

Location and allocation of primary and backup shelters in transboundary disasters

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ABSTRACT

Disaster management is plagued by uncertainty and chaotic situations, often crossing boundaries and affecting multiple jurisdictions. Collaboration in these settings is complicated, especially when authorities face failure in the infrastructure available leading to facilities operating over capacity and/or vulnerable people left without support. There are records about those experiences globally. There is a broad literature on shelter location/allocation, but few articles consider the potential failure facilities and none of those contributions consider the collaboration between multiple jurisdictions. This article introduces a novel bi-objective formulation for shelter location-allocation considering backup facilities for operations involving multiple jurisdictions. This approach is applied to a set of numerical examples and a real case of volcanic eruptions in Mexico. The results show the influence of transboundary coordination on the support provided to disaster victims, the value of backup facilities and the capacity of the model design to provide relevant alternatives in practice.

Keywords

Shelter location-allocation; transboundary coordination; backup facilities; stochastic optimization.

INTRODUCTION

Just in 2022, disasters caused by natural hazards threatened over 185 million people and caused an estimated US \$223.8 billion of economic losses (CRED, 2023). Humanitarian logistics has arisen as a critical field to develop solutions to handle the conditions created by disasters. It involves multiple stakeholders collaborating to deliver products and services to satisfy the needs of people affected by disasters (Gutjahr et al., 2020).

Evacuation and shelter selection influence the service experienced by people affected by disasters. Shelters are often prepared in advance, but emergency services and facilities can fail under disaster situations (Albareda-Sambola et al., 2015). Although there has been an increase of models incorporating backup facilities, there is limited information about the value of these facilities, especially when facility capacity is included in the formulations.

Humanitarian logistics is a multi-actor, multi-agency, and cross-jurisdictional activity involving private and public organizations (Oloruntoba, 2010). Despite the emphasis on the interaction between different stakeholders, coordination under disaster circumstances remains a key challenge (Balcik et al., 2010). This complexity is further

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fueled by the need to conduct joint operations for crises across boundaries affecting different jurisdictions (Boin et al., 2014) because each jurisdiction has defined responsibility and attributions.

Disasters can transcend political, functional and temporal boundaries, which is translated into significant complications to handle them requiring extreme adaptation (Ansell et al., 2010). Recent research highlights the importance of incorporating the collaboration of agencies from different jurisdictions (Nurmala et al., 2017; Olsson, 2015). However, that has not been reflected in the development of cross-jurisdictional models for disaster response. This study answers two research questions: i) what is the effect of coordination for shelter selection between different jurisdictions in the service provided to people affected? and ii) what is the value of incorporating backup shelters for disaster response?

This research proposes a two-stage stochastic optimization model to support evacuation and shelter location decisions incorporating cross-jurisdictional collaboration. It is tested using a set of numerical examples and a case study. It contributes to the literature by proposing a model for operational collaboration in shelter management between stakeholders from different jurisdictions, acknowledging the possibility of failure of any facility using backup facilities, and investigating the impact of transboundary coordination on the experience of the people affected by the disaster.

LITERATURE REVIEW

Backup Shelters

Shelter location involves the selection of suitable safe points to provide protection to people affected by disasters (Kinay et al., 2018). The vulnerability of facilities inside the affected area has motivated studies looking into the use of backup facilities for distribution centers (Mohamadi et al., 2019; Rahmani et al., 2018; Yahyaei & Bozorgi-Amiri, 2019). The need for backup shelters to react to failures in sheltering, however, has been understudied, with many studies neglecting to consider shelter failure (Ma et al., 2016).

There is a stream of articles focused on selecting the location for building shelters in suitable areas (Aghaie & Karimi, 2022; Geng et al., 2021), thereby reducing the possibility of shelter failure. However, in many countries the policy is to use existing facilities as shelters (Liu et al., 2011), which are vulnerable to failure. The work of Gangwal et al. (2023) and Wang and Xu (2023) shows that it is important to look at the vulnerability of the shelter not only because of damage on the facility itself, but also because of road failure leading to isolated shelters.

Albareda-Sambola et al. (2015) introduce the use of the p-next center problem to select primary and backup facilities closer to the victims in case they reach their closest center and it is closed. Albareda-Sambola et al. (2019) extend that idea by considering different strata of people requiring different services whereas Hinojosa et al. (2023) use a hierarchical process where the planner sets service centers based on the worst-case behavior of the public and the beneficiaries select the center based on their preferences. Although this is a promising avenue of research, all the models disregard the capacity of the facilities, which is a very practical constraint in reality. An et al. (2013) propose a formulation assuming each facility is subject to independent probabilistic disruptions which are represented in a set of scenarios. Their formulation defines the allocation upon the realization of the corresponding scenario, which requires the government to notify and direct all the evacuees. Aiming to maximize network reliability and considering facility capacity, Babashahiet al. (2020) use reserve hub elements as backup components to prevent failure considering failure probabilities calculated based on incoming traffic. Nonetheless, these models consider a single jurisdiction affected by the disaster.

Coordination Across Jurisdictions

Disasters are often connected across different jurisdictions, with the outcome of one jurisdiction affecting the situation on another one (Ansell et al., 2010) and requiring to manage conflicting objectives (Rui et al., 2008). In these environments, deciding whose resources to use is a complex decision because of the inability to ensure fair allocation of joint operations (Schulz & Blecken, 2010), leading to concerns about fair distribution of shared workload (Schulz & Blecken, 2010). The combination of these problems can negatively influence the cost and service level provided.

Research has discussed the problems associated with formal structures in handling new and complex problems (Olsson, 2015) and underlines the importance of adopting cross-sector partnerships in humanitarian logistics (Nurmala et al., 2017). Ansell et al. (2010) argue the need for a transboundary authority structure that can be triggered in times of crisis and that will help minimize confusion and bureaucratic infighting. Collaboration between municipalities and different services, for instance, can enable more effective operations (Zikeloglou et

al., 2024). That is the reason the European Union has led the first European Disaster Response Exercise (Hollis, 2020) and some articles have considered the collaboration between different agencies using agent-based simulation (Lebcir & Roy, 2023; Valaei Sharif et al., 2023), game theory (Coskun et al., 2019; Ergün et al., 2023), and Industry 4.0 technologies (Kumar & Singh, 2022). Nonetheless, less effort has been invested into humanitarian logistics activities. Wojtalewicz et al. (2014) use the case of the Regional Hub Reception Center (RHRC) led by the Purdue Homeland Security Institute involving 17 jurisdictions to propose the use of simulation to efficiently assess the use of facilities to improve coordinated responses. Polese et al. (2024) propose an approach for cross-border multi-risk assessment as an answer for single-risk and independent assessments which neglect the cascading effects between jurisdictions. Wang et al. (2022) use a regional healthcare coalition to collaborate for stock pre-positioning and post-disaster procurement and transshipment to serve affected areas. However, current models are ill-equipped to consider the coordination of different jurisdictions for shelter management.

This paper designs and tests a novel optimization model to allow for the location and allocation of primary and backup shelters enabling the coordination and use of resources from different jurisdictions. The contributions of this article are threefold; i) provides a model allowing operational collaboration between stakeholders from different jurisdictions for shelter management, which is an area neglected in the literature; ii) proposes a capacitated formulation increasing the reliability of the response by acknowledging the possibility of failure of any facility, an approach understudied in the literature; and iii) shows the impact of transboundary coordination on the experience of the people affected by the disaster, which can foster the development of more contributions incorporating transboundary coordination.

METHODOLOGY

This study develops a two-stage optimization model to guide the selection of primary and backup shelters for people affected by disasters considering transboundary coordination. The aim is to find the best combination of the decisions that can lead to a good level of service for disaster beneficiaries.

Optimization is a commonly used method to determine the ‘optimal’ location of facilities because it allows investigating the different possibilities and define the most appropriate option based on the objective functions (Kinay et al., 2018). It has been selected for this research because it allows balancing the support provided to disaster victims and the resources available during disasters. There have been discussions in the literature about the best performance measures for humanitarian logistics. Although minimization of cost is often used to ensure efficiency in the operations, this research argues that the effectiveness of the operations (i.e. the support given to affected people) needs to be a priority. This research incorporates both objectives in a multi-objective formulation to guide decision-making. The use of two-stage optimization allows us to incorporate the uncertainty about the impact of the disaster and the state of the infrastructure (Rodríguez-Espíndola et al., 2020), where the first stage is at the imminent pre-disaster stage and the response stage uses information about the impact of the disaster to guide response decisions.

Context of the Situation

The model proposed promotes the coordination between different jurisdictions to make allocation decisions of primary and backup shelters. The allocation of people is guided by two objective functions. The first objective function minimizes the total distance travelled by the people affected to focus on effectiveness. With the possibility of transboundary coordination, people evacuated in a demand area can move to a different jurisdiction if it is beneficial for them. To ensure that there is a level of fairness between authorities from different jurisdictions, especially looking at the expenses incurred, the second objective function of the model minimizes the maximum cost per person per jurisdiction. It balances the expected cost (i.e. the sum of facility cost and transportation cost) to avoid overburdening any one of the jurisdictions.

In the two-stage formulation, first stage decisions are focused on facility selection and the flow of people from demand areas to shelters right before the event. Given the range of time for the arrival of people, it is assumed people will get there by their own means. Second-stage decisions take place at the response stage. Considering uncertainty on the magnitude and impact of the disaster, a set of disaster scenarios can be used to guide decision-making. The model incorporates damage to shelters and to the road network to plan the transportation of people allocated to those facilities in buses provided by authorities. Hence, the second stage is focused on the decisions about transportation of people, defining the number of people to move to the same or different jurisdictions.

Notation

Sets

I	Set of demand areas
J	Set of potential shelter locations
L	Set of jurisdictions
D^l	Set of demand areas in jurisdiction l
L^l	Set of shelters in jurisdiction l
S	Set of scenarios
<u>Parameters</u>	
TM	Capacity of the buses
TC	Transportation cost per km
$N1$	Percentage of population served by their own jurisdiction at stage 1
$Budget_l$	Operational budget at jurisdiction l
d_{ij}	Distance between demand area i and shelter j
e_{jk}	Distance between shelter j and shelter k
π_s	Probability of scenario s
Cap_j	Capacity of shelter j
Pop_i	Demand in area i
Bus_l	Number of buses available in jurisdiction l
G_j	Cost of locating facility j
H_{ks}	Availability shelter k in scenario s .
W_{jks}	Road connectivity between shelter j and shelter k in scenario s
<u>Decision variables</u>	
x_{ij}	Number of people sent from demand area i to shelter j
y_{jks}	Number of people sent from shelter j to shelter k in scenario s
A_j	Use of shelter j
R_{jks}	Number of buses going from shelter j to shelter k in scenario s
M	Maximum operational cost per person

Model

$$\text{Min } z = \sum_{i \in I} \sum_{j \in J} d_{ij} x_{ij} + \sum_{j, k \in J: j \neq k} \sum_{s \in S} \pi_s e_{jk} y_{jks} \quad (1)$$

$$\text{Min } M \quad (2)$$

$$M \sum_{i \in D^l} Pop_i \geq \sum_{j \in L^l} G_j A_j + \sum_{j \in L^l} \sum_{k \in J: j \neq k} \sum_{s \in S} \pi_s TC e_{jk} R_{jks} \quad \forall l \in L \quad (3)$$

$$\sum_{i \in I} x_{ij} + \sum_{k \in J: j \neq k} (1 - H_{ks}) y_{kjs} \leq Cap_j A_j \quad \forall j \in J, s \in S, H_{js} = 1 \quad (4)$$

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

$$\sum_{i \in I} x_{ij} = \sum_{k \in J, j \neq k, H_{ks} = 1} W_{jks} y_{jks} \quad \forall j \in J, s \in S, H_{js} = 0 \quad (6)$$

$$y_{jks} \leq TM R_{jks} \quad \forall j \in J, s \in S, H_{js} = 0 \quad (7)$$

$$\sum_{k \in J, j \neq k} R_{jks} \leq Bus_l \quad \forall l \in L, j \in L^l, s \in S, H_{js} = 0 \quad (8)$$

$$y_{kjs} \leq Cap_k \quad \forall j, k \in J, s \in S, H_{js} = 1, H_{ks} = 0 \quad (9)$$

$$\sum_{i \in D^l} \sum_{j \in L^l} x_{ij} \geq N1 \sum_{i \in D^l} Pop_i \quad \forall l \in L \quad (10)$$

$$A_j \in \{0, 1\}; x_{ij}, y_{jks}, R_{jks} \in Z^+$$

Objective function (1) minimizes the total sum of the distance travelled to go to primary and backup shelters. Objective function (2) minimizes the maximum cost of the operations (M) per person per jurisdiction to balance the burden of the different jurisdictions. The cost is calculated in inequality (3) to incorporate the cost of opening facilities and transporting people from primary to backup shelters by the number of people originally residing in the area. Inequality (4) ensures the capacity of the shelters is not exceeded, whereas equation (5) forces the system to allocate all the people in the affected area to a shelter. Equation (6) defines the number of people allocated to a primary shelter that has been damaged to transfer them to the backup shelter. Inequality (7) defines the number of buses needed whilst inequality (8) ensures the number of buses allocated does not exceed the number of available vehicles. Inequality (9) sets a limit on the number of people who can move from a damaged shelter to the backup shelter. Inequality (10) is activated if there is an agreement to ensure a percentage of the population of a jurisdiction is served by the same jurisdiction at the first stage tuning the parameter $N1$. Finally, variables are declared.

Solution Method

This research assumes that the overarching priority for authorities is to protect people. Considering the relative importance of objective function (1) over function (2), the model is solved using a lexicographic approach. The model is initially solved to minimize objective function (1) and using objective function (2) as a constraint. Then, the term LEX is introduced to fix the value of the total distance using the following equation:

$$LEX = DIS$$

A new inequality can be defined using the term LEX:

$$LEX \geq \sum_{i \in I} \sum_{j \in J} d_{ij} x_{ij} + \sum_{j,k \in J: j \neq k} \sum_{s \in S} \pi_s e_{jk} y_{jks} \quad (11)$$

Equation (11) substitutes Equation (1) in the original formulation and it becomes a constraint. The model is then solved minimizing (2) to obtain a single value that can be presented to the decision-maker.

ANALYSIS OF RESULTS

This study is divided into two parts: one using numerical examples and the second one using information from a real case study. This study uses a set of numerical experiments in the first part to analyze the performance of the model, the importance of backup shelters and to explore the value of the stochastic solution in instances of different sizes. The second part is focused on the case of an eruption of the Popocatepetl volcano in Mexico to look at the impact of transboundary coordination under real conditions.

Numerical Instances

Model Results

The model was initially tested using a set of randomly generated numerical examples. The experiments were set based on three instances of different impact shown on Table 1.

Table 1. Characteristics of the numerical examples

Instance	Demand areas p/jurisdiction	Shelters p/jurisdiction	Jurisdictions	Scenarios	Demand
<i>Low</i>	50	50	3	5	51,310
<i>Medium</i>	75	75	4	15	68,991
<i>High</i>	100	100	5	30	86,152

Parameters for the numerical examples were generated using a random number generator based on the type of variables (e.g. binary, integer). The information was coded into GAMS 35.2.0 and solved using Cplex following a lexicographic approach. Each instance was solved allowing a maximum of 12 hours for solution time per model. The process followed was to minimize objective function (1) first, then fixing the objective value, and then minimizing objective function (2) to obtain the solution. A summary of the findings is presented in Table 2. The optimality gap is defined as the distance between the objective value of the feasible solution found and its optimal value. The first two instances had a gap below 10% within the time limit of 43,200 seconds, whereas the gap of over 15% of the high instance is deemed acceptable because of its size. The results suggest that longer solution

times or heuristic algorithms might be required to close the gap in large-scale instances.

Table 2. Summary of the findings

Inst.	Total distance p/person (km)	Max buses p/1000 people	% of people across jurisdictions (Stage 1)	Max % of people across jurisdictions (Stage 2)	Max % people transferred to backup	Gap (%)	Solution time (s)
L	1.55	0.61	35.54	1.39	2.57	0.18	5.10
M	2.4	3.33	59.84	11.46	13.18	5.6	43,200
H	3.29	4.59	77.86	19.39	21.26	15.85	43,200

The results show a large percentage of people travelling across jurisdictions and requiring backup shelters. Additionally, the model was able to split the expenditure across the different jurisdictions successfully as shown in Table 3. That is also reflected in the number of shelters opened in different jurisdictions, trying to find the best combination of resources without burdening any jurisdiction.

Table 3. Analysis per jurisdiction

Instance	Cost/person/jurisdiction (MXN)		Shelters p/1000 people	
	R1	R2	R1	R2
L	62.06	62.35	0.31	0.35
	61.21	-	0.31	-
	-	-	-	-
	71.35	72.17	0.41	0.48
	71.75	72.08	0.41	0.42
M	-	-	-	-
	73.89	73.79	0.45	0.45
	73.82	74.18	0.48	0.45
	74.18	73.87	0.45	0.42
	73.87	-	0.42	-

Value of the Stochastic Solutions

To investigate the value of the stochastic solution, we calculated two traditional measures: the expected value of perfect information (EVPI) and the value of the stochastic solution (VSS) shown on Table 4. EVPI is calculated using the value of the recourse problem (RP) and the wait-and-see solution (WS) using the formula: $EVPI = z^{RP} - z^{WS}$. VSS is calculated using the values of the expected value problem (EV) and the Expectation of the Expected Value Solution (EEV) with the formula: $VSS = z^{EEV} - z^{RP}$.

Table 4. Value of the stochastic solution

Instance	EVPI		VSS (Relaxed A and C)	
	Total distance travelled p/person (km)	Max Cost/person /jurisdiction (MXN)	Total distance travelled p/person (km)	Max Cost/person /jurisdiction (MXN)
Low	0.02	12.01	0.25	13.15
Medium	0.14	21.17	0.32	0.82
High	0.29	19.35	0.28	9.13

Figure 1 shows the different solutions obtained for the problem. For all iterations we found that the values obtained

in the RP solution were higher than the values from the wait-and-see problem ($EVPI \in R^+$). The high value of EVPI, particularly in the distance travelled, shows a significant difference between the RP and WS values, which means that the variability in the problem has a significant effect on the number of people served.

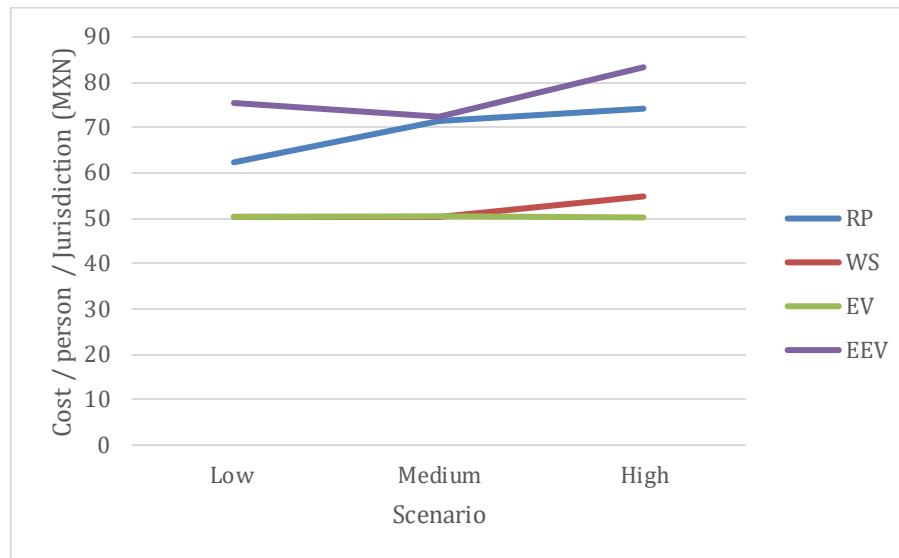


Figure 1. Results of the VSS and EVPI analysis.

The second part of the analysis looked at the cost of ignoring the uncertainty in decision-making. Initially, all the EEV problems were unfeasible when we fixed the variables from the EV solutions. That means that making decisions based on a unique expected value significantly increases the impact on people affected by the disaster. An alternative to obtain feasible EEV values is relaxing some of the first stage variables. After different tests, variable A_j was unfixed to obtain the values shown in the Table. From the practical perspective this result makes sense, given that the availability and capacity of the shelters affect the decisions about backup shelters.

Case Study

Context

The study used real information from a case study in México to investigate the impact of cross-jurisdictional coordination in disaster management. The characteristics of the case can be found in Table 5.

Table 5. Characteristics of the case study

Jurisdiction	Demand areas	Shelters	Demand (people)
EDOMEX	48	60	28,303
PUEBLA	168	141	25,495
MORELOS	107	8	4,998

The eruption of the Popocatepetl volcano in Mexico is used as a case study because of the potential impact on different States of the country. The volcano is located inside a very populated region close to Mexico city, with over 165,000 inhabitants living within 20 km from the crater and surrounded by critical infrastructure (García et al., 2023). It represents one of the latent hazards in the country (medium to high level alert) and it is surrounded by three different States: Estado de Mexico (EDOMEX) Puebla and Morelos, each one of them with response plans. The combination of latent danger of an eruption, a densely populated area and the presence of different jurisdictions make the case relevant to show the application of the model and to draw useful insights.

The purpose of this analysis was to look closer into response mechanisms considering the collaboration (or lack thereof) between the authorities of these States.

Data Collection and Gathering

The demand areas and people to evacuate were estimated using a radius of 30 km of the volcano based on

estimations from Mexican authorities. We used the census data (<https://www.inegi.org.mx/programas/ccpv/2020/>) and road networks (<https://www.gob.mx/imt/acciones-y-programas/red-nacional-de-caminos>) from Mexican authorities. The catalogues of facilities with their capacities were obtained from the States of Mexico (<https://cgproteccioncivil.edomex.gob.mx/refugios-temporales>), Puebla (<https://proteccioncivil.puebla.gob.mx/refugios-temporales>) and Morelos (<https://obrapublicas.morelos.gob.mx/pdf/rutas-de-evacuacion-y-refugios-temporales>). Shelter costs were estimated using the capacities of the shelters and the requirements per person from Mexican authorities (https://www.dof.gob.mx/nota_detalle.php?codigo=5257322&fecha=03/07/2012#gsc.tab=0). The number of buses was assumed to be 1,250 per jurisdiction.

The digitized information was used to determine demand based on distances to the volcano. The distances were calculated using Transcad© after digitizing the facilities found in catalogues from authorities and using the centroids of each one of the AGEBS (Área Geostadística Básica in Spanish – Basic Geostatistical Area). AGEBS are population units used in Mexico (similar to neighborhoods). Those distances were used to estimate transportation cost based on the consumption of diesel from Serrano-Guevara et al. (2022) and average Diesel cost in Mexico.

Two dimensions were used to generate scenarios: magnitude of the disaster and damage to the infrastructure. Using 4 levels (low, low-medium, medium-high, high), a total of $2^4 = 16$ scenarios were generated for the analysis. The probability of scenarios was generated assuming probabilities of 0.5 for low magnitude/damage, 0.25 for low-medium magnitude/damage, 0.15 for low-high magnitude/damage, and 0.1 for high magnitude/damage. The availability of facilities was defined using a random number generator [0,1].

Findings

The first part of the analysis was concentrated on coordination. The model proposed was compared with two similar models: one not allowing coordination (i.e., each State handles their own population) and another one with partial coordination (i.e., people is directed to shelters in their jurisdiction in the first instance but allowed to go to other jurisdictions for backup shelters). The results are shown in Table 6. Very small gaps show that the solutions obtained are very close to the optimal value in all the instances with solution times below 4 minutes in all cases.

Table 6. Comparison of coordination scenarios

	Total distance travelled (km)	Max cost/person/jurisdiction (MXN)	Gap	Time
Total coordination	1,298,902.38	1,828.76	0.01	204.04
Partial coordination	2,519,124.89	1,096.03	0.01	200.13
No coordination	2,547,299.96	769.18	0.00	180.74

The distance travelled by the affected people is significantly reduced by the mobility across jurisdictions, cutting the value nearly in half. An interesting aspect though is that the cost per person per jurisdiction is considerably lower when no coordination is permitted. To delve closer into that result, Table 7 is used to contrast the cost per person at each one of the jurisdictions, showing that a flow of people travels from EDOMEX and PUEBLA to MORELOS when coordination is allowed.

Table 7. Cost per person per jurisdiction

Cost/person/jurisdiction	EDOMEX	PUEBLA	MORELOS
Total coordination	715.28	891.11	1,828.76
Partial coordination	740.43	872.28	1,096.03
No coordination	713.93	659.92	769.18

We used a sensitivity analysis with partial coordination to see the behavior of the system. The results can be seen in Table 8. All the gaps were below 5%, which shows that the solutions obtained are very close to the optimal value in all the instances. Solution times are below one hour which is considered acceptable for the planning horizon of the model. The model is forcing a percentage of people (from 10% to 100%) to be served in their original State in the first stage, although there is flexibility to move to another jurisdiction in the second stage.

The results show consistent changes in distance and cost when the percentage of people is modified.

Table 8. Sensitivity analysis

Same jurisdiction	Total distance travelled (km)	Max cost/person/jurisdiction (MXN)	Time (s)	Gap
10%	1,320,293.53	1,790.93	253.60	0.17%
20%	1,364,022.34	1,753.10	464.71	4.60%
30%	1,417,004.34	1,734.19	711.82	1.40%
40%	1,490,484.15	1,647.18	962.45	0.69%
50%	1,586,394.40	1,584.34	1,218.67	0.00%
60%	1,710,150.91	1,722.72	1,481.07	0.00%
70%	1,860,978.08	1,402.67	1,736.04	2.80%
80%	2,050,855.03	1,311.74	1,991.38	4.20%
90%	2,280,056.95	1,152.80	2,239.88	0.14%
100%	2,519,124.89	1,096.04	2,478.48	0.91%

DISCUSSION

Numerical Examples

The number of people crossing boundaries to find safe places at stage one is noteworthy. The results show that nearly more than a third of the population evacuated is moving to a shelter in a neighboring jurisdiction in all three instances, with more than half of the population doing so in the medium and large instances. The number increases with the magnitude of the disaster, showing that coordination and collaboration among jurisdictions can be instrumental to protect affected people, especially for large-scale disasters.

Several articles in the literature neglect considering shelter failure and its impact on the population. Our results underscore that backup shelters are particularly important for the medium and high impact instances, although less common in the small instance. These results highlight the importance of backup shelters and transboundary coordination in disaster settings. The findings underscore the potential of the model proposed to balance the burden for the jurisdictions involved. The comparison of the different instances shows that the model maintained a similar level of expenses for all the jurisdictions involved, trying to push down the maximum cost per person per jurisdiction following the second objective function.

The analysis about the value of the stochastic solution derived large values of EVPI and VSS, showing the relevance of the two-stage stochastic formulation. Inadvertently, the unfeasibility of EEV points out a problem already identified in practice. When backup shelters are neglected, there is vulnerability in the system to have a shortage of capacity to shelter all the population needed. The VSS results confirm that neglecting to consider the uncertainty in the different instances has a significant negative effect on the outcome of the operations.

Case Study

The reason behind the lower distance traveled when cross-jurisdictional coordination is allowed compared to the instance with no coordination is because different communities from the three States are in close proximity, making it easier for them to move to some of them rather than going across their State.

It was noteworthy to find that the cost per jurisdiction was lower in the instance with no coordination compared to the instance allowing coordination. The closeness between some communities from different States and the lexicographic approach prioritizing distance travelled influence this result. When coordination is allowed people from EDOMEX and PUEBLA go to MORELOS, increasing the overall cost in that State. Once the minimum distance is fixed, the model is unable to find an answer that can balance the cost of the three States. That is an important consequence to have in mind given the importance of reducing the total distance travelled.

The sensitivity analysis shows how, the least flexibility is allowed for people to go to other States, the higher the distance they need to travel to reach a safe destination. That stresses the importance of coordination between different jurisdictions to improve the conditions faced by people affected by disasters. Maximum cost per person per jurisdiction is less clear because it depends on the results of the minimization of the total distance travelled

and the particular network in study.

Overall, the results from the numerical examples and the case study provide three main points: i) coordination and interoperability makes a significant difference in the service provided to people affected by disasters; ii) it is important to contemplate the possibility of failures in primary shelters and the need of secondary/backup shelters to successfully provide housing for people displaced by the disaster; and iii) ignoring the uncertainty in the event when making sheltering decisions has a significant negative effect in the performance of humanitarian operations.

CONCLUSIONS

This article introduces a two-stage stochastic model for the selection of primary and backup shelters for vulnerable population considering the collaboration between different jurisdictions. This study is the first one in the literature to incorporate transboundary coordination into primary and backup shelter location. The literature on transboundary coordination is still at a nascent stage, but the findings from this study show the impact of ignoring the interaction between authorities from different boundaries. Although jurisdictional and political issues can affect disaster planning, this article provides evidence that a well-coordinated joint response can be beneficial for the victims, and even for the authorities involved.

There are different opportunities for further research. The extension of policies such as the p-next center problem (Albareda-Sambola et al., 2015) can be valuable to advance similar models in the future. The experimentation with different objective functions could be useful to see the behavior of the model under different policies. Finally, the development of a heuristic to reduce solution times for larger instances would be beneficial for the application of the model in practice.

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