3280	-97.3469	15954
62	127	SAN_JERÓNIMO_XAYACATLÁN	18.2185	-97.9140	3606
63	128	SAN_JOSÉ_CHIAPA	19.2401	-97.7672	10443
64	129	SAN_JOSÉ_MIAHUATLÁN	18.2905	-97.2884	14018
65	130	SAN_JUAN_ATENCO	19.0852	-97.5391	3604
66	131	SAN_JUAN_ATZOMPA	18.7452	-98.0246	975
67	133	SAN_MARTÍN_TOTOLTEPEC	18.6516	-98.3455	692
68	135	SAN_MIGUEL_IXITLÁN	18.0015	-97.7737	526
69	137	SAN_NICOLÁS_BUENOS_AIRES	19.1646	-97.5539	10464
70	139	SAN_PABLO_ANICANO	18.1225	-98.0846	3759
71	141	SAN_PEDRO_YELOIXTLAHUACA	18.1165	-98.0765	3488
72	142	SAN_SALVADOR_EL_SECO	19.1347	-97.6400	30639
73	144	SAN_SALVADOR_HUIXCOLOTLA	18.9165	-97.7756	16790
74	145	SAN_SEBASTIAN_TLACOTEPEC	18.4080	-96.8014	13189
75	146	SANTA_CATARINA_TLALTEMPAN	18.6152	-98.0799	749
76	147	SANTA_INÉS_AHUATEMPAN	18.4128	-98.0193	6341
77	149	SANTIAGO_MIAHUATLÁN	18.5438	-97.4395	30309
78	150	HUEHUETLÁN_EL_GRANDE	18.7296	-98.1623	6105
79	151	SANTO_TOMÁS_HUEYOTLIPAN	18.8919	-97.8642	9315
80	152	SOLTEPEC	19.1249	-97.7144	12631
81	153	TECALI_DE_HERRERA	18.8995	-97.9729	23625
82	154	TECAMACHALCO	18.8806	-97.7328	80771
83	155	TECOMATLÁN	18.1086	-98.3131	6830
84	156	TEHUACÁN	18.4609	-97.4068	327312
85	157	TEHUITZINGO	18.3312	-98.2721	12672
86	159	TEOPANTLÁN	18.7129	-98.2627	3836
87	160	TEOTLALCO	18.4691	-98.7782	3689
88	161	TEPANCO_DE_LÓPEZ	18.5553	-97.5606	22218
89	164	TEPEACA	18.9723	-97.8987	84270
90	165	TEPEMAXALCO	18.7357	-98.6293	1216
91	166	TEPEOJUMA	18.7234	-98.4466	8918
92	168	TEPEXCO	18.6414	-98.6893	7523
93	169	TEPEXI_DE_RODRÍGUEZ	18.5781	-97.9259	22331
94	171	TEPEYAHUALCO_DE_CUAUHTEMOC	18.8137	-97.8768	3851
95	176	TILAPA	18.5959	-98.5545	9664
96	177	TLACOTEPEC_DE_BENITO_JUÁREZ	18.6789	-97.6478	54757
97	179	TLACHICHUCA	19.1136	-97.4192	31639
98	182	TLANEPANTLA	18.8626	-97.8854	5390
99	185	TLAPANALÁ	18.6964	-98.5337	10344
100	189	TOCHTEPEC	18.8405	-97.8237	22454
101	190	TOTOLTEPEC_DE_GUERRERO	18.2221	-97.8556	1187
102	191	TULCINGO	18.0452	-98.4219	9871
103	193	TZICATLACOYAN	18.8406	-98.0473	6476
104	195	VICENTE_GUERRERO	18.5427	-97.1996	26559
105	196	XAYACATLÁN_DE_BRAVO	18.2382	-97.9754	1570
106	198	XICOTLÁN	18.0605	-98.5250	1312
107	201	XOCHILTEPEC	18.6489	-98.3406	3375
108	203	XOCHITLÁN_TODOS_SANTOS	18.6987	-97.7734	7178
109	205	YEHUALTEPEC	18.7907	-97.6630	26392
110	206	ZACAPALA	18.5934	-98.0658	4647
111	209	ZAPOTITLÁN	18.3301	-97.4686	8595
112	214	ZINACATEPEC	18.3355	-97.2450	18359
113	217	ZOQUITLÁN	18.3325	-97.0192	20335

Note that j = 1,…, P which is the location index for the required facilities, where there are P possible locations available. Each location j has a capacity determined by b_j. i = 1,…, N is the customer index, where there are N customers. Each customer i has a given demand d_i, F_j is the cost of opening facility j, c_{ij} is the cost/time/distance to serve customer i from facility j, and y_j is a binary decision variable which has a value of "1" if facility j is opened, and has a value of "0" if contrary. On the other hand, x_{ij} is another binary decision variable that has value of "1" if customer i is assigned or served by facility j, and has a value of "0" otherwise.

In the context of our problem, P is defined as the number of shelters to establish, while N is the number of municipalities to cover in case of a seismic-type disaster. c_{ij} is determined as the distance in km between municipality i and shelter j. To do this, we will use the geographic arc length metric which requires the longitude and latitude coordinates of each community and refuge to estimate the distance in kilometers considering the dimensions of the Earth [12]. Regarding the capacity of the shelters, this is a matter of controversy since there is no standard for it. Also, not all inhabitants in a community are affected in the same way (only a fraction of the population effectively will require the use of the shelter). For this, we consider the most recent data regarding the earthquake of 7 and 19 of September of the year 2017, where an approximate of 12,000,000 people were affected by these events in 9 states: Chiapas, Oaxaca, Tabasco, CDMX and Mexico State, Tlaxcala, Hidalgo, Puebla, Morelos and Guerrero [13].

These damages do not only cover the aspect of housing, they also cover the interruptions of basic services (water, electricity), schools and culture. For this seismic event, the Federal Government reported for the state of Puebla the following statistics: 23,680 houses with partial damage, 3,214 houses with total damage, and 918 relocations [14]. Considering the houses with total damage and those that required relocation, and that on average there are 5 people per house, there is an approximate of (3,214+918) 5 = 20660 people in need for temporary and long-term shelter.

Taking as a reference the capacity limits for the shelters used to receive groups of migrants, a lower limit of 140 people was set [14,15]. In the same way, according to what was reported in [15], these shelters have shown an overcrowding of 180%, which establishes an upper bound of 252 people.

Considering the long-term use of these shelters during and after the seismic events, a bound of 260 people is established for b_j. It is worth mentioning that the shelters cannot be larger given that the high density of people in limited spaces favors the proliferation of diseases, gastrointestinal disorders and insecurity [9].

In general, for the state of Puebla in the high-risk area, approximately 20,660 / 260 = 80 shelters would be required. The number of people in this area is approximately 3,738,881. This provides a ratio of 20,660/ 3'738,881 = 0.05% of the population that can be affected in this type of events. Note that this calculation includes the capital in which, despite having the highest population density, is the one with the greatest resources to solve a disaster situation. The same happens with the municipalities of Amozoc and Tehuacan. Therefore, these three municipalities will not be considered in the assignment problem.

Finally, the estimation of d_i for each municipality i in the high-risk area is estimated as 0.05% of the population registered in it. For convenience, F_j is set to 1.0 for all shelters.

4.3 Solution Method for the Location Problem

The solution to the location problem consists of two stages:

- **Location:** determine the number and location of the centers (shelters) required to provide coverage
- **Allocation or Assignment:** determine the clients (communities) whose demand (inhabitants) will be covered by each center (shelter). A client must be covered by only one center. This allocation must meet the facility's capacity constraint.

These stages must be carried out in parallel, ensuring that the cost minimization criterion is met (in this case, distances between the shelters and the affected communities). Fig. 2 illustrates this iterative process of location and assignment as well as the tools used in each stage.

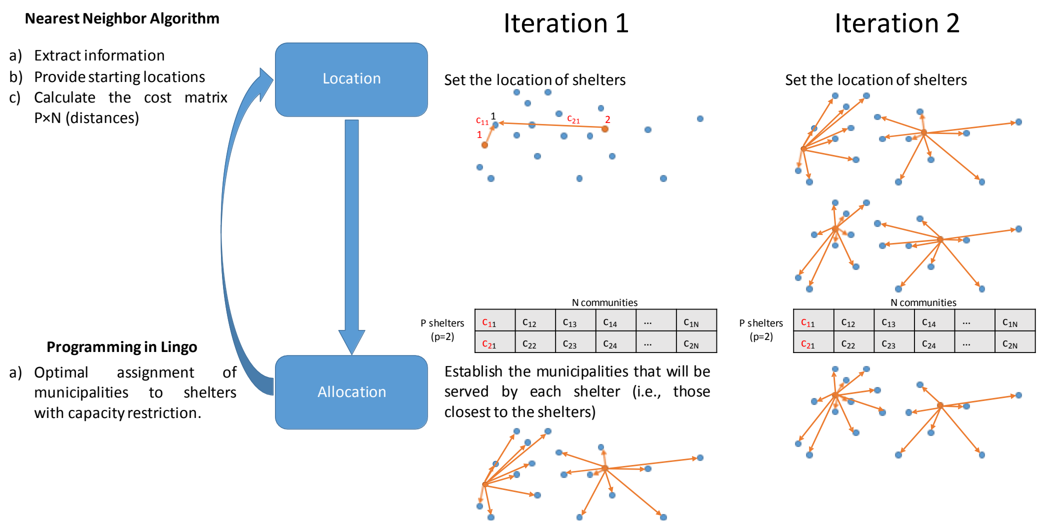

Fig. 2. Solution Strategy for the Problem of Location and Assignment of Municipalities and Shelters

Step 0: Obtain value for *P* (number of shelters) and b_j (capacity of each shelter *j*). Give random values to longitude (lon_j) and latitude (lat_j) coordinates for the *P* shelters

Step 1: Calculate the distance c_{ij} between each shelter *j* and community *i*. These distances will be stored in the distance matrix *D* of dimension *P*×*N*.

Step 2: Based on the information in *D*, assign to each shelter *j* the closest community *i*.

Step 3: Based on Weber's criterion of minimum distance, for each shelter *j*, determine its new location (lon_j, lat_j) considering the coordinates of the closest communities assigned to it (Simplex method).

Step 4: Repeat **Step 1**

Step 5: Carry out the optimal assignment of communities *i* to shelters *j* through mixed programming (LINGO) and considering the constraints of capacity b_j and demand d_i of each shelter and community, respectively.

Step 6: Iterate from **Step 3** until *S* = 10 iterations.

Fig. 3. Heuristic of Nearest Neighbor for the Problem of Location and Assignment of Municipalities and Shelters

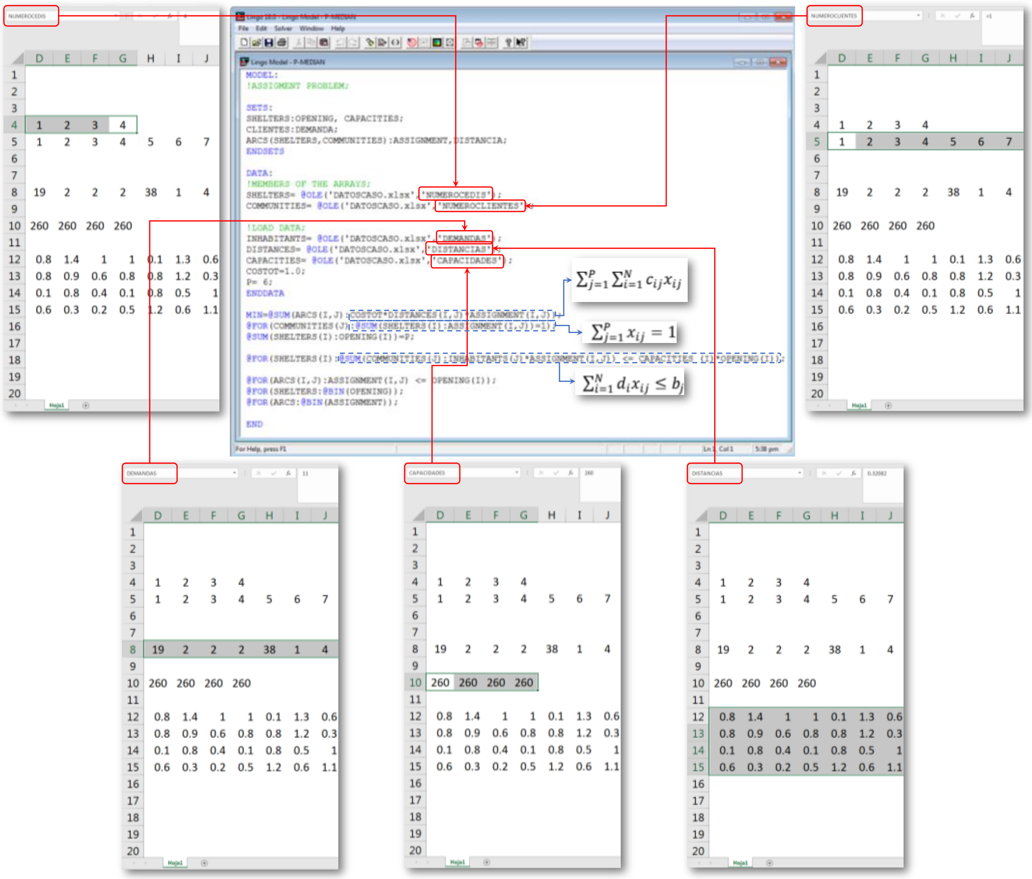

Fig. 4. Lingo Code for Optimal Allocation for the Communities and Shelters Location and Allocation Problem

4.3.1 Nearest neighbor

The nearest neighbor heuristic has the structure described by the steps in Fig. 3. This sequence of steps is performed in accordance with the strategy presented in Fig. 2. As can be seen, the heuristic has the objective of giving an initial (random) location to the shelters in order to later make a direct assignment (without capacity restriction). Based on this assignment, the distance matrix of the problem is calculated and the locations of the shelters are adjusted or updated. Weber's criterion is used to locate the facility where it minimizes the distance between it and its customers or communities. This problem is easily solved by the Simplex method.

Once the first location adjustment for the shelters has been made, the optimum community assignment is done according to the capacity restrictions of the shelters and the demands of the communities. From this assignment, the distance matrix calculation process, shelter location adjustment, and optimal assignment with capacity restriction are repeated.

4.3.2 Programming in lingo

Fig. 4 presents the Lingo code to solve the problem of optimal allocation of communities to shelters considering capacity and demand constraints.

5. RESULTS

The nearest neighbor heuristic was coded in Octave v4.4.1 while the assignment was done with Lingo v18.0. Both software were executed on a Z230 HP Wokstation with an Intel XEON processor at 3.40 GHz and 8GB RAM.

Based on the analysis in Section 4.2, it was determined that there are a total of 854 people in the high-risk communities (excluding the municipalities of Puebla, Tehuacan and Amozoc) who will require shelter in the short, medium and long term. This amount represents 0.05% of the total population in them. Regarding the level for the number of necessary shelters, it was estimated that 854/260 = 3.28 = 4 shelters.

Fig. 5 presents the results corresponding to each phase of the solution methodology. The final result, shown in Fig. 5(c), shows the shortcomings of only considering P=4 shelters with the capacity restriction (that is, communities closer to a shelter, due to lack of capacity, have to be assigned to shelters further away). Therefore, options with P = 5, 6 and 7 shelters were explored, obtaining the results shown in Fig. 6.

As can be seen, the solutions with P = 6 and P = 7 shelters maintain an allocation to the closest shelters without compromising capacity constraints. Considering the objective function criterion (equation 1), the solution with P = 7 shelters is the one that meets it (additional tests with more shelters increase the value of the objective function). Table 3 presents the details of this solution, including the geographical location of the shelters.

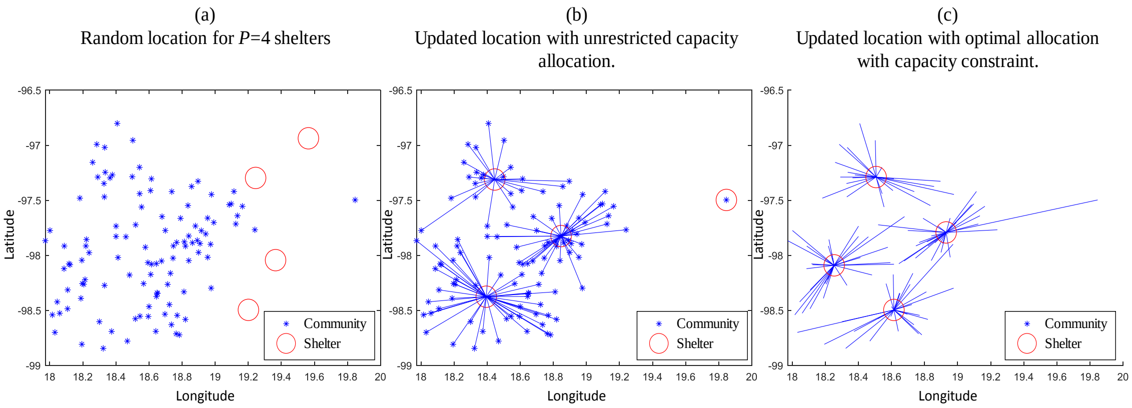

Fig. 5. Location and assignment for P=4 shelters in High Risk Zone: (a) random location, (b) locations adjusted based on unconstrained nearest neighbor direct assignment, (c) locations adjusted based on optimal assignment with demand and capacity constraints

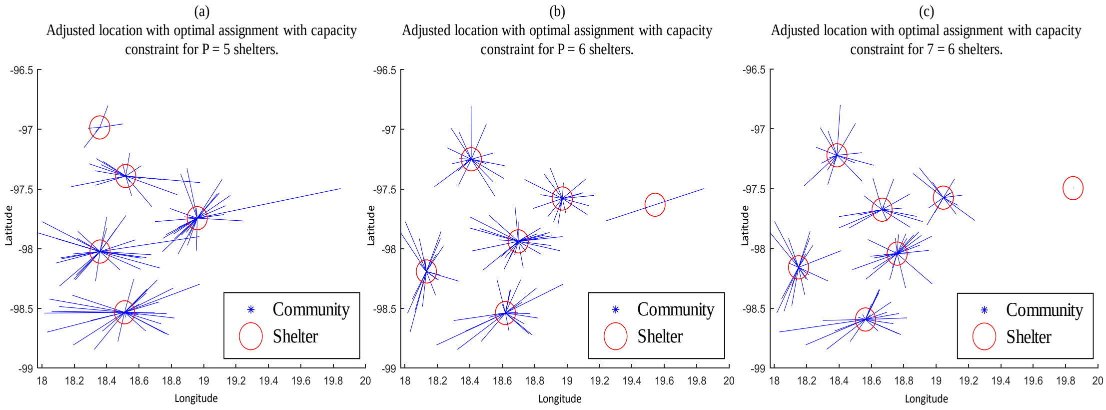

Fig. 6. Locations adjusted based on optimal allocation with demand and capacity constraints for: a) P = 5 shelters, b) P = 6 shelters, c) P = 7 shelters

Table 3. Geographic details of shelter locations and community names assigned to each one

Shelter	1	2	3
Lat	18.1499	18.5634	18.3872
Lon	-98.1585	-98.5945	-97.2215
Communities	ACATLÁN	ACTEOPAN	AJALPAN
	AHUEHUETITLA	ATZALA	ALTEPEXI
	ALBINO_ZERTUCHE	ATZITZIHUACÁN	CALTEPEC
	AXUTLA	COHETZALA	COXCATLÁN
	CHILA	COHUECAN	COYOMEAPAN
	CHILA_DE_LA_SAL	CHIAUTLA	ELOXOCHITLÁN
	CHINANTLA	CHIETLA	NICOLÁS_BRAVO
	GUADALUPE	EPATLÁN	SAN_ANTONIO_CAÑADA
	PETLALCINGO	HUAQUECHULA	SAN_GABRIEL_CHILAC
	PIAXTLA	HUEHUETLÁN_EL_CHICO	SAN_JOSÉ_MIAHUATLÁN
	SAN_JERÓNIMO_XAYACATLÁN	IXCAMILPA_DE_GUERRERO	SAN_SEBASTIAN_TLACOTEPEC
	SAN_MIGUEL_IXITLÁN	IZÚCAR_DE_MATAMOROS	SANTIAGO_MIAHUATLÁN
	SAN_PABLO_ANICANO	JOLALPAN	VICENTE_GUERRERO
	SAN_PEDRO_YELOIXTLAHUACA	SAN_MARTÍN_TOTOLTEPEC	ZAPOTITLÁN
	SANTA_INÉS_AHUATEMPAN	TEOTLALCO	ZINACATEPEC
	TECOMATLÁN	TEPEMAXALCO	ZOQUITLÁN
	TEHUITZINGO	TEPEOJUMA	
	TOTOLTEPEC_DE_GUERRERO	TEPEXCO	
	TULCINGO	TILAPA	
	XAYACATLÁN_DE_BRAVO	TLAPANALÁ	
	XICOTLÁN	XOCHILTEPEC	
Shelter	4	5	6
Lat	19.0447	18.6661	18.7593
Lon	-97.5754	-97.6765	-98.0436
Communities	ALJOJUCA	ATEXCAL	AHUATLÁN
	ATZITZINTLA	COYOTEPEC	ATOYATEMPAN
	CHALCHICOMULA_DE_SESMA	CHAPULCO	COATZINGO
	ESPERANZA	IXCAQUIXTLA	CUAUTINCHÁN
	GRAL._FELIPE_ANGELES	JUAN_N._MÉNDEZ	CUAYUCA_DE_ANDRADE
	QUECHOLAC	CAÑADA_MORELOS	CHIGMECATITLÁN
	LOS_REYES_DE_JUÁREZ	PALMAR_DE_BRAVO	HUATLATLAUCA
	SAN_JOSÉ_CHIAPA	SAN_SALVADOR_HUIXCOLOTLA	SANTA_CLARA_HUITZILTEPEC
	SAN_JUAN_ATENCO	TECAMACHALCO	MIXTLA
	SAN_NICOLÁS_BUENOS_AIRES	TEPANCO_DE_LÓPEZ	MOLCAXAC
	SAN_SALVADOR_EL_SECO	TLACOTEPEC_DE_BENITO_JUÁREZ	OCOYUCAN
	SOLTEPEC	TOCHTEPEC	SAN_DIEGO_LA_MESA_TOCHIMILTZINGO
	TLACHICHUCA	XOCHITLÁN_TODOS_SANTOS	SAN_JUAN_ATZOMPA
		YEHUALTEPEC	SANTA_CATARINA_TLALTEMPAN
			HUEHUETLÁN_EL_GRANDE
			SANTO_TOMÁS_HUEYOTLIPAN
			TECALI_DE_HERRERA
			TEOPANTLÁN
			TEPEACA
			TEPEXI_DE_RODRÍGUEZ
			TEPEYAHUALCO_DE_CUAUHTEMOC
			TLANEPANTLA
			TZICATLACOYAN
			ZACAPALA
Shelter	7		
Lat	19.8462		
Lon	-97.4962		
Communities	LA_M._TLATLAQUILOTEPEC		

6. DISCUSSION AND CONCLUSIONS

This methodology can be applied to other regions of the country (or other countries) to estimate the number of shelters needed to assist people in vulnerable situations, particularly without space to live in the short, medium and long term. Similarly, these shelters could be used for other assistance tasks such as stockpiling food or providing medical services in the absence of a natural disaster.

An additional contribution of the present project is that the population allocation and analysis can provide information to make a better estimate of the final capacity of the shelter. For example, Shelter 4 to which only the Tlatlaquilotepec community is assigned, may have a capacity of less than 260 (i.e., 100). Based on the results obtained, most of the estimated shelters would have an average occupancy of 180 spaces or 70.0%. This can help design more compact and functional shelters. This has been evident in the natural disasters of recent years, and the need for shelters for people made vulnerable by other situations (e.g., immigration for social and security reasons).

A limitation of this work is the value of F_j which was set to 1.0. A change in F_j can lead to significant changes in shelter location and allocation of communities. F_j can be a probability (from 0.0 to 1.0) or a cost (i.e., an opening cost which integrates construction materials and resources for appropriate maintenance). Here, we assumed the same probability and same opening costs because no economic data was available regarding regional building costs for these shelters. Also, transportation costs between these communities and shelters are unknown.

Thus, much work remains to be done because shelter planning is a complex task beyond the location / allocation processes. In example, control of indoor thermal environment may not be available in some communities [16]. Also, transportation infrastructure is important for the construction of the shelters and, in the event of disaster, transportation to/from the shelters and the communities. Particularly, route planning is another logistic aspect which is crucial for evacuation purposes [17].

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors."

COMPETING INTERESTS

Authors have declared that no competing interests exist**.**

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