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Transport logistics key in disaster situations: a case study in Mexico

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Abstract: Climate change has brought a significant series of environmental, economic, and social problems. An example is the disasters caused by natural phenomena, of which hydrometeorological phenomena stand out. The state of Veracruz is one of the five Mexican entities that has suffered most from these phenomena, and which is reflected in the number of emergency declarations by its municipalities. For this reason, it's essential to determine the location of humanitarian warehouses in Veracruz, to maintain the population's quality of life. With the objective of generating a strategy through which basic necessities can be supplied to victims, the Capacitated Vehicle Routing Problem is applied. This will allow for the establishment of a humanitarian warehouse located in the Altas Montañas (High Mountains) region to supply routes to 66 municipalities located in the aforementioned region together with the Capital Region, whose city governments have made emergency declarations during the period of 2012-2016. The results show 13 supply routes, with an average of 300 km traveled per route. In the normality assessments, the values of $p = 0.511$ for the kilometer variable and $p = 0.603$ for the time variable indicate that both variables do not significantly deviate from normality, suggesting that its distributions are normal.

1 Introduction

Logistic activity has increasing worldwide relevance, not only in the business and industrial fields, but also in social fields. It can be said that logistics is the tool through which an efficient and effective flow of resources and information is achieved as well as its integration with the activities along the supply chain, with the focus of strengthening and increasing levels of customer service. In the logistics field, the denomination humanitarian logistics is found (HL), which is derived from the concern in looking for solutions to diverse problems; among which are problems related to climate change, such as the presence, impact, and frequency of natural phenomena, which have also been a motive of interest of governments, organizations, and researchers all around the world.

For Gutiérrez-Guzmán et al. [1], humanitarian logistics refers to a logistics system dedicated to planning, implementation, and supervision of the storage and distribution of resources in areas affected by some type of crisis. Discussing climate change eludes to long-term changes in temperature and climate patterns; among the causes are: *a)* energy generation; *b)* product manufacturing; *c)* deforestation; *d)* use of transportation; *d)* food production; *e)* energy in buildings, and *f)* excessive consumption; thereby bringing consequences such as: 1. Rising temperatures; 2. More potent storms; 3. Increase in worldwide droughts; 4. Rise in ocean level and increasing water temperatures; 5. Disappearance of species; 6. Food scarcity; 7. Health risks, and 8. Poverty and displacement [2,3]. One of the main concerns of the foreseeable effects of climate change is the occurrence of disasters resulting from the combination of structural vulnerability and the incidence of hydrometeorological phenomena [4].

In this field, the United Nations Office for the Reduction of Disaster Risks [5] defines *disaster* as a serious interruption in the function of a society derived from threatening events that interact with conditions of vulnerability, exposure, and capacity, generating human, economic, material, and environmental losses and impact. The General Law of Civil Protection [6] mentions that *hydrometeorological phenomena* are disturbing agents generated by atmospheric agents such as tropical cyclones, extreme rains, floods, blizzards, hail, droughts, heat and cold waves, and tornados.

The National System of Civil Protection [SINAPROC] [7] mentions that Mexico is in an intertropical region which subjects it to being battered by hurricanes generated in the

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Atlantic Ocean as well as the Pacific. The impacts of these phenomena mostly affect the coastal zones of the Pacific, the Gulf of Mexico, and the Caribbean. During the period of 2000-2020 2,223 declarations were made by SINAPROC, which were divided in *a)* climatological contingency declaration, 18.58%; *b)* disaster declaration, 30.72%, and *c)* emergency declaration, 50.70%. 92.85% were caused by hydrometeorological phenomena [8,9]. It is worth mentioning that among the states that have municipalities with “very high” risk from this type of phenomena are the states of *Veracruz*, Chiapas, and Guerrero [10].

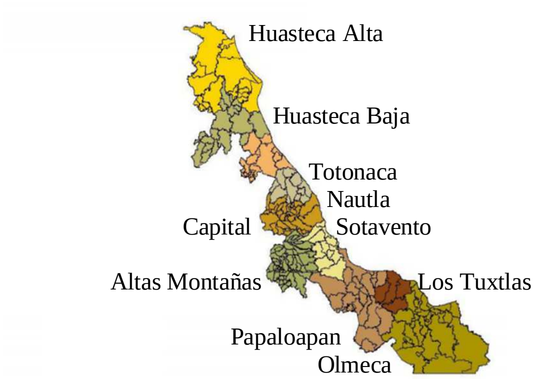
Problem approach

With a surface of 78,815 km^2, the state of Veracruz represents 3.7% of the surface of Mexican territory and is located in the central part of the slope of the Gulf of Mexico and is adjacent to the state of Tamaulipas in the north, San Luis Potosí, Hidalgo, and Puebla in the west, Oaxaca in the south, and Chiapas and Tabasco in the southeast. Veracruz has 212 municipalities with 8,062,579 inhabitants [11].

The regions that make up Veracruz and are considered in the Veracruz Development Plan [12] are (1) Huasteca Alta, (2) Huasteca Baja, (3) Totonaca, (4) Nautla, (5) Capital, (6) Sotavento, (7) Montañas, (8) Papaloapan, (9) Tuxtlas and (10) Olmeca. The location of Veracruz and its regions are shown in Table 1.

Table 1 State of Veracruz [13,14]

Location of the state of Veracruz	Regions of the state of Veracruz



Throughout time, due to its geographical location, the state of Veracruz has been frequently and strongly affected by hydrometeorological phenomena, which has given rise to the declaration of natural disasters to help people affected. An analysis carried out with data emitted by the National Fund of Natural Disasters (FONDEN) during the period of 2012-2016 depicted in Table 2 shows the *a)* number of municipalities that make up each of the regions that are in the state of Veracruz; *2)* name of the region; *3)* percentage of municipalities in each region; *4)* number of emergency declarations emitted by each region; *5)* percentage of declarations, and *6)* the compound factor between declarations and municipalities.

Table 2 Emergency declarations [15]

Number of municipalities	Region	Percentage municipalities	Number declarations	Percentage declarations	Factor declarations/municipalities
11	Nautla	5.19%	89.00	11.08%	8.09
15	Totonaca	7.08%	39.00	4.86%	2.60
18	Huasteca Baja	8.49%	73.00	9.09%	4.06
15	Huasteca Alta	7.08%	39.00	4.86%	2.60
33	Capital	15.57%	153.00	19.05%	4.64
57	Las Montañas	26.89%	172.00	21.42%	3.02
4	Los Tuxtlas	1.89%	24.00	2.99%	6.00
25	Olmeca	11.79%	122.00	15.19%	4.88
22	Papaloapan	10.38%	45.00	5.60%	2.05
12	Sotavento	5.66%	47.00	5.85%	3.92
212		100.00%	803.00	100.00%	

We can see that the largest number of declarations is in the region of Las Montañas, followed by the capital region, regions that also have the largest number of municipalities, 26.89%, and 15.57% respectively, and that are next to each other. For the effects of this investigation, it is worth mentioning that Mexico has a social supply distribution network for communities with marginalized conditions. The state of Veracruz has three units of this network, through which service is given to the municipalities and communities with stores that have different characteristics derived from the supply zone, characteristics that make them apt to function as a humanitarian warehouse in case of disaster.

The aforementioned is why this investigation, cataloged as a case study, hopes to develop from a social supply unit in the Altas Montañas region and as of now we will call this unit a humanitarian supply warehouse, as well as the routing of vehicles through which products will be supplied to people affected by natural disasters in the Altas Montañas and capital regions in the state of Veracruz. The declaration of emergencies emitted during the period of 2012-2016 by FONDEN is used as a foundation for analysis of supply zones and victims.

The research is divided into four parts, the introduction, a revision of the literature, where a series of investigations that deal with and give solutions to the routing problem through different methods and combinations are presented. Finally, the conclusions are presented to finalize the study with consulted sources for the development of the manuscript.

2 Literature review

While climate change has brought environmental, social, and economic problems, it has awoken the interest of researchers all over the world who, through the application and/or generation of different methods, methodologies, and immersive techniques in different areas, have developed solutions that allow for the minimization of adverse effects. In the case of the present investigation, Table 3 displays articles that have years of developed material in humanitarian logistics, especially regarding the vehicle routing problem.

Table 3 Revision of the state of art

Title	Authors	Year	Description
Modeling integrated supply chain logistics in real-time large-scale disaster relief operations	A. Afshar & A. Haghani.	2012	- Response to natural disasters. - Mathematical model: a) optimal locations; b) Vehicles route; c) pickup and delivery schedules; d) capacity restrictions for each facility, and e) transportation system. - Evaluated through numerical experiments [16].
Transportation in disaster response operations	D. Berkoune, J. Renaud, Monia Rekik & Ángel Ruiz.	2012	- Emergency situations. - Modeling of a transport problem. - Development of an enumeration heuristic of collections and genetic algorithm [17].
An exact solution approach for multi-objective location–transportation problem for disaster response	R. Abounacer & M. Rekik	2014	- Humanitarian help. - Mathematical formulation of multi-objective localization and transport problems: a) minimizes the total duration of transportation of the necessary products from the distribution centers to points of demand; b) minimizes the number of agents to open and operate the distribution centers, and c) minimizes demand not supplied. - Modification of the algorithm for the generation of rough solutions - Comparison of results [18].
A bi-level optimization model for aid distribution after the occurrence of a disaster	J.F. Camacho-Vallejo, E. González-Rodríguez, F.J. Almaguer & R.G. González-Ramírez.	2015	- Humanitarian logistics. - Two-level mathematical programming model, with a reduction to a one-level non-linear mathematical model; linearized to obtain a mixed programming problem. - Distribution of humanitarian help after a disaster. - Real case study of the earthquake in Chile in 2010 [19].
A humanitarian logistics model for disaster relief operation considering	M. Ahmadi, A. Seifi & B. Tootooni.	2015	- Humanitarian logistical operations. - Two-level Stochastic Mixed-Integer Programming Models with random travel time to determine the location of local deposits and routing for last-mile distribution.

network failure and standard relief time: A case study on San Francisco district			- GAMS. - Case study of San Francisco, California [20].
A dynamic multi-objective location–routing model for relief logistic planning under uncertainty on demand, travel time, and cost parameters	A. Bozorgi-Amiri & M. Khorsi.	2016	- Humanitarian help logistics. - Facility location, inventory quantity, and vehicle routing. - Model of multi-objective mixed-integer programming: a) minimize the maximum quantity of scarcity between the areas affected in all periods; b) minimize the total time of the trip, and c) minimize the sum of the costs before and after the disaster. - GAMS/CPLEX. - Tehran case study [21].
Allocation of temporary disaster response facilities under demand uncertainty: An earthquake case study	F. Cavdur, M. Kose-Kucuk & A. Sebatli.	2016	- Short-term disaster assistance operations. - Two-level Stochastic Mixed-Integer Programming Models to minimize the total distance traveled, unsatisfied demand, and the total number of facilities. - Temporary assignment of facilities during disaster response problems. - Case study developed by the Prime Ministry Disaster and Emergency Management Authority [22].
Pre-positioning of relief items in humanitarian logistics considering lateral transshipment opportunities	S. Baskaya, M. A. Ertem & S. Duran	2017	- Humanitarian help chain - Development and comparison of mathematical models for the location, number of facilities and inventory: a) direct shipping model; b) lateral transfer model, and c) maritime lateral transfer model. - GAMS/CPLEX - Istanbul case study [23].
Plant Location, Inventory Levels, and Supply of Products to Areas Affected by a Natural Phenomenon	E. Barojas-Payán, E, V. Juárez-Rivera, R. Villafuerte-Díaz & J. Medina-Cervantes.	2019	- Humanitarian logistics. - Mathematical model that combines the facility location, inventory levels, and vehicle routing. - Lingo - Case study in Veracruz, México [24].
Logistics Solutions in the Preparation Phase for the Appearance of Disasters	E. Barojas-Payán, D. Sánchez-Partida, M.J. Heredia-Roldan, V. Juárez-Rivera, J. Medina-Cervantes	2020	- Humanitarian logistics - natural disasters - Evaluation of a logistic model of literature whose fundaments are *a)* the classic p-median problem for the location of a prepositioned warehouse; *b)* an extension of the model (*q*-*R*) for calculating the inventory of different products, according to different types of demand, and *c)* the Capacitated Vehicle Routing Problem. - Lingo. - Case study in Veracruz, México [25].
A Multi-criteria Decision-Making Framework for the Design of the Relief Distribution Routes	F. Regis-Hernández, A. Ruiz & J. Mora-Vargas	2022	- Humanitarian help. - Multiple criteria methodology for the design of a help distribution network using the Analytical Hierarchy Process. - Quantitative models to maximize the performance of the distribution network. - Academic case [26].

The previous Table offers a structured vision of a part of the existing literature about humanitarian logistics in natural disasters, facilitating the comparison and the analysis of different focuses, as well as distinct models and methods with which various researchers have offered solutions to the routing problem in case of disaster.

3 Methodology

The following methodology is displayed in Figure 1, dividing the collection of information as follows: quantity of people in need, distances between municipalities and information about the vehicle used for deliveries, as well as other information. Below is the supplied information and the execution of the model with Lingo® software, followed by the presentation of the results and the statistics of time and distance variables.

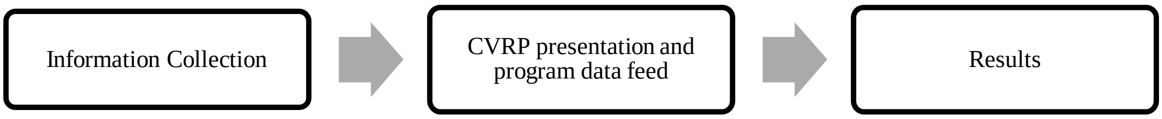


Figure 1 Methodology

Step 1. Information Collection

1. *Location of humanitarian supply warehouses (HSW)*, to carry out the present investigation, the humanitarian supply warehouse located in Orizaba was categorized as a supply point.

2. *Municipalities that declared emergencies*, from the data in [15], Table 4 is generated, where we can observe a total of 90 municipalities, 66 have been affected by a hydrometeorological natural phenomenon which has been the cause of a declared emergency, for which s supply points will be sixty-six.

Table 4 Municipalities with declared emergencies

Region	Number of municipalities	Municipalities with declared emergencies
Capital	33	17
Altas Montañas	57	49
Total	90	66

3. *Databases for the program which will be developed and supply data for the vehicle routing problem.*

- Distance matrix between municipalities that have declared emergencies and HSW, obtained with Google Earth®.
- Demand estimate from declared emergencies during 2012-2016.
- Vehicular capacity of 12000 kg of basic necessity products, this information is supplied by the document from Barojas-Payán et al. [27].

Step 2. Vehicular routing

To carry out the vehicular routing design for the supply of municipalities that have declared emergencies, a routing of capacitated vehicles is used, which is described below:

The objective of the classic vehicle routing problem (VRP) is to make routes for a fleet of homogeneous vehicles in order to serve a group of clients. Every client is visited once by one vehicle, every vehicle route begins and ends with a deposit and fulfills some lateral restrictions [28].

The Capacitated Vehicle Routing Problem (CVRP) case has a special twist: the cargo capacity that the driver has from the origin to the destination. A fleet of capacitated vehicles is located at a distribution center, the clients are in different geographical spaces and represent a demand. The distribution costs are integrated by *a)* a fixed cost associated with every truck, and *b)* a variable cost per unit of traveled distance. Every route starts and ends at the same distribution center, and the vehicle capacity should not be overloaded [29,30]. The description of the variables and parameters are shown in Table 5.

Table 5 Parameters and variables [30]

Parameters	Description
$\boldsymbol{A}$	*Capacity of each vehicle.*
$\boldsymbol{V}$	*Maximum number of vehicles.*
$\boldsymbol{F_{ij}}$	*Nuclear flow from node i to node j.*
$\boldsymbol{Z}$	*Total cost of transportation.*
$\boldsymbol{d_i}$	*Demand at node i.*
$\boldsymbol{c_{ij}}$	*Distance between node i and node j.*
Variable	**Description**
$\boldsymbol{X_{ij}}$	*1 if the vehicle moves from node i to node j, 0 if the opposite is true.*

According to [30] the general model for a CVRP is the following:

$$Min\ Z = \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} c_{ij} x_{ij} \tag{1}$$

Subject to:

$$\sum_{l=2,k\neq 1}^{N} x_{lk} + x_{1k} = 1 \quad \forall k \tag{2}$$

$$\sum_{l=2,k\neq 1}^{N} x_{kl} + x_{k1} = 1 \quad \forall k \tag{3}$$

$$\sum_{k=2}^{N} x_{1k} \leq V \tag{4}$$

$$\sum_{j=1,j\neq i}^{N} x_{ij} = \sum_{j=1,j\neq i}^{N} x_{ji} \quad \forall k \tag{5}$$

$$x_{kk} = 0 \quad \forall k \tag{6}$$

$$x_{lk} + x_{kl} = 1 \quad \forall k, l_{k\neq 1} \tag{7}$$

$$\sum_{j=1,j\neq i}^{N} F_{ij} = \sum_{j=1,j\neq i}^{N} F_{ji} + d_i \quad \forall k \tag{8}$$

$$d_i x_{ij} \leq + F_{ij} \quad \forall i, j_{i\neq j} \tag{9}$$

$$F_{ij} \leq (A - d_j) x_{ij} \quad \forall i, j_{i\neq j} \tag{10}$$

Equation (1), represents the objective function of the model which is to minimize the total traveled distance; equations (2) and (3), establish that there is exactly one exit from node i; equation (4) establishes the total number of vehicles that should not be exceeded; equation (5) establishes the balance between the arrival and departure arcs in a determined node; equation (6) eliminates the flow from node i to node i; equation (7) is a trivial sub-tour elimination restriction, and equations (8), (9) and (10) establish the balance between the flow entering and exiting the node.

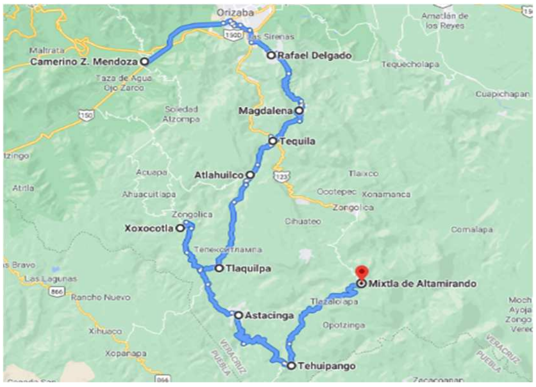
With Lingo 19.0® software and the obtained information in Step 1, we begin to resolve the capacitated vehicular routing problem, obtaining a total of 13 routes and 3,972.10 km traveled, for 66 municipalities that have declared emergencies. The route with the largest number of destination nodes is the first, with a total of 183.4 km traveled and a demand of 11,069 kg.

Step 3. Presentation of results

Table 6 presents one of the obtained routes through the programming of the capacitated vehicular routing problem: with a total distance traveled of 183.4 km for the delivery of products in the municipalities of Delgado, Magdalena, Tequila, Atlahuilco, Tlaquilpa, Xoxocotla, Astacinga, Tehuipango, Mixta Altamirano, Texhuacán, Zongolica and Los Reyes, supplying 11,069 kilograms of products, determined as route 1, while Table 7 shows that route 6 supplies Ixtaczoquitlán, Fortín de las Flores, Chocamán, Tomatlán, Ixhuatlán del Café, Tepatlaxco, Paso del Macho and Camarón de Tejeda, with a total of 210 km traveled. In addition to the description of the routes, the weight of the load, the distance traveled, and a map obtained with Google Maps® is shown with the respective route.

Table 6 Route 1. Optimization model

Route	Delivery municipalities				kg	km
1	Rafael Delgado	Magdalena	Tequila	Atlahuilco	11,885	183.4
	Tlaquilpa / Xoxocotla	Astacinga	Tehuipango			
	Mixtla de Altamirano	Texhuacán	Zongolica	Los Reyes		



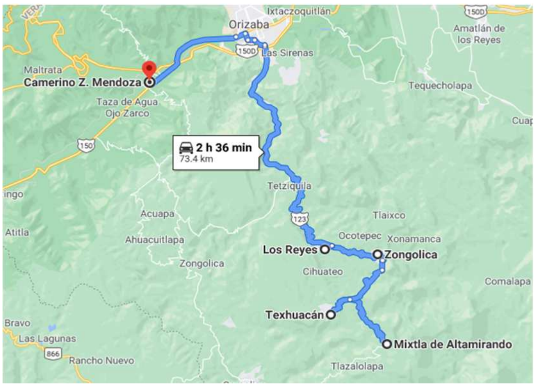


Table 7 Route 7. Optimization model

Route	Delivery municipalities				kg	km
6	Ixtaczoquitlán	Fortín de las Flores	Chocamán	Tomatlán	11,664	210.0
	Ixhuatlán del Café	Tepatlaxco	Paso del Macho	Camarón de Tejeda		

4 Results

Table 8 shows the results of the application of the capacitated vehicular routing problem, with a total of 13 routes and 3900 km traveled for the supply of 66 municipalities. With an average of 300 km per route and a standard deviation of 178.62 km, likewise, the average delivery time is 478.62 min (7.9 hours). We can conclude that the delivery of products to people affected by natural phenomena can be carried out efficiently, supposing that there are no transit problems or issues on the highways or access routes to the affected municipalities.

Table 8 Lingo19® programming result.

Route	Kilometers	Minutes
1	183.4	387
2	561.0	755
3	596.0	896
4	385.0	579
5	259.0	475
6	210.0	384
7	535.0	804
8	124.0	179
9	230.0	397
10	52.9	135
11	326.0	507
12	343.0	499
13	94.8	225
Sum	3,900 km	6,222 min
Average	300.00	478.62
Dev.Std.	178.68	235.22

With the finality of examining the characteristic of the kilometer variable with a statistical focus that compares the distribution of the data with a normal distribution, Figure 2 shows the adjustment of the variable to the normal distribution through the graph, where we can determine whether the variable shows significant normality deviations which could have important implications for the validity of the statistical analyses and the conclusions of the investigation. The value of p for this normality test is greater than the $p > 0.05$ significance level, therefore, the data follows a normal distribution for this variable.

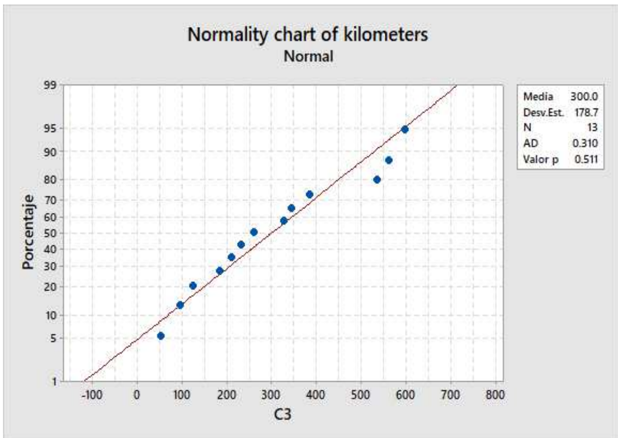


Figure 2 Normality chart of kilometers

With the normality chart, we observe that in the time variable, the value of p for the normality test is 0.603, therefore, the data follows a normal distribution for this variable (Figure 3).

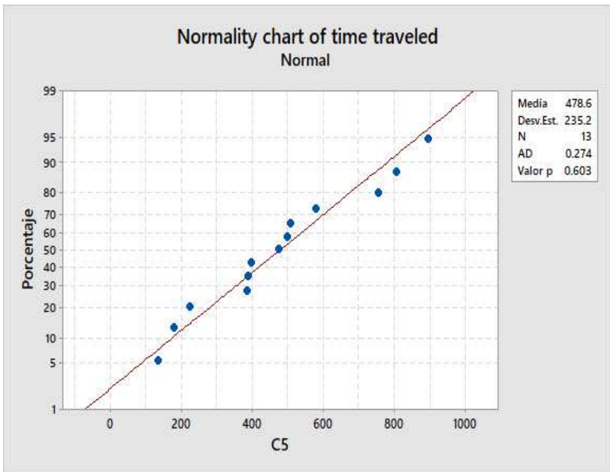


Figure 3 Normality chart of time traveled

5 Conclusions

One of the concerns with climate change is the presence of extreme natural phenomena, a situation that makes it imperative to develop plans that allow for quick and effective decisions for victims not only for the best assistance possible but also for it to be fast and efficient.

In the literature, several works have addressed the topic of humanitarian logistics in Mexico. For example, [24] have developed a model that combines the problem of facility location, inventory level establishment, and vehicle routing for one of the ten regions that constitute Veracruz. Unlike this work, they propose a new warehouse that would entail a considerable monetary investment in vehicles, since it would be in the city of Fortin de las Flores and have 14 delivery routes. Furthermore, [31] study vehicle routing in Chiapas, México. Chiapas is one of the five states with the greatest impacts derived from climatic phenomena. The authors weighed the variables to determine the location of two warehouses and their vehicular routing. They compare the results, selecting the best choice of infrastructure, viability, and response time. However, a considerable monetary investment is required.

The research presented shows the capacitated vehicular routing problem for the regions of the capital and the Altas Montañas in Veracruz, based on emergencies declared by FONDEN during 2012-2016, the municipalities that form part of the route are established with the goal of being supplied. They have a humanitarian supply warehouse in the city of Orizaba as an origin and destination point.

The objective of the generation of routes is to have complete coverage throughout the studied regions (Capital and Altas Montañas) allowing for an efficient supply by balancing deliveries, decreasing distances, and above all decreasing delivery times.

The results show the establishment of 13 routes with an average traveled distance of 300 km, in an average time of approximately 7.9 hours. In the same way, with the normality charts with the route time and distance variables, the adjustment of the normal distribution variables is shown. These results obtained in the normality charts show that the variable *kilometers* ($p = 0.511$) as well as the *time* variable ($p = 0.603$) have a normal distribution, which guarantees a validity of the analysis.

Unlike the articles mentioned previously, this document proposes a warehouse with characteristics and the infrastructure that allows reliable distribution, without a high investment. Also, the location of this warehouse will reach a greater number of municipalities per route, in an acceptable delivery time. As future work, we will integrate to the proposed model logistics elements such as warehouses and inventories, affected municipalities, temporary shelters, and collection points, among others.

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