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ORIGINAL RESEARCH

Location and allocation of primary and backup shelters in transboundary disasters

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Abstract
There are records of people being unable to find shelter after a disaster or reaching facilities operating over capacity because of facility failure. Natural hazards do not respect geographical or political boundaries and often surpass the capacity of single jurisdictions operating with limited resources. Coordination between jurisdictions can become a solution, but it has been neglected in the literature. This article is the first to investigate the use of backup facilities as a strategy facilitated by transboundary coordination. It proposes a novel solution incorporating collaboration between multiple jurisdictions to establish a shelter location-allocation approach to protect people affected by disasters considering facility failure. The article presents a stochastic bi-objective formulation for transboundary coordination, incorporating the responsibility, priorities, and resources of each jurisdiction whilst considering the possibility of facility failure during disaster management. The objective of the model is to provide shelter to beneficiaries of all the jurisdictions by pooling resources whilst reducing the travel distance and minimizing the maximum cost for each jurisdiction. The contribution of the article is to introduce the formulation, assess the impact of transboundary coordination, and analyze the value of backup facilities in the service provided to people affected by disasters. The model has been applied to a set of numerical examples and a real case of volcanic eruptions in Mexico. The results show the influence of cross-jurisdictional coordination on the support provided to disaster victims, the value of backup facilities, and the capacity of the model designed to provide relevant alternatives in humanitarian logistics.

Keywords Multi-objective optimization · Shelter location-allocation · Cross-jurisdictional coordination · Backup facilities · Climate action

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1 Introduction

Over one million people were forced out of their homes after hurricane Katrina affected the U.S. in 2005. Although 45 pre-defined shelters were activated, a breach of the seventeenth street canal combined with the lack of preparation in the New Orleans Convention Centre forced the relocation of evacuees to other safe facilities (Nigg et al., 2006). Similarly, different reports state that facilities designated as public shelters were unavailable following the floods in Villahermosa in 2007 (Rodríguez-Espíndola et al., 2018). Recently, there has been evidence about the use of inadequate shelters and shortage of facilities after earthquakes in Morocco and Turkey (British_Red_Cross, 2023; Save_the_Children, 2023). The uncertainty about the nature of the hazard and the possibility of secondary disasters complicate the selection of reliable facilities (Ommi & Janalipour, 2022). That leads to situations where people are left without shelters or having to find refuge in shelters exceeding capacity (Ozbay et al., 2019), often with the constant risk of having to relocate evacuees multiple times (Nigg et al., 2006). That means there is a need to enhance the resilience of disaster response plans by incorporating a strategy considering potential facility failure and ensuring people allocated to those facilities can be relocated quickly and efficiently to different safe areas.

From 2020 to 2023, EM-DAT (2024) reports that natural hazards displaced more than 1.6 million people. These evacuees require the availability of safe facilities for protection and support. Shelters are often prepared in advance, but emergency services and facilities often fail in disaster situations (Albareda-Sambola et al., 2015). That is the reason facility reliability is a relevant consideration in disaster management (Hinojosa et al., 2023). The uncertainty of natural hazards and their impact on local infrastructure requires having alternative strategies to ensure there is enough capacity to shelter affected people. At the same time, limited resources from disaster management authorities constrain the availability of facilities to act as shelters. Although there are different articles in the literature calling for the construction of shelters in optimal locations (Aghaie & Karimi, 2022; Geng et al., 2021), that is an unfeasible approach for developing economies, where authorities rely on using public facilities as shelters (Liu et al., 2011). The probability of shelter failure has led to research on opening extra alternative facilities (Albareda-Sambola et al., 2015; Snyder & Daskin, 2005). In this article those alternative facilities are called backup shelters, and these are used to reduce the possibility of overcrowded shelters or leaving people without shelter. It is worth noting that backup shelters are very taxing on the resources of local authorities. In practice, these authorities have limited resources, including facilities, which hinder the implementation of the strategy of backup facilities. Current literature disregards that a strategy based on backup shelters might require facilities beyond the resources of single authorities, often working under assumptions of unlimited shelter capacity. That unrealistic assumption is translated in practice into people without shelter support.

Drafting mutual aid agreements can be an important solution for local authorities from different jurisdictions (Henstra, 2010). The collaboration of agencies from different jurisdictions is warranted because natural hazards often transcend political, functional, and temporal boundaries (Ansell et al., 2010; Nurmala et al., 2017; E.-K. Olsson, 2015a). The proximity between jurisdictions affected by the same hazard simultaneously can be used as an asset to foster the use of backup facilities (Baghersad et al., 2023). Indeed, the alternative facilities needed to operationalize the use of backup shelters can be obtained by

pooling resources from different jurisdictions through joint operations (Balcik et al., 2010; Boin et al., 2014). However, that area remains unexplored in the literature. The limited number of models incorporating this dimension is explained by the complexity of considering the interaction of different actors, resources, and responsibilities. The literature often assumes a single decision-maker with control over all of the resources, which contradicts the importance of the organizational and response structure of different countries (Rodríguez-Espíndola et al., 2018). Allowing for the interoperability of stakeholders with different resources and responsibilities adds an extra layer that is neglected by models looking at shelter management. These formulations need to include financial decisions between jurisdictions, facilitate a clear definition of activities, and promote the fair distribution of the workload in practice (Mutebi et al., 2022; Schulz & Blecken, 2010). This is an area that needs to be developed further to facilitate operations in the field. Tackling these problems requires answering two key questions: (i) How can we increase the reliability of shelter planning for disaster management? (ii) How can shelter management plans become more robust in transboundary settings?

The aim of this research is to integrate cross-jurisdictional collaboration into a stochastic multi-objective formulation for reliable shelter planning using backup shelters, an area neglected in the literature but highly relevant in practice. Stochastic programming is widely popular to address the complexity of humanitarian logistics because of its capacity to incorporate uncertainty regarding the characteristics of the disruption in the literature (Gao, 2022; Jamali et al., 2022). Stochastic optimization can be used to analyze potential scenarios and balance the resources from different stakeholders to support critical decisions in humanitarian logistics (Rodríguez-Espíndola et al., 2023). This research proposes a two-stage stochastic bi-objective optimization model to support evacuation and shelter location decisions incorporating cross-jurisdictional collaboration. The model will provide a shelter management policy based on the use of backup shelters enabled by pooling resources from different jurisdictions. The formulation is the first of its kind to incorporate the collaboration between different jurisdictions for shelter management considering the reliability of facilities and roads. The model balances the resources of multiple participants and develops the relocation plan to backup shelters whilst considering the capacity of both primary and backup facilities. The purpose is to shed light on the impact of including cross-jurisdictional coordination in humanitarian logistics models and the value of backup shelters as a viable strategy to ensure people affected by disasters can find safe facilities.

The model is tested using a set of numerical examples and a case study. The article extends current literature in three ways: (i) it proposes a novel model for operational collaboration in shelter management between stakeholders from different jurisdictions, acknowledging the possibility of the failure of any facility through the use of backup facilities, (ii) it evaluates the value of backup shelters to provide support to affected people using a set of numerical examples, and (iii) the study provides an analysis about the impact of cross-jurisdictional coordination on the experience of the people affected by the disaster using real data from a case in Puebla, Mexico. Current literature on backup facilities assumes one single actor with control of either infinite resources or not constrained by facility capacity. The model proposed in this study incorporates cross-jurisdictional coordination as an approach to enable and operationalize a shelter management policy based on the use of backup shelters. This feature also extends the literature by including a measure of fairness balancing the resources from different stakeholders. The analysis of the numerical examples contributes to

the literature by showing the percentage of the population that is likely to be allocated to an unreliable facility. The purpose is to show the positive impact that backup facilities can have in preventing leaving people without shelters or being forced to go to overcrowded shelters. Finally, the analysis of the case study contributes to the discussion about the importance of collaboration between authorities from different jurisdictions by providing evidence of the impact that collaboration can have on the level of support provided to evacuees.

The article is structured as follows: The next section shows the current state of the art of shelter management and cross-jurisdictional coordination in humanitarian logistics to show the gap this article fills. Then, we introduce the optimization model, while the next section provides the analysis of numerical examples and the case study. Finally, the conclusions are presented.

2 Literature review

2.1 Backup shelters

Shelters rendered unavailable because of the impact of disasters can create a domino effect leading to people without shelters, people living in shelters exceeding capacity, or people having to relocate constantly (British_Red_Cross, 2023; Nigg et al., 2006; Save_the_Children, 2023). That is the reason models need to consider facility failure to enhance the resilience of disaster management operations. The vulnerability of infrastructure inside areas affected by disruptions 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) and the reliability of transfer paths (Renkli & Duran, 2015; Wang & Xu, 2023). Shelters also represent key facilities for disaster management, because these are spaces used to protect people affected by disasters and to provide them with basic products and services (Eriskin & Karatas, 2024). These facilities have a major effect on the perceived experience and suffering of evacuees because several of the services received by them are provided in shelters. Shelter location involves the selection of suitable safe points to provide protection to people affected by disruptions (Kınay et al., 2018). The ample literature on shelter location (Esposito Amideo et al., 2019; Kınay et al., 2018) often overlooks shelters at the response stage (Kamyabniya et al., 2024) despite of the well-known combination of potential road damage with facility disruption that occurs after a hazard hits any area (Bera et al., 2023; Esposito Amideo et al., 2019). Most contributions in the literature focus on closeness to the population or convenience for relief supply, but more research is needed about instances where shelters are subject to failure (Ma et al., 2016).

Among the articles paying attention to potential shelter failure, there is a stream of papers focused on building facilities in suitable areas, thereby reducing the possibility of having unsuitable facilities. Aghaie and Karimi (2022) propose a two-stage robust location-allocation formulation supported by geographical information systems to minimize the cost and time of the operations solved with NSGA-II, whilst Geng et al., (2021) introduce a bi-objective location-allocation model maximizing the suitability of the shelter based on qualitative factors, and minimizing the number of facilities. However, in many countries the policy is to adapt existing facilities as shelters (Liu et al., 2011), which are often vulnerable to failure. Facilities can be rendered unusable because of external factors as well. For

instance, the work of Gangwal et al., (2023) and Wang and Xu (2023) show that road failure can lead to isolated shelters regardless of their actual location.

A different stream of research advocates for having alternative facilities to transport people in case of shelter failure, i.e. backup shelters. This is an interesting approach because it adds flexibility to the operations and helps manage the uncertainty about the actual impact of the disruption. There are a few deterministic models in the literature tackling this area. Albareda-Sambola et al., (2015) base their analysis on the p-center problem to select primary and backup facilities for victims. The three-indexed, two-indexed, and covering formulations locate shelters close to the victims in case they reach their closest center, but it is closed. The article introduces an assessment of the efficiency of the formulations based on small and large-scale instances solved with the Xpress Optimizer. Albareda-Sambola et al., (2019) extend that idea by considering different strata of people requiring different services. The article proposes formulations with stratum-covering variables, site-covering variables and combining both, which are solved using the sample average approximation method. Beyond some deterministic approaches, most studies in the literature incorporate uncertainty in the situation through the use of two-stage stochastic programming. Hinojosa et al., (2023) extend the p-next center problem by incorporating the preferences of the users. The article proposes a three-indexed, straight and radius formulations which are solved using a tailored heuristic algorithm. The model adopts 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 presented disregard the capacity of the facilities. In practice, there are reports of shelters operating over capacity and its negative impact on the support provided to people affected by the disaster (Kilci et al., 2015; Ozbay et al., 2019), which is a limitation acknowledged by Albareda-Sambola et al., (2015). An et al., (2013) propose a two-stage formulation assuming that each facility is subject to independent probabilistic disruptions which are represented in a set of scenarios. The objective of the model is to minimize total cost and it is solved using CPLEX in GAMS. Their formulation defines the allocation upon the realization of the corresponding scenario, which requires the government to notify and direct all the evacuees. Babashahi et al., (2020) use stochastic modelling for a bi-objective formulation maximizing network reliability whilst minimizing cost considering facility capacity. The study uses reserve hub elements as backup components to prevent failure considering failure probabilities calculated based on incoming traffic. The authors propose solving the model with Cplex and NSGA-II. Nonetheless, the location and re-location of shelters is still a critical gap in need of more research (Kamyabniya et al., 2024). A challenge to pursue this approach is resource constraints in the operations, especially because of the lack of flexibility about suitable facilities. Enabling collaborative mechanisms to pool resources and collaborate across jurisdictions to manage the situation is critical to consider nature of disasters affecting multiple areas simultaneously under resource constraints (Rodríguez-Espíndola, 2022). That is a dimension currently missing in existent models in the literature.

2.2 Coordination across jurisdictions

Disasters are often connected across jurisdictions, with the outcome of one jurisdiction affecting the situation in another one (Ansell et al., 2010) and involving conflicting objectives (Rui et al., 2008). Recent studies show that, in many cases, each jurisdiction has their

own response policies (Baghersad et al., 2023). Deciding whose resources to use in these environments is complex because of the inability to ensure fair allocation of joint operations, leading to concerns about fair distribution of shared workload and significant ambiguity about activities and responsibilities (Mutebi et al., 2022; Schulz & Blecken, 2010). The combination of these problems can negatively influence the efficiency and service level provided, which is the reason research can facilitate this complex collaboration. Still, the review of Kamyabniya et al., (2024) looking at optimization models for disaster response operations show that less than 13% of the papers considered the collaboration of relief actors, with far less looking into cross-jurisdictional collaboration. That makes developing models incorporating the interaction between different stakeholders a gap that needs to be filled in the area, especially developing formulations using equity among participants, which is only adopted by one article in the category of shelter location (Kamyabniya et al., 2024).

Research discusses the problems associated with formal structures in handling new and complex problems (Olsson, 2015a) 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 to minimize confusion and bureaucratic infighting. Collaboration between municipalities, countries and different services, for instance, can enable more effective operations (Ruktanonchai et al., 2020; Zikeloglou et al., 2024). Although it is acknowledged that having customized responses at each jurisdiction is useful, the lack of mechanisms enabling cross-jurisdictional collaboration can effectively hinder the impact of such plans (Baghersad et al., 2023). That is the reason the European Union 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). For instance, Polese et al., (2024) propose an approach for cross-border multi-risk assessment as an answer for single-risk and independent assessments. Nonetheless, this area has been less studied in the context of 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. The study proposes a discrete-event simulation implemented in AnyLogic to test the scenario of a nuclear device detonating in the middle of an urban area to efficiently assess the use of facilities to improve coordinated responses. Wang et al., (2022) propose a two-stage stochastic model to support the collaboration and coordination of a regional healthcare coalition. The model minimizes total cost and the maximum expected supply shortage rate over all member hospitals and supply types. The study proposes the use of the linear weighting method to obtain the solution. The model facilitates collaboration for stock pre-positioning and post-disaster procurement and transshipment to serve affected areas. Baghersad et al., (2023) propose a quadratic-programming model to identify optimal coordination jurisdictions to manage an epidemic based on population mobility. The formulation maximizes modularity, and it is solved using a heuristic and column-generation algorithm. The approach proposed allows identifying interconnected contiguous locations to join them as coordination communities, but it creates these new jurisdictions rather than supporting the coordination of established political jurisdictions. Overall, the literature available fails to facilitate cross-jurisdictional coordination in instances facing facility failure. The summary of models found in the literature is illustrated in Table 1.

Table 1 Comparison of similar models

Article	Problem	Type of modelling	Objective(s)	Multiple actors	Reliability of facility	Reliability road	Capacity	Solution
An et al., (2013)	Facility location, allocation and evacuation	Two-stage stochastic	Minimize cost		✓			Cplex
Albareda-Sambola et al., (2015)	Facility location-allocation	Deterministic modelling	Minimize maximum cost of allocation		✓			Xpress
Albareda-Sambola et al., (2019)	Facility location-allocation	Deterministic modelling	Minimize the weighted average of the largest distance for each people stratum		✓			Sample average approximation in Xpress
Babashahi et al., (2020)	Facility location, allocation and evacuation	Stochastic modelling	Minimize cost Maximize reliability		✓		✓	E-constraint method using Cplex and NSGA-II
Wang et al., (2022)	Facility location, pre-positioning and procurement	Two-stage stochastic	Minimize cost Minimize maximum expected shortage	✓			✓	Gurobi
Hinojosa et al., (2023)	Facility location-allocation	Two-stage stochastic	Minimize the maximum of the distances travelled by the users		✓			Heuristic algorithm
Baghersad et al., (2023)	Community detection	Deterministic modelling	Maximize modularity of communities	✓				Column generation algorithm
This study	Facility location-allocation	Two-stage stochastic	Minimize distance. Minimize maximum cost per person per jurisdiction	✓	✓	✓	✓	Lexicographic optimisation in Cplex

2.3 Research gap

The need for research looking at shelter management at the response stage (Kamyabniya et al., 2024) is reflected in the limited number of articles considering alternative facilities to manage shelter failure and isolation. In practice, that means experiences of shelters operating over capacity or leaving people without shelter. This article argues that shelter management needs to incorporate pre-disaster and post-disaster conditions. This task can be achieved through the development of models facilitating coordination across different jurisdictions that are affected by transboundary disasters. This paper designs and tests a novel optimization model to locate and allocate primary and backup shelters enabling the coordination and use of resources from different jurisdictions. The bi-objective two-stage stochastic formulation proposed in this article has suitable novelties compared with the works found in the current literature, such as:

2.3.1 Cross-jurisdictional coordination considering shelter failure

Although there is wide agreement about the need to consider different participants in disaster management and the potential of cascading effects between them (Rodríguez-Espíndola, 2023), our review agrees with claims from Nowell et al., (2022) about the limited understanding about cooperative management during crises and disasters, which is reflected in the fact that current optimization models are ill-equipped to consider the coordination of different jurisdictions for shelter management. The limited number of optimization models considering the interaction between stakeholders, none of which has been developed considering shelter failure (Kamyabniya et al., 2024) is noteworthy. This article argues that the limitation of neglecting capacity in several optimization models looking at backup shelters in the past can be tackled by incorporating the collaboration between different stakeholders. This article provides the first formulation combining cross-jurisdictional coordination with the possibility of allowing people to go to backup shelters when their primary shelters are unavailable.

2.3.2 Reliability in the facility, road and capacity

Facilities can be rendered useless by damage to the facility itself, along with isolation caused by damage around the facility. The model proposed in this research accounts for that by introducing the possibility of damage to facilities or roads along with limited capacity in the remaining facilities. That approach allows having more reliable and realistic plans to enhance the evacuation of people affected by disasters.

2.3.3 Use of equity as an objective criterion in cross-jurisdictional coordination

Most of the articles looking at shelter failure aim to minimize cost and distance during evacuation activities to define the allocation of people to facilities. Although equity between disaster victims has been explored before (Zhu et al., 2019), equity between participants is often disregarded in these formulations. This article proposes an objective function minimizing the maximum use of resources from each one of the jurisdictions involved to promote the collaboration between different stakeholders.

The article is tested in a set of numerical examples and using information from real conditions of a volcano eruption in Puebla, Mexico. The case study provides insight into the importance of coordination between jurisdictions for evacuation and shelter management through the comparison of scenarios with total collaboration, partial collaboration and null collaboration. The results can be used to foster the development of more contributions incorporating transboundary coordination.

3 Mathematical model

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

Optimization is commonly used 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 (Kınay et al., 2018). It has been selected in prior research in the area because it allows balancing the support provided to disaster victims and the resources available during disasters (Aghaie & Karimi, 2022; Ergün et al., 2023; Hinojosa et al., 2023). Optimization is seen as a good fit for supporting decision-making in humanitarian logistics because of its capacity to handle different variables in complex problems (Baharmand et al., 2022).

Two-stage stochastic optimization is a popular approach to tackle complex problems involving uncertainty (Gao, 2022). In the context of humanitarian logistics, two-stage models allow tackling some decisions focused on the stage before the occurrence of the disaster, and other decisions after the disaster strikes (Jamali et al., 2022). The use of two-stage optimization allows us to incorporate the uncertainty about the impact of the disaster and the state of the infrastructure, where the first stage focuses on the primary allocation of facilities and the second stage uses information about the impact of the disaster to guide response decisions including the allocation to backup facilities considering different scenarios.

3.1 Problem description

Disasters do not respect jurisdictional borders (Lane & Hesselman, 2017). Cross-jurisdictional coordination allows people evacuated in a demand area to travel to the most beneficial facility for them, regardless of the jurisdiction. That maximizes the use of resources from different participants whilst enabling people to attend their closest facility. This idea is aligned with the findings from Ruktanonchai et al., (2020) after the COVID-19 pandemic, which suggest that coordinating different countries geographically connected can boost effectiveness. The cooperation of different authorities can add a degree of resilience to disaster management plans because it facilitates reaching any of the participants and reduces the possibility of any of them being overwhelmed by the conditions of the disaster. However, this area has not been explored before. The use of backup shelters is acknowledged as a valuable policy to manage facility failure, but it is difficult to implement because of the capacity of the facilities. That is reflected in articles neglecting capacity constraints in these settings (Albareda-Sambola et al., 2015). Transboundary coordination can enable the

use of backup shelters because of the possibility of pooling resources (Balcik et al., 2010; Boin et al., 2014), but it is met with complications about the responsibilities, priorities and resources of different jurisdictions (Nowell et al., 2022). The contribution of the model is to facilitate the use of capacitated facilities from different jurisdictions to serve affected people whilst considering the agreements about the minimum number of people served per jurisdiction, reducing the financial burden for any single jurisdiction and allowing the transference between jurisdictions in the event of facility or road failure to maximize the service provided. This is achieved using two-stage stochastic programming to account for decisions before and after the disaster, along with multi objective optimization balancing the service provided to the victims with fairness in the use of resources from different jurisdictions.

In the formulation, first stage decisions are focused on facility selection and the flow of people from demand areas to primary shelters right before the event. Given the range of time for the arrival of people, it is assumed that people will get there by their own means before the disaster strikes. That means all eligible vulnerable people proceed to evacuate their homes at the stage when evacuation orders are issued, forcing authorities to prepare the plan to cater to all the pre-identified people using demographic information and risk maps. First stage variables include the allocation to primary shelters and the activation of facilities as shelters. Second-stage decisions are based on different scenarios incorporating the uncertainty about the infrastructure and including the allocation of people in unsuitable shelters to backup shelter and the number of buses required to transfer people to backup facilities. That means the second stage considers scenarios based on the uncertainty of the disaster and the impact on infrastructure. Buses are resources provided by authorities and they are assumed to have information about their availability in advance. It is important to note that the model considers the availability of backup shelters and the connectivity to reach them from affected shelters. Given the importance of consider the influence of preparedness activities on disaster response (Seraji et al., 2022), this approach provides more realistic solutions for decision-makers. The decisions made by the model are reflected in Fig. 1.

The model uses information about the damage to the road network and to the different facilities to transfer people to safe facilities. The assumption in the model is that authori-

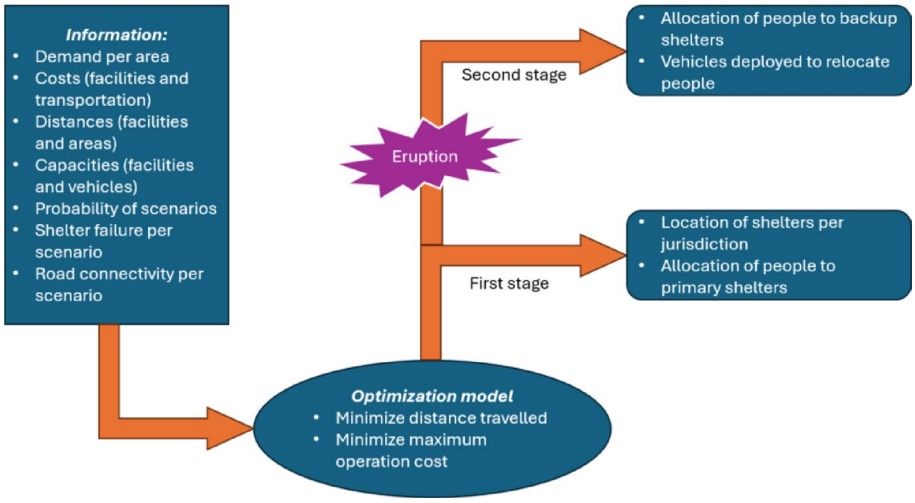

Fig. 1 Diagram of the situation

ties will make buses available to take people from unsuitable facilities to backup shelters. A set of disaster scenarios is used to guide these decisions to consider uncertainty on the magnitude and impact of the disaster. The second stage is focused on the decisions about transportation of people, defining the number of people to move to facilities in the same or different jurisdictions. The coordination of authorities from different jurisdictions is critical to achieve successful operations in transboundary disasters (Ansell et al., 2010). The model can allocate people freely across all jurisdictions (full coordination), or it can accommodate the possibility to force a minimum percentage of the population from each jurisdiction to be served by its jurisdiction at the first stage (partial coordination) to respect pre-defined agreements. The latter adds flexibility to the negotiations between stakeholders to facilitate agreements.

3.2 Model assumptions

- Mandatory evacuation orders have been issued.
- The number of people evacuating in each jurisdiction is known by authorities.
- The number of buses available for evacuation operations is known in advance by authorities.
- Every eligible person affected must be served.
- People make their way to primary shelters, but they are transferred to backup shelters on buses (if needed).
- Shelters can be used as primary and backup simultaneously.
- Only road transportation is available.
- There is uncertainty about the magnitude and the impact of the disaster.
- Different jurisdictions share their resources and accept people from nearby jurisdictions in their facilities.

3.3 Notation

The notation of the model is as follows:

Sets	
I	Set of demand areas
J	Set of potential shelter locations
L	Set of jurisdictions
D^l	Set of demand areas in jurisdiction $l \in L$
L^l	Set of shelters in jurisdiction $l \in L$
S	Set of scenarios
Parameters	
α	Capacity of the buses
β	Transportation cost per km
Ω	Percentage of population served by their own jurisdiction at stage 1
δ_{ij}	Distance between demand area $i \in I$ and shelter $j \in J$
e_{jk}	Distance between shelter $j \in J$ and backup shelter $k \in J$
π_s	Probability of scenario $s \in S$

Sets	
γ_j	Capacity of shelter $j \in J$
μ_i	People in demand area $i \in I$
σ_l	Number of buses available in jurisdiction $l \in L$
ξ_j	Cost of locating facility $j \in J$
ψ_{ks}	Availability of shelter $k \in J$ in scenario $s \in S$
λ_{jks}	Road connectivity between shelter $j \in J$ and shelter $k \in J$ in scenario $s \in S$
Decision variables	
x_{ij}	Number of people sent from demand area $i \in I$ to shelter $j \in J$
y_{jks}	Number of people sent from shelter $j \in J$ to shelter $k \in J$ in scenario $s \in S$
A_j	Use of shelter $j \in J$
R_{jks}	Number of buses traveling from shelter $j \in J$ to shelter $k \in J$ in scenario $s \in S$
C_k	Spare capacity of shelter $k \in J$
M	Maximum operational cost per person among all jurisdictions

The model is as follows:

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

$$Min\ M \tag{2}$$

The objective functions of the optimization problem are critical to ensure the solutions are relevant for decision-makers. The discussions in the literature about the best performance measures for humanitarian logistics involve efficiency, effectiveness and flexibility measures (Beamon & Balcik, 2008). The complexity of humanitarian operations is difficult to encapsulate in a single performance measure. That is the reason several articles consider more than one objective function to ensure efficiency in the operations (Gutjahr & Nolz, 2016). Indeed, there are several arguments in the literature about the importance of incorporating multiple objectives to address the complexity of disaster management (Burkart et al., 2017). The objectives of the model have been developed considering the context and the problem and the perspectives of different jurisdictions. Initially, aligned with the need to give a good level of support to people affected (Farahani et al., 2020), the first objective of this research (1) is to minimize the distance traveled by people affected to primary and secondary shelters. Given the limited resources available during humanitarian operations, the second objective function is efficiency based. The minimization of costs is widely used in the field because it considers the use of resources at different stages. The flexibility of this measure (Alem et al., 2016) enables incorporating the fairness between jurisdictions. Neighboring jurisdictions are more willing to collaborate when overall costs can be reduced whilst providing support to the people affected (Hollis, 2020). To promote that collaboration, the second objective function (2) minimizes the maximum cost of the operations per person per jurisdiction to balance the burden of the different jurisdictions.

Subject to:

$$M \sum_{i \in D^l} \mu_i \geq \sum_{j \in L^l} \xi_j A_j + \sum_{j \in L^l} \sum_{k \in J: j \neq k} \sum_{s \in S} \pi_s \beta\ e_{jk} R_{jks} \quad \forall\ l \in L \tag{3}$$

$$\sum_{i \in I} x_{ij} \leq \gamma_j \; A_j \quad \forall j \in J \tag{4}$$

$$\sum_{j \in J} x_{ij} = \mu_i \quad \forall \; i \in I \tag{5}$$

$$C_k = A_k \gamma_k - \sum_{i \in I} x_{ik} \quad \forall \; k \in J \tag{6}$$

$$\sum_{i \in I} x_{ij} = \sum_{k \in J, j \neq k, \psi_{ks}=1} \lambda_{jks} y_{jks} \quad \forall \; j \in J, \; s \in S, \psi_{js} = 0 \tag{7}$$

$$y_{jks} \leq \alpha \; R_{jks} \quad \forall \; j \in J, \; s \in S, \psi_{js} = 0 \tag{8}$$

$$\sum_{k \in J, j \neq k} R_{jks} \leq \sigma_l \quad \forall \; l \in L, j \in L^l, \; s \in S, \psi_{js} = 0 \tag{9}$$

$$\sum_{j \in J} y_{jk} \leq C_k \psi_{ks} \quad \forall \; k \in J, \; s \in S \tag{10}$$

$$\sum_{i \in D^l} \sum_{j \in L^l} x_{ij} \geq \Omega \sum_{i \in D^l} \mu_i \quad \forall \; l \in L \tag{11}$$

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

The cost is calculated in expression (3) weighing the cost of opening facilities and transporting people from primary to backup shelters by the number of people originally residing in the area. Expression (4) ensures the capacity of the shelters is not exceeded, whereas Eq. (5) forces the system to allocate all the people in the affected area. Equation (6) determines the spare capacity of the shelters after primary allocation to use the facility for backup. Expression (7) defines the number of people allocated to a primary shelter that has been damaged to transfer them to the backup shelter. Constraint (8) defines the number of buses needed whilst Expression (9) ensures the number of buses allocated does not exceed the number of available vehicles. Expression (10) ensures people transferred to unaffected backup shelters do not exceed their spare capacity and Constraint (11) enforces any agreements to ensure a percentage of the population of a jurisdiction is served by the same jurisdiction at the first stage. Finally, variables are declared.

3.4 Solution method

There are several approaches to solving multi-objective formulations because these models do not provide a single solution, but a set of non-dominated solutions (Gutjahr & Nolz, 2016; Rodríguez-Espíndola, 2022). Decision-makers have the possibility to look at the different non-dominated solutions to select the most appropriate one for them according to their preferences and priorities (Lu et al., 2022). Some approaches include linearizing the weighted objectives and the use of the epsilon constraint model (Burkart et al., 2017; Wang

et al., 2022). This article assumes that authorities have the primary objective of protecting people. That means there is a hierarchy between the objectives, which makes a lexicographic approach suitable to solve the model (See Dang et al., 2023). The model is initially solved by minimizing objective function (1). Then, the term LEX is introduced to fix the value of the total distance obtained using the following equation:

$$LEX = DIS$$

A new inequality can be defined using the term LEX:

$$LEX \geq \sum_{i \in I} \sum_{j \in J} \delta_{ij} x_{ij} + \sum_{j,k \in J: j \neq k} \sum_{s \in S} \pi_s e_{jk} y_{jks} \tag{12}$$

Equation (12) substitutes Eq. (1) in the original formulation and it becomes a constraint. The model is then solved by minimizing (2) to obtain a single solution that can be presented to the decision-maker.

4 Analysis of results

This section introduces a set of experiments to show the behavior of the model, investigate the value of the stochastic approach used and analyze the impact of cross-jurisdictional coordination to provide shelter support to people affected by disasters. The study is divided into two parts: the first part is based on the use of numerical examples, and the second part is conducted based on information from a real case study in Mexico. Numerical experiments in the first part serve 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 provides evidence about the performance of the model considering real conditions to discuss the impact of cross-jurisdictional coordination based on the need of using real data sources to enhance the validity of the outcomes of the model (Kamyabniya et al., 2024). The case selected for the analysis is an eruption of the Popocatepetl volcano in Mexico, which is one of the most challenging scenarios for the country.

4.1 Numerical instances

The model was tested using a set of randomly generated numerical examples. The examples represent instances of different magnitudes; low, medium and large. The characteristics of the three instances are shown in Table 2. The parameters for each example were generated using a random number generator based on the type of variables (e.g. binary, integer).

4.1.1 Results analysis

The information was coded into GAMS 35.2.0 and solved using Cplex with the lexicographic approach explained in the previous section. The model was run on a computer with an Intel Core i7 processor and 16 GB of RAM. Each instance was set to have a maximum of 12 hours for solution time. The model was run allowing total coordination between the dif-

Table 2 Characteristics of the numerical examples

Instance	Demand areas *p*/jurisdiction	Shelters *p*/jurisdiction	Jurisdictions	Scenarios	Demand (people)
Low	50	50	3	5	51,310
Medium	75	75	4	15	68,991
Large	100	100	5	30	86,152

Table 3 Summary of the findings

Inst.	Average distance *p*/person (km)	% of people crossing jurisdictions (Stage 1)	Max % of people across jurisdictions (Stage 2)	Max % people transferred to backup	Gap (%)	Solution time (s)
Low	1.55	35.54	1.39	2.57	0.18	5.10
Medium	2.4	59.84	11.46	13.18	5.6	43,200
Large	3.29	77.86	19.39	21.26	15.85	43,200

ferent jurisdictions involved in the situation. The process followed was to minimize objective function (1) first, then fix the objective value, and finally minimize objective function (2) subject to the fixed value of (1). A summary of the findings is presented in Table 3. The optimality gap is 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, whereas the gap of around 15% of the large instance is deemed acceptable because of the size of the problem. The experiments conducted suggest that longer solution times or heuristic algorithms might be required to close the gap in very large-scale instances.

The number of people crossing boundaries to find safe places at stage one is noteworthy. The results show that more than a third of the population evacuated is moving to a shelter in a neighboring jurisdiction in all the 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. This result supports the claim that the larger the magnitude of the disaster, the more cross-jurisdictional it becomes (Ansell et al., 2010). The percentage is lower at the second stage, but there are still cases of people needing a backup shelter that are transferred to one of the neighboring jurisdictions, especially in instances of large magnitude. We also need to consider that the percentage of people moving across jurisdictions at the second stage does not include people that moved between jurisdictions at the first stage and stayed in that new jurisdiction at the second stage, so the percentage of people that crossed jurisdictions during both stages is very high in the three instances.

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 magnitude instances. In the high magnitude instance, more than one in every five people affected requires being transferred to backup shelters at the second stage because of damage to the infrastructure. Those medium and large magnitude instances are the focus of humanitarian logistics models, showing that facility failure should be an important consideration at the response stage in these models. In practice, managers can look at

Table 4 Results of backup shelters

Instance	Max people requiring backup shelter	Max number of buses	Average distance *p*/person	Max % of people attending shelters across jurisdictions
Low	1,318	31	10.83	69.27
Medium	9,090	191	8.06	87.00
Large	18,314	386	9.44	91.24

Table 5 Analysis per jurisdiction

Instance	Cost/person/jurisdiction (MXN)		Shelters *p*/1000 people	
L	R1	62.06	R1	0.31
	R2	62.35	R2	0.35
	R3	61.21	R3	0.31
M	R1	71.35	R1	0.41
	R2	72.17	R2	0.48
	R3	71.75	R3	0.41
	R4	72.08	R4	0.42
H	R1	73.89	R1	0.45
	R2	73.79	R2	0.45
	R3	73.82	R3	0.48
	R4	74.18	R4	0.45
	R5	73.87	R5	0.42

the percentage of people without available shelters or the number of facilities that need to be closed after the disaster to recognize the impact of facility failure in their operations.

Table 4 shows the results about backup shelters. Although the average distance per person is higher than the distances found at the first stage, the trip to backup shelters is done by buses from authorities, making the distance acceptable. This table also shows the effect of combining cross-jurisdictional coordination with backup shelters, as most of the people requiring a backup shelter are travelling to a neighboring jurisdiction in the three cases.

The use of financial resources is a complex issue in humanitarian operations. The opportunity to deliver effective results whilst carefully managing the expenditure for participants can foster collaboration (Hollis, 2020). The model has been designed to find the best combination of resources to allow reducing the burden for all jurisdictions. The rationale is that different jurisdictions will be more willing to collaborate if there is a fair distribution of the workload and more clarity about the expenditure required. After the minimum travelled distance for all the beneficiaries is achieved, the model tries to balance the cost by minimizing the maximum cost for each one of the jurisdictions involved. This was tested by analyzing the cost and number of facilities required per jurisdiction for each one of the instances. The results shown in Table 5 suggest that the solution offered by the model is splitting the expenditure across the different jurisdictions successfully. In all instances, the difference in the expenditure per person between jurisdictions is small and there is a balance in the number of shelters activated per 1,000 people.

Overall, these results highlight the importance of backup shelters and cross-jurisdictional coordination in disaster settings. Coordination can be valuable to provide more and better alternatives to people affected, especially when combined with the strategy of using backup

shelters to enhance the robustness of the relief network. The findings also 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.

4.1.2 Value of the stochastic solutions

Stochastic optimization assumes some data can be represented with uncertain parameters, which can be used to make a set of decisions before the event (first-stage) and another set of decisions after the event (second-stage) (Birge & Louveaux, 2011). The decision to use stochastic programming introduces a higher level of complexity in the optimization model because it becomes more difficult to solve (Shapiro & Nemirovski, 2005). That increased complexity needs to be balanced with the advantage of modelling different risk attitudes, the necessity to introduce uncertainty in the situation, and the need for more realistic solutions (Chang et al., 2022; Kamyabniya et al., 2024; Nazemi et al., 2021). Although several models in the literature have stated the value of two-stage stochastic models for disaster relief (Kamyabniya et al., 2024; Ozbay et al., 2019), the complexity of stochastic models requires addressing problems where the stochastic solution is relevant and it can contribute to get an useful solution to the problem. Hence, this article investigates the suitability of two-stage stochastic programming for the problem at hand.

The value of the stochastic solution is analyzed using two traditional measures: the expected value of perfect information (EVPI) and the value of the stochastic solution (VSS) shown in Table 6. EVPI is calculated using the value of the recourse problem (RP) and the wait-and-see solution (WS) through the formula: $EVPI = z^{RP} - z^{WS}$ (Mahootchi & Golmohammadi, 2018). VSS is calculated using the expected value problem (EV) and the Expectation of the Expected Value Solution (EEV) through the formula: $VSS = z^{EEV} - z^{RP}$. Both measures are useful to test the benefits of using stochastic models to tackle the problem.

The Table shows positive and significant values for both measures. The analysis of both objective functions allowed us to understand more about the behavior of the model. Figure 2 shows the RP, WS, EV and EEV values for the three instances for the first objective function. In all instances, the RP values were higher than WS and EV values, and lower than the EVV values, as expected, whereas the EV and WS values were nearly the same.

Figure 3 shows the different solutions obtained for the problem for the second objective function, with similar behavior, although WS was higher than EV in the third instance. Overall, in both functions the values obtained in the RP solution were higher than the values

Table 6 Value of the stochastic solution

	EVPI ($z^{RP} - z^{WS}$)		VSS ($z^{EEV} - z^{RP}$) *	
Instance	Difference in the total distance travelled (km)	Difference in the Max Cost/person /jurisdiction (MXN)	Difference in the total distance travelled (km)	Difference in the Max Cost/person /jurisdiction (MXN)
Low	791.39	12.01	12,627.55	13.15
Medium	9,769.97	21.17	22,008.32	0.82
High	24,708.94	19.35	24,023.32	9.13

* Relaxed A_j and C_k

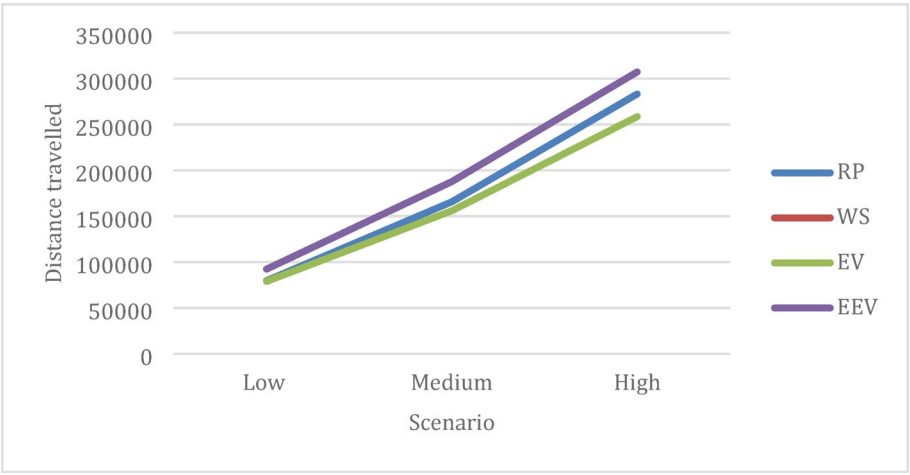

Fig. 2 Results of the VSS and EVPI analysis for objective function (1)

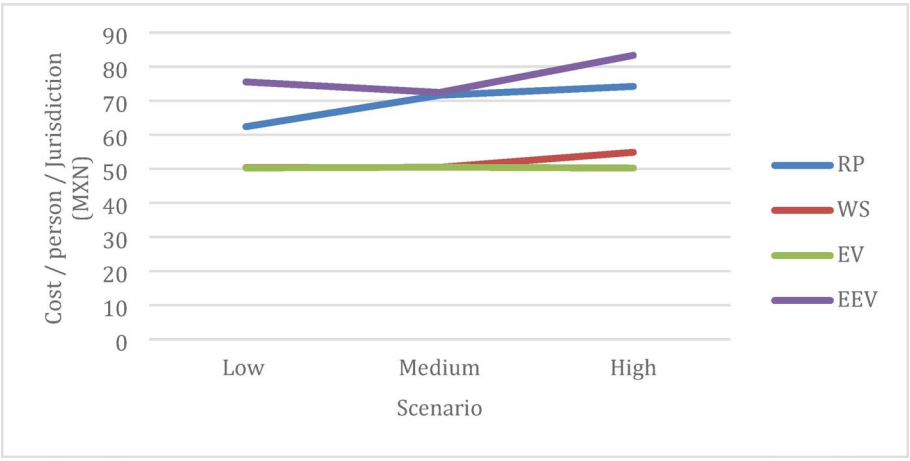

Fig. 3 Results of the VSS and EVPI analysis

from the wait-and-see problem ($EVPI \in R^{+}$). The high value of EVPI, particularly in the distance travelled, is the result of a significant difference between the RP and WS values, which means that the variability in the problem has a significant effect on the distance travelled and the expected cost per person per jurisdiction.

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 first-stage decisions from the EV solutions. That means that making decisions based on a unique expected value rather than the proposed set of scenarios significantly increases the distance travelled and the expected cost per person per jurisdiction. Inadvertently, this result points towards a problem already identified in previous events. When the need for backup shelters is neglected, the system is vulnerable to shelter shortages and/or the use of resources increases

considerably. From the practical perspective this result makes sense, given that overlooking facility failure would complicate having the capacity to provide support to all the beneficiaries. An alternative to reach feasible EEV values is relaxing some of the first stage variables. After different tests, variables A_j and C_k were unfixed to obtain the values shown in the Table. When the availability of shelters and their capacity are unfixed, then the model can find solutions to shelter all the people available. The VSS results confirm that neglecting uncertainty in the different instances has a significant negative effect on the outcome of the operations. Overall, our analysis shows that stochastic modelling is relevant to tackling the coordination of multiple jurisdictions for shelter management considering facility failure.

4.2 Case study

4.2.1 Context

Testing the model under real conditions allows us to get more insights about the impact of cross-jurisdictional coordination for shelter location and allocation and its practical implications. The study used information from a case study in México to analyze the research questions. The characteristics of the case can be found in Table 7.

The eruption of the Popocatépetl 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 which is very close to Mexico City, with over 165,000 inhabitants living within 20 km from the crater. The risk is increased by the presence of critical infrastructure in the surrounding area (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. Currently, civil protection departments follow their operative plan for management of a disaster caused by the volcano at each one of the States (Civil_Protection_Edomex, 2025; Civil_Protection_Morelos, 2019; Civil_Protection_Puebla, 2025). Although the documents suggest interaction between jurisdictions when the emergency is at Federal level (Civil_Protection_Edomex, 2025), current plans for evacuation routes favors response within jurisdictions (Civil_Protection_Puebla, 2025). There is a need to define mechanisms to facilitate the cooperation between jurisdictions to improve the level of service provided to people affected. The combination of latent danger of an eruption, a densely populated area and the presence of different jurisdictions makes the case relevant to show the application of the model and to draw 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.

4.2.2 Data collection and gathering

The demand areas and people to evacuate were defined using a radius of 30 km of the volcano based on estimations from Mexican authorities. The jurisdictions involved are the three States potentially affected. We used the census data (https://www.inegi.org.mx/pro

Table 7 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

gramas/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 to the States of Mexico (https://cgproteccioncivil.edomex.gob.mx/refugios_temporales), Puebla (https://proteccioncivil.puebla.gob.mx/refugios-temporales) and Morelos (https://obraspublicas.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?%20codigo=5257322&fecha=03/07/2012#gsc.tab=0). The maximum 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 Geoestadística Básica in Spanish – Basic Geostatistical Area). AGEBs are population units used in Mexico and defined by the Instituto Nacional de Estadística y Geografía (INEGI) (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: impact 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 impact/damage, 0.25 for low-medium impact/damage, 0.15 for low-high impact/damage, and 0.1 for high magnitude/damage. The availability of facilities was defined using a random number generator [0,1].

4.2.3 Findings

The purpose of this part was to investigate the existence of any benefits of allowing the coordination of multiple jurisdictions to shelter people affected by the eruption. The model proposed was compared with another two similar models: one not allowing coordination (i.e., each State handles the needs of their own population) and another one with partial coordination (i.e., people are required to be served in their own jurisdiction at the first stage but allowed to go to any jurisdiction if they require a backup shelter). The results are shown in Table 8. Very small gaps suggest that the solutions obtained by Cplex using the lexicographic approach proposed are very close to the optimal value in all the instances, with solution times below four minutes in all cases. Although two-stage models are more complex to solve (Shapiro & Nemirovski, 2005), the results are encouraging in the sense that the lexicographic solution approach allows users to get solutions quickly to inform decision-making in a real-size instances. Given the importance of uncertainty in the problem and the solution

Table 8 Comparison of coordination scenarios

Instance	Total distance travelled (km)	Max cost/ person /jurisdiction (MXN)	Max people crossing jurisdictions (stage 1)	Max people across jurisdictions (stage 2)	Max people in backup	Gap (%)	Time (s)
Total coordination	1,298,902	1,828.76	25,957	212	19,729	0.01	204.04
Partial coordination	2,519,125	1,096.03	0	4,796	24,907	0.91	238.6
No coordination	2,547,300	769.18	0	0	19,242	0	180.74

time results, the characteristic of the model proposed can be relevant for implementation in practice.

The distance travelled by the affected people is significantly reduced by the mobility across jurisdictions, cutting the value nearly in half. The reason behind the lower distance traveled when cross-jurisdictional coordination is allowed is because different communities from the three States are in close proximity, making it easier for them to move to some of the adjoining jurisdictions rather than going farther into their State. Our findings support the claims from the Geographical Information System analysis of Eom et al., (2022) about the potential of cross-jurisdictional coordination to reduce evacuation time, and it extends it by showing that the collaboration is essential when there is system failure. Facilitating a coordinated response as opposed to approaches that promote responses within each jurisdiction can have a significant effect on the people affected. According to our results, if evacuation routes and facility decisions are pre-planned considering a single State, the distance travelled by people will be significantly higher, especially considering the potential uncertainty in the area and the disruptions to the infrastructure. That is clearly reflected in over 44% of people finding shelter in a different jurisdiction at the first stage when coordination is allowed. This is sensible as the model considers the geographical distribution of the people affected and the safe areas, rather than limiting the support to political and/or jurisdictional boundaries. In that sense, the model is making better use of the combined resources of the different jurisdictions whilst considering their individual impact.

In all cases, around one third or more of the population requires transport to backup shelters. That result shows that the uncertainty about infrastructure damage and accessibility can affect the capacity of providing safe shelters to the affected people (Bera et al., 2023; Esposito Amideo et al., 2019). The case also shows that cross-jurisdictional coordination can be more impactful at the first stage rather than at the second stage. In the case allowing total coordination, once people reach a different jurisdiction they remain in that jurisdiction when looking for backup shelters, which is reflected in a little over 1% of people moving to a different jurisdiction. In the situation with partial coordination, over 19% of the people needing a backup shelter moves to an adjoining jurisdiction. Although travelling a longer distance to reach a primary shelter in their own jurisdiction at stage one facilitates reaching backup shelters in the same jurisdiction, nearly one in five people still benefit from the possibility of moving across jurisdictions at that stage.

It is worth noticing that the distance travelled by people affected in situations with partial coordination is nearly the same as in situations without any coordination. This finding is aligned with the results from the numerical experiments, which also support the idea that most people benefit far more from having freedom to move across jurisdictions at the first stage rather than at the second stage. An interesting aspect though is that the maximum cost per person per jurisdiction is considerably lower when no coordination is permitted, as opposed to the expectation that cost would be reduced to all the jurisdictions when total coordination is allowed. To investigate that result closer, Table 9 is used to contrast the cost per person at each one of the jurisdictions, showing that Morelos becomes a key destination when coordination is allowed.

When total coordination is permitted, people from EDOMEX and Puebla go to Morelos, increasing the overall cost for that State. The reason is the closeness between some communities from different States combined with the lexicographic approach. Political boundaries can divide communities into different States even though they might be physically closer

Table 9 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

together. That is the case of several communities from the three States studied, where several shelters in Morelos are closer to people from communities at the outskirts of Puebla and EDOMEX than other areas in their same State. On the other hand, the formulation proposed prioritizes reducing travelled distance. 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 model provides the advantage of looking at the flow of evacuees between the different jurisdictions to inform agreements about the operation in these situations. It is a tool that can facilitate a transition from disaster planning considering the resources and needs of single States, to a coordinated response leveraging the resources from different states and the proximity between them. This case is an excellent example of how cross-jurisdictional collaboration needs to be considered. After running the model, it is evident that it is complicated to balance the workload between the three states in instances with free mobility. After looking at this scenario, there are different options that can be taken. Initially, the excess workload allocated to Morelos can be discussed to reach agreements about how the other jurisdictions can ease that workload. It can also be agreed to limit the level of freedom of mobility of the people affected to reach acceptable levels. Alternatively, as the model is considering both objective functions, it can easily be run reversing the order of the objectives to ensure the workload is fairly distributed first, looking at the best policy to minimize distance within those constraints. The purpose of this analysis is to investigate different policies and agree on the best approach to ensure people are protected at the same time as there is a common understanding and acceptance about the workload for the different jurisdictions.

We used a sensitivity analysis with partial coordination to see the behavior of the system. The results can be seen in Table 10. All the gaps were below 5% and all solution times were below 5 min, which shows that the solutions obtained are very close to the optimal value in all the instances and these are reached within a sensible time. The model is forcing a percentage of people (from 10% to 100%) to be served in their original State at 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. There is also an increase in the number of people crossing jurisdictions at the second stage when moving across jurisdiction at the first stage is increasingly discouraged.

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. This can be seen as an opportunity to improve current plans. Facility planning and evacuation routes promoting isolated response within States (Civil_Protection_Puebla, 2025) limit the flexibility of people affected to attend different shelters. That can be problematic considering the uncertainty about the damage to local infrastructure caused by the disaster and the potential need to relocate people. A coordinated approach across jurisdictions can benefit the public and also authorities, who can make agreements for the collaboration and use their resources efficiently whilst serving the public. When

Table 10 Sensitivity analysis

Same jurisdiction (%)	Total distance travelled (km)	Max cost/person/jurisdiction (MXN)	Max people crossing jurisdictions (stage 1)	Max people across jurisdictions (stage 2)
10	1,320,293.53	1,790.93	25,840	442
20	1,364,022.34	1,753.10	22,964	374
30	1,417,004.34	1,734.19	20,081	454
40	1,490,484.15	1,647.18	17,235	712
50	1,586,394.40	1,584.34	14,368	1,034
60	1,710,150.91	1,722.72	11,564	3,382
70	1,860,978.08	1,402.67	8,806	3,908
80	2,050,855.03	1,311.74	5,856	4,566
90	2,280,056.95	1,152.80	2,898	4,987
100	2,519,124.89	1,096.04	0	4,796

cross-jurisdictional coordination is not allowed at the first stage, the number of people moving across jurisdictions increases later on. The major benefits from the perspective of people affected are gained when cross-jurisdictional coordination is allowed from the beginning. That stresses the importance of planning and preparing for 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 support three main points: (i) coordination and interoperability between jurisdictions 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.

5 Conclusions

This article introduces a two-stage stochastic model for the selection of primary and backup shelters for vulnerable population considering the coordination of different jurisdictions. The balance between the service provided to people affected by the disaster and the use of individual resources from each one of the jurisdictions is tackled using a stochastic bi-objective formulation. The model introduces different levels of coordination between jurisdictions to develop strategies considering failure in the infrastructure. This study is the first one in the literature to incorporate cross-jurisdictional coordination into primary and backup shelter location.

The results from numerical experiments show the importance of infrastructure failure in situations with medium and high impact, the value of allowing people to move across jurisdictions, and the importance of considering uncertainty in the formulation. An interesting finding is the latent risk of capacity shortage in cases where there is facility failure or when the capacity of the facilities is not considered, as in many cases in the

literature. The case study using real information highlighted the importance of backup shelters in real conditions and the increased value of allowing cross-jurisdictional coordination at the first stage over the alternative of allowing coordination only at the second stage or not at all.

It is important to note that the model can be used by authorities to facilitate transboundary coordination and to implement a shelter strategy considering backup shelters in different conditions. The formulation can be implemented using risk maps and information about vulnerable areas to different types of disasters and it is appropriate for planning purposes up to a short period before the occurrence of the disaster, as shown by the solution times from the analysis. Although the model considers existent shelters based on current practice, it is flexible to the use prospective areas for shelters to suggest the location of temporary facilities or new shelters as well. One important aspect to note is the assumption of horizontal collaboration between independent jurisdictions. The model can accommodate situations where jurisdictions work independently (within or between countries) or where they fall under the umbrella of a coordinating emergency body (Rodríguez-Espíndola et al., 2018). However, the application of the model needs to carefully consider the governance systems, along with the type of collaboration agreed between jurisdictions, especially when international collaboration is required. This includes when jurisdictions are not contiguous, as that can limit the flow of people between them and the effectiveness of the model.

The literature on cross-jurisdictional coordination is still at a nascent stage, but the findings from this study show that ignoring the interaction between authorities from different jurisdictions can negatively affect the experience of people affected by disasters. Although jurisdictional and political issues can affect disaster planning, this article provides evidence that a well-coordinated joint response can deliver benefits for authorities and people affected. There are different avenues for further research building on the results of this article. The extension of approaches such as the p-next center problem with capacity constraints can foster the advancement of similar models in the future (Albareda-Sambola et al., 2015). The development of integrated models incorporating cross-jurisdictional aspects based on the expertise and experience of different jurisdictions would advance the efficiency and effectiveness of humanitarian supply chains. The design of dynamic models for cross-jurisdictional coordination would be useful for complex emergencies caused by simultaneous and secondary hazards. Finally, the use of robust optimization can be valuable for problems where the stochastic parameters are difficult to estimate.

Declarations

Conflict of interest The authors have no competing or conflicting interests to declare that are relevant to the content of this article.

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