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RAPID RESPONSE CENTERS FOR DISASTERS IN MEXICO: A THEORETICAL STUDY

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Abstract: After a disaster, reaction speed becomes one of the most important elements. To act in the best possible way, Disaster Operations Management must have the most accurate information on the affected area. To aid in these moments, a network of centers for Rapid Response is proposed here. Those centers would be equipped with short takeoff and landing aircraft, and would send them as soon as possible to the affected area, to gather information, and bring some type of aid. This research focuses on the theoretical foundation for such centers, including objectives, locations, missions, and equipment. This foundation is obtained through a literature review, which helps find the need for rapid response, and the main objectives and missions to be carried out. The number of centers and their locations are found by the use of a facility location model, considering the risk of each location. Finally, the number and type of aircraft needed in each center, as well as the missions for each one are found by the use of an assignment model. This research was made with the southeastern region of Mexico as its objective, but the resulting network of Rapid Response Centers could be setup in some other areas of the world.

1 Introduction

In many cases, after a disaster, logistics networks are damaged or unusable, mainly because the roads are affected. The road infrastructure can even suffer weakening after flooding. The increase in traffic before and after a disaster, sometimes caused by poorly planned evacuation procedures, and the increase in demand for supplies after a catastrophic event, adds stress to the road network, which in turn reduces, or even stops, the whole logistics network, preventing aid from arriving in the affected areas. Roads are rendered useless sometimes because of the large amount of vehicles evacuating the area, which causes strong traffic jams [1-5].

From 1900 to 2016, almost 60% of the recorded disasters in Mexico have a hydro-meteorological cause. In recent times, the southeastern region of the country has used as much as 75% of the resources for disaster recovery from the Mexican government. The region is affected by those type of events every year, causing the need for humanitarian response. Also, disasters that were accounted between 1990 and 2016 were 1.73 times more than those recorded between 1900 and 1990 [6-9].

1.1 Method

This research tries to find out if a faster humanitarian response infrastructure would be useful to reduce the adverse effects of disasters in the southeastern region of Mexico. The questions that will be tried to answer are:

1. Is there a need for a faster response after a disaster?
2. What type of objectives should such response address?
3. Are aerial operations the best solution for a faster response?

These questions are answered through a literature review in section 2. After these questions are answered, a proposal for a network of Rapid Response Centers (RRCs) to address these problems in an improved way, compared to the current situation in the country, is presented. Then the main questions of the research are answered. Such questions are the following:

4. What is the purpose and mission of the network of RRCs?
5. How many centers, and where should be set up?
6. What type of aerial equipment or vehicles should the RRCs have?

7. What type of mission should each type of vehicle perform?

These questions are addressed in sections 2 to 6, using both literature review and mathematical models. Conclusions and future work are presented in section 7, where the whole concept of the RRCs network is summarized.

2 Literature review

2.1 The need for fast response

Disaster relief can typically be divided in three phases: preparation, immediate response, and reconstruction. While addressing the three phases is needed, this research focuses mainly on the immediate response (IR) phase. When disaster has already happened, the post-disaster phase changes the dynamics of the logistics activity. The need for faster operations becomes extremely important. One of the main objectives of the humanitarian effort in that case is to reduce the average response time so that help can arrive as soon as possible [5,10-14].

During the IR phase, there are also several actions that take place, although there is no consensus among authors about the operations carried out in each phase of the disaster management cycle. Three main types of functions can be addressed in this phase: Demand management, supply management, and fulfillment management. These functions pose a challenge because of the unpredictability of the demand, as well as the many challenges arising from the disaster itself. In several research papers and literature reviews, it is noted that a lack of coordination is present in many disaster scenarios [13,15-18].

The purpose of an emergency supply network is to support the Emergency Logistics Operations, and that coordination is one of the areas where improvement can be made [19].

Question 1 is answered, because it is well established that, after a disaster, there is indeed a need for response, and as fast as possible.

2.2 The need for coordination and expedited information gathering

Many humanitarian operations have shown lack of coordination as a problem. Furthermore, when evacuation is needed, usually the demand is unknown. The importance of timely coordination after a disaster has been stated by different authors, all of them noting that it poses a challenge, and that it should be improved. One of the operations during the IR phase of DOM is the gathering of information. In many cases, maps are not the most accurate, especially in the areas where more poor people settle, and those areas usually are the most affected in a disaster. Official maps are not able to keep up with the rapid change of those settlements [1,15-17,20,21].

The characteristics of the humanitarian effort include, in many cases, the wish to bring help as soon as possible. 72 hours after the disaster could be an acceptable time frame. But to be able to bring help within that time frame, it is necessary to know what type of help is needed. This, in turn, reduces the available time to obtain information about the situation within the affected zone. It is important to reduce response time, bringing that time closer to real-time communication when dealing with DRO. Such information gathering is essential for anticipating the healthcare needs of survivors, managing critical conditions, and allocating limited resources [11,17,22-24].

The answer to question 2 is also well-established, and resides in the obtaining of information on the affected area. But some other functions can be performed, that we will address in some of the following sections.

2.3 Aerial operations

After disaster strikes, be it flooding, volcanic eruptions, earthquakes, or other types of disasters, sometimes the roads, or even the whole roadway system, are damaged, making it almost impossible to bring help to the affected areas. Sometimes it is necessary to use unconventional delivery systems to get help and supplies. Still, it is important to bring help, and as soon as possible. Speed is very important when in face of a disaster, as the arrival time of aid directly affects survival and suffering of the affected people. When the road network is damaged, or completely destroyed, communities are isolated, unless an effective way to bring supplies is established. In this cases, the best means of transport are aircraft [2,3,12,24-28].

Helicopters have long been perceived as the most practical vehicles to reach affected people when roads are damaged. In recent times, other types of aircraft have been developed, which can become alternatives for aerial operations, like unmanned aerial vehicles (UAVs), or drones [29-33].

Air transport is currently the fastest means of transport, and it is not limited by the status of the terrain. This also means that a flood, landslide, or broken road, does not prevent the operations from bringing help. Thus, the use of aerial vehicles in DRO can make sense, because help can arrive sooner to the affected area [34].

One of the areas where big advantages can be obtained from aerial operations is in the mapping of the affected zones. A high resolution map of the current situation of the area can be quickly obtained by deploying sensors and cameras aboard an aircraft, and sending such aircraft to the affected area. Unmanned aircraft, or drones, can be useful to attain such objective. Aerial survey at a close distance can also help locate victims or stranded people [29,35,36].

Mapping, victim location, information gathering for assessment of the situation, and transport of goods, are just some of the operations that can be carried out by aerial vehicles, provided that they are close enough to the affected area. If some type of aerial vehicles can be deployed quickly to perform one or more of these tasks, valuable time can be saved in the whole disaster operations management process. This, in turn answers question 3, in

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the sense that aerial operations are the best solution for faster response.

3 Discussion

To increase efficiency and speed in the humanitarian effort, keeping an inventory of emergency supplies close to the areas prone to suffer disasters is a commonly-used method. This method is also referred-to as *prepositioning.* Correct facility location can improve response time, by increasing the reaction speed [37-42].
Several prepositioning efforts have already been carried out, as those from Non-Government Organizations (NGOs), and others are still in planning phases, or proposals. Within the southeastern region of Mexico, a network of prepositioned inventory for disasters has also been proposed for the state of Veracruz. Most of them consider storing goods that can be sent to the affected areas in case of a disaster. Similar networks, providing services, instead of goods, have been setup using operations research methods [10,38-40,43-45]. To our knowledge, no dedicated air network of this type has been proposed to date.

The range of an aircraft, being limited, creates the need for some facilities to be located *close enough* to the possibly affected areas. If prepositioning has proved useful in the past, a *variation* of this method might make sense, by locating aircraft in facilities, so that such aircraft can arrive to the area of the disaster in as little time as possible.

4 Rapid response centers

Immediately after a disaster, response activities include, among others, search and rescue operations (S&R) and first aid medical attention. As speed is an important factor, and prepositioning is useful, it is helpful to have aerial vehicles within close distance to the affected area, ready to deploy immediately after a disaster, that can help with such operations. The main function of such vehicles would be aerial mapping, to provide useful and up-to-date information to the organizations taking part in the DOM. Additional benefits of such mapping include the location of people in need, and if possible, sending some type of help, provided that it can be packed in a compact and light manner [46].

So, as such facilities could be established, the humanitarian effort in the region could in turn be improved. The network of Rapid Response Centers has been proposed previously, including a first approach on the locations for such centers. The proposed network's goal is that no community, of the ones historically affected by disasters, is farther away than 250 km from any of the centers. This is for the affected areas to be at most one and a half hour of flight from a RRC [6,7,45].

In the following section, the location will be addressed, considering location risk factors not included in the existing solutions.

4.1 Facility location

The main objective of the RRC network is to position aircraft at the affected area as soon as possible, to start gathering information that can help improve DOM. This could mean that such centers would be located within areas that could also be affected. The correct design of a logistics network in humanitarian operations is critical. Careful planning should be done to place each of the RRCs in a safe location, while providing the best possible coverage. A similar approach has already been taken for facility location in the context of humanitarian response, within the Mexican territory, with favorable results. Although this research tries to find full coverage, instead of a maximal one [19,44,47].

4.2 Facility location considering risk factors

To consider risk within a facility location model has proven useful in research. On the other hand, to be able to arrive to the affected area as soon as possible, several facilities must be considered, so that aerial vehicles are close enough to such affected area. A facility location solution has been found previously, with a relatively simple method. A confirmation of such result, or a new one, was sought, considering risk factors. A database had already been obtained and prepared with a data mining method. A facility location model, considering locations with high risk as repellants, and locations with existing shelters as attractors, was solved. The model also included a maximum distance from every location to the closest center [6,7,43,47].

This model resembles the constrained Weber problem with attraction and repulsion. In that model, a single source is sought, and sinks may attract or repel the source. This model uses the multi-source approach, that has already been studied extensively in the past. The model tries to minimize the Euclidean distance, but the cost of travelling such distance is modified by the attractors and repellants calculated from the risk factors, and the cost of setting up each service center is also considered. A maximum distance is also set up as a restriction [48,49].

The mathematical formulation of the model is the following (1)-(6):

$$minimize \sum_{i=1}^{n}\sum_{j=1}^{m} u_{ij} w_{ij} \left(\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\right) + c_i s_i$$

s.t.

$$\forall j \le m: \sum_{i=1}^{n} u_{ij} = 1 \quad (1)$$

$$\forall i \le n: c_i s_i > \sum_{j=1}^{m} u_{ij} \quad (2)$$

$$\forall i \le n, \forall j \le m: u_{ij}\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \le d_{max} \quad (3)$$

$$\forall i \le n, \forall j \le m, \forall k \le o \middle| R_{kj} \ne 0 \;\&\; \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \le r_j : w_{ij} =$$

$$\prod_{k=1}^{o}\left(1+R_{jk}\left(1-\frac{\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}}{r_j}\right)\right) \quad (4)$$

$$\forall j \le m, \forall i \le n : u_{ij} \in \{0,1\} \quad (5)$$

$$\forall i \le n : s_i \in \{0,1\} \quad (6)$$

Where the decision variables are:

x_i, y_i are the *x* and *y* coordinates of the service center *i*, greater than zero.

s_i is a binary indicator, 1 if service center *i* will be set up.

u_{ij} is a binary indicator, 1 if service center *i* will serve the location *j*.

And the model parameters are:

n is the number of service centers, *m* is the number of locations to serve.

w_{ij} is the weight factor, adjusted by attractors and repellants, of travelling from *i* to *j*.

x_j, y_j are the *x* and *y* coordinates of location *j*, greater than zero.

c_i is the cost of setting up service center *i*.

d_{max} is the maximum allowed distance from the service center to each location.

o is the number of risk factors to be considered.

r_j is the risk radius of location *j*.

R_{jk} is the risk factor *k* of location *j*.

The restrictions, explained, are:

1. The sum of *used* for each location must be 1, every location must receive service from one service center.
2. The cost of setting up each service center must be accounted for.
3. The distance from each location to its used service center must not exceed the maximum distance.
4. The *weight* of travelling from a location to its assigned service center gets altered by the risk factor. It is multiplied by 1+the risk factor, thus attracting or repelling the service center.

4.3 *Solving method for locations*

For the multi-facility weber problem, the Simulated Annealing algorithm is one of the most effective options. This algorithm requires the presence of an initial solution. A previous research considering rapid response centers, but not considering risk factors, was used as the initial solution for the current model [7,50-52].

4.4 *Facility location results*

Instances considering five to seven centers were solved, obtaining the best results with six centers, considering risk factors. The nature of the RRCs prevents them from being setup anywhere, mainly because they need to be resupplied. Should a disruption on the supply chain of the center be present, the goal of said center would not be achieved. As such, there is the need to care for the center itself. The center must then be placed within close distance of existing supply chains. The proposed locations for each center are the closest town or city to the raw result of the model. These locations are presented in Table 1. This, in turn, answers question 5, showing that 6 centers should be placed in the mentioned locations [53].

Table 1 Facility location model results

Center	Latitude	Longitude	Closest Town/City
1	16° 34' 52.32"	-96° 18' 49.68"	Santa María Zoquitlán, Oax
2	20° 34' 23.88"	-89° 0' 17.28"	Sotuta, Yuc
3	17° 14' 56.04"	-97° 24' 1.08"	San Juan Diuxi, Oax
4	16° 46' 55.56"	-92° 15' 19.8"	Abasolo, Chis
5	20° 2' 40.2"	-97° 57' 51.48"	Tepetla, Pue
6	18° 0' 5.76"	-99° 16' 31.44"	Tulimán, Gro

5 RRCs Mission

To improve the effectiveness, and reduce the response time of all the actors in the humanitarian effort after a disaster, the best possible and up-to-date information should be obtained. Operators of the vehicles pre-positioned at each Rapid Response Center could perform the task of Aerial Surveillance, as soon as possible after disaster has occurred. Aerial photo or video of the area, with enough resolution for decision makers within the DRO management to evaluate the situation, is the expected main result of such flights [29,36].

If the vehicles are not large, their operational cost should also be small, although that also comes with a limitation on the side objectives such vehicles can attain. Still, they can be helpful when combined with other types of vehicles. Small vehicles that are not capable of evacuating a person, or a family, can still be equipped to mark the place where those people can be found, and then a larger vehicle can be sent specifically for that task. Smaller unmanned vehicles can access places that manned aircraft can't reach. Smaller vehicles can be used for last-mile delivery of goods in disaster scenarios. A vehicle too small for evacuating procedures could still be large enough to carry small and light survival or first-aid emergency kits, that could be air-dropped very close to people that need them. These two secondary objectives can help reduce the overall cost of the DRO, and improve the effectiveness of the humanitarian effort [32,54,55].

The answer to question 4, the mission of the RRCs, is then:

1. Aerial Surveillance As Soon as Possible After Disaster (Information Gathering),

2. Emergency Evacuation Marking,
3. Air-Drop of Basic First-Aid / Survival kits.

6 Mission assignment

6.1 Types of aerial vehicles

Different types of vehicles can perform different tasks. From a distance point of view, fixed wing and large aircraft can be helpful outside of the affected area, and helicopters or smaller aircraft can be useful within the affected area. When disaster operations are still on its planning stage, having as much information as possible on the disaster effects is paramount, but DRO do not have infinite resources, so larger aircraft with higher operational cost should be used carefully. On the other side, the size of technological devices has been decreasing steadily, and is currently small enough for cameras and sensors to be fit on smartphones or wearable devices. Such sensors could be mounted on almost any aircraft, but to carry some type of cargo, there are size limitations [23,25,56-58].

To classify the different types of aircraft that could be used for the RRCs, three main categories could be considered. First, the size of an aircraft, which directly affects its ability to maneuver through the affected zone, while also determines how much the ship would be affected by wind and weather. Second, the type of lift or propulsion, which affects its maneuverability, speed, and range. Third, cabin type, because aircraft design follows very strict rules, and usually makers design the aircraft specifically for passengers, or cargo, although some cross applications can be found. Still, the cabin type can be used or adapted for different applications, so the types of aircraft will only be classified by size, and lift technology [59-64].

The types of vehicles, divided by lift type, that can be considered, are:

1. Fixed hard wing. Where lift is provided by one or more wings, which remain fixed in place, although some parts of them might still be moving [65].
2. Flexible wing. Where the lift is provided by a large surface of flexible material, like fabric. Can have a hard frame or only the flexible parts [61].
3. Powered rotary wing. Lift is provided by a series of wing-shaped blades or rotors connected to an engine, where the rotation of such wings provide lift. One or two sets of such wings shall be considered in this category [66].
4. Powered multiple rotary wings. Like the previous category but using three or more rotors. Samples between 3 and 8 rotors are currently available in the market, and are increasing in popularity [67].
5. Unpowered rotary wing. Where lift is provided by a rotor, but it spins freely, without power from an engine. The vehicle uses a powered propulsion method, and the rotor spins because of the air flow through it, producing lift [68].
6. Tilting powered rotary wing. A combination of a fixed wing for large distances and higher speeds, but with large propellers or rotors that provide lift at takeoff and landing stages [69].
7. Lighter than air. Vehicles that do not use a wing, but a large container of a fluid with a lesser weight than that of air [70].

The *size* category can vary greatly, depending on the type of scale that would be used. A simple scale can be created for this, depending on how many passengers or weight such aircraft could carry. Unmanned aircraft, not big enough to carry 20 kilograms will be considered very small. Aircraft capable of carrying more than 20 kg, or from 1 to 4 people will be considered small, 5 to 20 people will be considered medium, 21 to 60 will be considered large, and anything larger than that will be considered very large.

Very large aircraft pose too many challenges for the type of operations proposed in this study, they require large landing strips, and their operational cost is too big. Those will be discarded. Very small aircraft with multiple powered rotary wings are currently found in many places around the world. These aircraft could also perform the search function, but the current state of such technology has a strong range limitation, averaging only 7 kilometers. This average range limitation could also be considered for other types of lift technology, but with the same size. Also, weather affects smaller aircraft more than larger ones, and some disaster types cause bad weather that could prevent very small aircraft from flying, and performance is currently not enough for them to be practical for the RRCs needs. Very small aircraft, of any lift type, will be discarded [67,71,72].

The type of lift of an aircraft also affects its ability and range. Lighter than air vehicles, like hot air balloons, or zeppelins, tend to have a very low speed. As speed is an integral part of the RRC network objective, lighter than air ships will be discarded. Additionally, some combinations currently do not exist. Flexible wings can only be found in small aircraft, multiple (More than two) powered rotary wings can not be currently found in medium or large vehicles, and finally, although there was a medium sized prototype of an unpowered rotary wing vehicle long time ago, those can only be found in small size in present times. Currently only one tilting rotor aircraft is available, and it is a medium aircraft, although some other vehicles of the same type are currently under development [70,73-75].

The size and type of lift, average speed of each type of aircraft, average landing/takeoff distance, and average carrying capacity (passengers or cargo) was compiled in Table 2, using publicly available information. As bad weather can affect the flight characteristics of each type of aircraft, usually less as size increases, a *Weather Sensitiveness* factor was included. This factor is 0 if the aircraft can fly in severe weather conditions, and 3 if it can not. If the aircraft can land in small spaces, and carry victims, the *Rescue* value is 1. The passenger capacity was considered as the average capacity of the size category [76-79].

Table 2 Aircraft types and characteristics

Aircraft Wing Type	Purchase cost (USD)	Cost / Hour (USD)	Speed (Km/h)	Rescue	Weather Sensitiveness	Cargo
Large fixed	50000000	1500	600	0	0	3
Medium fixed	3000000	500	300	0	1	3
Small fixed	500000	130	200	1	3	2
Small flexible	15000	45	70	1	3	0
Large powered rotating	12000000	400	300	1	1	3
Medium powered rotating	2000000	200	250	1	2	3
Small powered rotating	1000000	145	170	1	3	2
Medium multiple powered rotating	1000000	60	110	1	2	1
Small multiple powered rotating	500000	30	90	1	3	0
Small unpowered rotating	150000	50	160	1	2	1
Medium tilting	73000000	9000	450	1	1	3
Small tilting	20000000	4500	300	1	3	3

6.2 Disaster types

The type of disaster has a large influence on the type of vehicles and operations that could be performed by the vehicles of the RRCs. An earthquake's maximum duration is under 2 minutes, which does not prevent aerial vehicles from staying airborne, but volcanic eruptions do. Heavy rain and winds can be dangerous for smaller aircraft, but larger ones could resist the weather. On the other side, the cost of flying larger aircraft can be so high that some missions, like search and surveillance, consume too much resources, while smaller aerial vehicles can perform such missions at a much lower operational cost [80,81].

Table 3 Disaster types to be considered

Disaster Type	Weather Disruption Level	Aerial Evacuation	Survival Kits
Rain	2	1	1
Hurricane	3	1	2
Flooding	1	1	3
Volcanic Eruption	3	0	1
Slide	1	1	1
Earthquake	0	0	0

The types of disasters that will be considered, as shown in Table 3, are those found in previous research [47]: Rain / Hurricanes, Flooding, Volcanic Eruptions, Slides, and Earthquakes. Of those types, volcanic eruptions and hurricanes prevent all or some types of vehicles from flying, while the other types allow the operations of aircraft. Slides, flooding, and earthquakes can cause damage to a landing strip or facility within the affected area. Flooding or hurricanes can call for immediate evacuation of people trapped atop of buildings, that cannot be done by land, while after earthquakes usually evacuation can be done by land [80,82,83].

6.3 Assignment model

To reduce as much as possible the cost associated with the aerial operations on a disaster scenario, a mathematical model was used. On one side, the types of disasters that have already happened in the region, with the limitations they impose on flight operations, reconnaissance missions, or rescue operations. On the other side, the types of aircraft suitable for the RRC missions, with their limitations, and their average operating costs will also be considered. The model seeks the minimal cost associated with the missions performed in a disaster scenario.

The reconnaissance mission can be performed by any type of aircraft, and it can be performed at the same time as the air drop and rescue missions, so it is not considered for the model. The ability to perform the rescue and air drop missions depend heavily on the type of aircraft, and will be considered in the model. If the weather sensitivity of the aircraft is smaller than the weather disruption level of the type of disaster, such aircraft is not suitable to perform that mission in that disaster scenario. The same treatment is done to the need/ability to rescue victims. Aerial evacuation requires the ability to land in an unprepared space, or to hover above the victims while the procedures are carried on. For that purpose, some VTOL capacity would be required to cover the Aerial Evacuation need. The Survival Kits column considers the possibility to air-drop said kits from a close distance to the victims. More

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cargo carrying capacity means more kits and bring such help to more people, but at the same time, larger vehicles must have larger space to maneuver, and smaller vehicles can come closer to the affected people.

Current UAVs have strong range and endurance limitations, but those were omitted in the model, to give room for improvement of such technology. Some other considerations were made to ease the model solving. The time to rescue one victim was standardized to 30 minutes, and the maximum duration of a mission was set to 8 hours. Missions were required to be completed within a 48 hour time frame.

Several runs of the model were desired, one for each disaster type. The distance from the RRC to the affected area was tested using values of 25km, 125 km, and 250km. The number of victims in need for evacuation or air drop of kits was also changed, using 10, 50 and 100 victims. For each type of disaster, a combination of each case of distance and victim combination was set up as a scenario. The resulting list contains 9 scenarios for each disaster type. The model was prepared to find, for each disaster type, the combination of vehicles that would represent the lowest acquisition and operating cost to cover the needed operations in all scenarios, considering the abilities of each type of aircraft.

The mathematical formulation of the model is the following (7)-(15):

$$minimize \sum_{i=1}^{n} v_i a_i + \sum_{j=1}^{m} h_i mt_{ij}$$

s.t.

$$\forall_{i \le n}: v_i \in \mathbb{N} \quad (7)$$

$$\forall_{j \le m}: \sum_{i=1}^{n} \frac{r_{ij} v_i p_i}{rph} \ge vn_j \quad (8)$$

$$\forall_{j \le m}: \sum_{i=1}^{n} s_{ij} v_i \ge \sum_{i=1}^{n} r_{ij} v_i \, spv \quad (9)$$

$$\forall_{j \le m, i \le n}: mt_{ij} = t_{ij} + s_{ij} + r_{ij} \quad (10)$$

$$\forall_{j \le m, i \le n}: t_{ij} \ge 2 \frac{d_j}{sp_i} \left(\frac{s_{ij} + r_{ij}}{s_{ij} + r_{ij} + 0.001} \right) \quad (11)$$

$$\forall_{j \le m, i \le n}: mt_{ij} \le md \quad (12)$$

$$\forall_{j \le m, i \le n}: mt_{ij}(wd - ws_i) \ge 0 \quad (13)$$

$$\forall_{j \le m, i \le n}: rn_j r_{ij} \le ra_i r_{ij} \quad (14)$$

$$\forall_{j \le m, i \le n}: kn_j mt_{ij} \le ca_i mt_{ij} \quad (15)$$

Where the decision variable v_i is the number of vehicles of type i to be used.

And the parameters are:

n is the number of different types of aircraft
m is the number of different disaster types
a_i is the acquisition cost of type i vehicles
h_i is the cost per hour of type i vehicles
mt_{ij} is the total mission time of type i vehicles for scenario j
r_{ij} is the rescue time of type i vehicles for scenario j
p_i is the passenger capacity of type i vehicles
rph is the standardized number of victims per hour that can be rescued
vn_j is the number of victims in scenario j
s_{ij} is the search time of type i vehicles for scenario j
spv is the standardized search time per victim
t_{ij} is the travel time of type i vehicles for scenario j
d_j is the distance to the affected area in scenario j
sp_i is the average speed of type i vehicles
md is the standardized maximum mission duration
wd_j is the weather disruption in scenario j
ws_i is the weather sensitivity of type i vehicles
rn_j is the need for rescue in scenario j
ra_i is the rescue ability of type i vehicles
kn_j is the need for survival/first aid kits in scenario j
ca_i is the cargo ability of type i vehicles.

The restrictions, explained, are:

1. The number of vehicles must be an integer greater than 0.
2. The number of rescue hours must be enough to rescue all victims for each scenario.
3. The number of search hours must be that of the rescue hours multiplied by the search time per victim.
4. Mission time equals travel, search, and rescue times for each scenario.
5. Travel time is considered only if the vehicle performs search or rescue time.
6. Mission time must not exceed the maximum mission duration.
7. The vehicle type's weather endurance must be larger than the scenario's weather disruption.
8. The vehicle type's rescue ability must be larger than the scenario's rescue need.

The vehicle type's cargo ability must be larger than the scenario's kit need.

6.4 Assignment model results

The model was solved assuming that all types of vehicles have unlimited range. This was done to provide room for future growth in technology, mostly in UAV range and speed, but not limited to those types of aircraft. Results included the search, rescue, and travel time for each scenario and type of vehicle, and it was observed that the optimal vehicle combination for each one included a predominant mission for each type of aircraft, where some aircraft were preferred for search operations, and some for rescue operations. A table with those results was compiled and is presented in a simplified way. Table 4 shows the summarized results for each scenario, where the number of missions required to rescue all the victims is shown. The letters next to the number of missions show if the predominant mission is search (S), rescue (R), or both (S&R).

It is worth noting that the model shows large fixed wing aircraft as the ones preferred for earthquake scenarios, which were not marked as having STOL requirements, the explanation for this result lies in the assumption that airports might still be operational in such disaster scenario, and the possibility to evacuate people by land in such disaster type. It is noteworthy that, with the exception of earthquakes, all the other disaster types required a combination of vehicle types. Small vehicles with low operating costs are preferred for search operations in all scenarios, and powered rotating wing aircraft, or *helicopters*, are preferred for rescue operations.

Each mission can last up to 8 hours, and the effectiveness of the RRCs is larger between 0 and 48 hours after the disaster, so each aircraft could perform up to 6 missions in that time frame. The results of the model should then be divided by 6, to obtain the recommended quantity of aircraft for each scenario. This answers questions 6 and 7, the type of aerial vehicles that RRCs should have, and the type of mission each type of vehicle should perform.

Table 4 Number of vehicles resulting from the assignment model (Empty categories deleted)

	Number of missions					
Vehicle type	**Rain**	**Hurricane**	**Flood**	**Volcanic Eruption**	**Slide**	**Earthquake**
Large fixed wing						4 S&R
Medium fixed wing			2 S		2 S	
Small fixed wing		4 S				
Large powered rotating wing		1 R	2 S&R		2 S&R	
Medium powered rotating wing		1 R				
Medium multiple powered rotating wing	7 R			7 R		
Small unpowered rotating wing	12 S			12 S		

7 Conclusions

The main conclusion of the current theoretical study is the overall definition of the Rapid Response Centers, considering the locations obtained by solving the facility location model, and the suggested mission alignment, with the combination of vehicles obtained with the assignment model. They are the following:

Rapid Response Center for Disasters.

A network of facilities is proposed, with aerial vehicles ready to launch, that would perform the tasks of **information gathering, search for victims, and air-drop of small first-aid or survival kits**. The facilities would contain the adequate spaces to store, maintain (lightly) and launch or receive the aircraft. Landing spaces for Short/Vertical takeoff and Landing vehicles, fueling and control facilities should exist within the facilities. The centers also would need storing facilities for the small first aid or survival kits, and an adequate stock of such kits. Finally, the centers should have adequate data links to send the gathered information to the DRO management.

The suggested locations for the centers consider a maximum distance of 250 kilometers from every historically affected location to its closest center. The locations considered are: Santa María Zoquitlán, Oax; Sotuta, Yuc; San Juan Diuxi, Oax; Abasolo, Chis; Tepetla, Pue; and Tulimán, Gro.

The missions carried out by the aircraft in the RRCs are:

Information Gathering. Aircraft would be launched as soon as possible after disaster, to fly-over the affected area, obtaining video and photos of the zone. This information would be relayed to the DRO management, to provide a better knowledge of the state of the disaster zone.

Search and Rescue. While gathering photo and video, aerial operators can spot victims requiring evacuation or help. Depending on the capacity of each aircraft, either the evacuation procedure is carried on, or the place where there is the need for rescue is marked. If the aircraft is not big enough to perform the evacuation, it would mark the place and need for evacuation, and DRO would then send an adequate aircraft for the task.

Emergency kit Air-Drop. When victims are found that need help, but not immediate evacuation, a small emergency kit could be dropped close to them. The kit could be the one proposed in previous research: An emergency food bar, water filter/water purifying tablets, first aid kit (adhesive bandages, antiseptic towelettes, sterile gauze), and an emergency thermal blanket [45].

The required vehicles are:

It is suggested that each RRC contains 2 small unpowered rotating wing vehicles, or 2 medium fixed wing vehicles with STOL capabilities, for search operations, and one large powered rotating wing vehicle, or helicopter, for rescue operations. The search vehicles would be launched as soon as possible after a disaster has struck the coverage area of the RRC, to perform the search and information gathering missions. The same aircraft would mark the places where victims are located, so that the rescue vehicle can perform such task without time loss.

7.1 Future work

Very small aircraft can reach places where aircraft of other sizes can not, but their main limitation for this purpose is their range and low stability, which in case of heavy winds or rain could prevent them from flying. Still, a different approach on the RRCs, with mobile carriers, that could get close to the affected area by land, and then deploy the aircraft as a swarm, could mean that the main mission of the RRCs is possible with a different approach. Such approach could be evaluated in future work. On another side, a more comprehensive data collection on aircraft types and abilities, as well as for disaster scenarios, could represent a more accurate result on the assignment model.

Many areas of the RRC network are still not covered, like the physical design of the centers, as well as a detailed function and procedures description for each working place. Such research could result in a valuable source of information, should the actual network of RRCs be setup.

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Review process

Single-blind peer review process.