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ORIGINAL RESEARCH

Sustainability and intermodality in humanitarian logistics: a two-stage multi-objective programming formulation

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Abstract

When managing crises and disasters, decision-makers face high uncertainty levels, disrupted supply chains, and damaged infrastructure. This complicates delivering resources that are essential for the survival of the victims. Flexible and adaptable supply networks are needed to ensure a consistent flow of relief to the areas affected by disasters. Intermodality is a valuable approach when infrastructure is damaged, as it allows the use of different delivery modes to reach demand areas. Nevertheless, involving different transportation modes has an impact on the environment. Looking at the importance of helping victims and considering the environmental impact of humanitarian operations for long-term sustainability, intermodality and carbon emission reduction measures can be an interesting combination. This area, however, is currently understudied. This article introduces a two-stage stochastic formulation to fill that gap. The model addresses facility location, resource allocation, and intermodal relief distribution considering carbon emission reduction in facilities, intermodal activities, and distribution. The formulation minimises costs and the level of shortage of relief. The model is tested using a case study in Sinaloa, Mexico, to investigate the impact of intermodality and carbon emission reduction measures on costs and shortage of relief for disaster victims. The findings confirm that the model proposed allows for the diversification of transportation modes and reduces carbon emissions whilst achieving a good level of performance in both metrics. The comparison with a benchmark model without intermodality and carbon reduction measures suggests that the formulation can increase flexibility and reduce the level of CO_2 emissions whilst maintaining high satisfaction rates.

Keywords Carbon reduction · Humanitarian logistics · Intermodal transportation · Multi-objective optimisation · Sustainability

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1 Introduction

During 2020 alone, the average number of disasters and economic losses was higher than the average of the prior two decades (EM-DAT, 2021), threatening organisations and communities (Kovacs & Spens, 2009; Rodríguez-Espíndola, 2023). Humanitarian operations deploy a massive number of resources to different regions (John et al., 2019) in chaotic conditions with high levels of urgency (Kovacs & Spens, 2009). These activities influence the response time and service level provided for the victims and can represent up to 80% of the costs of relief agencies supporting disaster victims (Christopher & Tatham, 2011).

Logistics decisions such as the location of facilities and the flow of relief through the supply chain deal with damaged transportation infrastructure, congestion of supply chains, scarcity of vehicles, and uncertainty of demand information (Kovacs & Spens, 2009). Managers face complex circumstances requiring collaboration from stakeholders across supply chains (Chowdhury et al., 2022a, 2022b). Relief networks can involve multiple tiers and carriers in a trip as the products shipped to the area can be of local or international nature (Zhang et al., 2011). The damage to the affected area can create instances where the use of unimodal transportation can become unfeasible, making the combination of modes the only option to reach affected victims (Ertem et al., 2017). Intermodal transportation involves using multiple modes of transportation to move a transportation unit without the need to handle individual relief (Bilegan et al., 2022; Ertem et al., 2017). The use of single transportation units can increase efficiency, reduce product damage and mitigate problems with packaging (Ertem et al., 2017). Intermodal transportation allows hiring different carriers for different transportation legs to add flexibility to transportation when certain modes become unusable (Ke, 2022). Hence, this type of transportation is a valuable option to reach affected areas in humanitarian operations (Zhang et al., 2011), especially since evidence suggests that up to 40% of the trips in relief operations can involve a change of mode (Strawderman & Eksioglu, 2009). However, concerning the optimisation models considering multiple modes of transportation (Anaya-Arenas et al., 2014), just a handful of articles look into the use of intermodal transportation in humanitarian logistics (Ertem et al., 2017).

Along with the concept of efficiency, an aspect increasingly drawing attention in transportation is the inclusion of environmental considerations. Efficiently managing resources to satisfy social and economic needs whilst protecting the environment is an aspect that has become more prominent in several fields (Cetin et al., 2021), as ensuring the long-term sustainability of human activities is a global concern (Kunze et al., 2022). Environmental planning allows the connection of space, transportation and development (Cetin, 2015) to protect the natural environment from human activities (Çetin & Sevik, 2016). This has promoted reducing energy consumption and decreasing greenhouse gas emissions (Jayaraman et al., 2015) through the implementation of carbon reduction measures in commercial supply chains (Moshood et al., 2021) and the use of Geographical Information Systems (GIS) for sustainable planning (Çetin, 2015). The global focus on reducing CO_2 emissions and improving air quality (Sevik et al., 2017) is reflected in promising advances including carbon emission reduction measures for transportation (Fuli et al., 2020; Kaur & Singh, 2019), but concerns about their effect on urgent operations have prevented their inclusion. Multiple articles argue for the need to find ways to introduce similar practices in humanitarian supply chains (Kunz & Gold, 2017; Peretti et al., 2015). The high stakes and level of urgency found in humanitarian operations, however, take precedence over any other considerations (Kovacs & Spens, 2009). Relief distribution represents a valuable opportunity because of the need to use environmentally-responsible means of transportation (Çetin & Sevik, 2016). Although carbon emissions in transportation have somehow been addressed, less attention has been paid to carbon emissions at facilities. Evidence is needed to investigate the effects of carbon emission reduction measures throughout the whole relief supply chain.

Developing comprehensive logistics plans for humanitarian logistics involves many variables. Traditionally, optimisation models have shown the capacity to handle large amounts of data to establish solutions based on the optimal combination of variables to support decision-making (Caunhye et al., 2012). This approach can be valuable when looking into the impact of environmental concerns on humanitarian operations (Boostani et al., 2020). The opportunity to include these aspects in the objective function and constraints of the formulation can enable the analysis of the impact on the level of service provided to the victims. Additionally, the use of mathematical modelling can facilitate including intermodal transportation in the plan, as seen in previous research (Ertem et al., 2022). Considering the value of intermodal transportation for environmental sustainability shown in the literature on commercial logistics (Rossi et al., 2021), this article uses mathematical modelling to answer the following research questions:

- *RQ1*—How can intermodality and carbon reduction measures be incorporated into a formulation for facility location, resource allocation and relief distribution in humanitarian operations?
- *RQ2*—What is the impact of incorporating intermodality and carbon reduction measures on costs and shortages in humanitarian operations?

This article aims to design a model incorporating intermodality and carbon reduction measures to investigate their impact on the service provided to disaster victims, an approach never undertaken before. To achieve that aim, the study will pursue the following objectives: (i) to design a novel formulation for facility location, resource allocation, and intermodal relief distribution in humanitarian operations and (ii) to investigate the impact of incorporating intermodality and carbon reduction measures on costs and shortages, using real information from a case study in the state of Sinaloa, Mexico.

Achieving the objectives of this research will extend knowledge by providing a new solution for sustainable humanitarian operations and delivering evidence about the impact on the effectiveness of these operations. The contribution is twofold: The design of a multi-objective programming formulation for humanitarian logistics incorporating intermodal transportation and carbon reduction measures and the analysis of the impact of carbon emission reduction measures and intermodal transportation in humanitarian logistics.

The article is structured as follows. The next section introduces the current state of the art, looking at intermodality and sustainability in humanitarian logistics to define the gap tackled by this research. Section 3 introduces the mathematical formulation. Section 4 describes the case study and the information that is entered into the model to deliver the results presented in Sect. 5. Section 6 provides the discussion of the findings and Sect. 7 introduces the conclusions of the research and future directions stemming from the results of this study.

2 Literature review

Anaya-Arenas et al. (2014) highlight the value of multi-modal formulations for disaster relief distribution. A heterogeneous fleet provides a pool of vehicles from different stakeholders that can be combined for last-mile relief distribution. Transporting relief across long distances using a single carrier for door-to-door delivery, however, can be complicated because of the state of the road network. Therefore, intermodal transportation can be an attractive option for relief distribution.

2.1 Intermodal transportation in humanitarian logistics

Intermodal transportation has been considered a suitable alternative to introduce redundancy and mitigate the impact of unexpected disruptions in commercial supply chains (Ishfaq, 2013). Similarly, it can be crucial in disaster events where infrastructure is damaged (Stich, 2014). Adivar et al. (2010) provide evidence of the potential savings for NGOs caused by using intermodal transportation. Therefore, authors have developed intermodal formulations for humanitarian support in the literature. Ruan et al. (2014) propose a two-step approach to delivering medical supplies using intermodal networks. The first stage determines the location of facilities using a fuzzy-logic-based method and a heuristic algorithm, whereas the second stage defines the delivery routes using an optimisation model. The model minimises the total duration of the delivery routes. Ruan et al. (2016) design a model for the intermodal delivery of medical supplies focused on helicopters and automobiles that minimises total time. The proposed method determines the allocation of medical aid points, selects the emergency distribution centres, and determines the intermodal transportation routes. Ruan et al. (2018) extend that work by developing a recovery model to reduce the disturbance caused by changes in the emergency transfer centres. The model aims to minimise disturbances in supply arrival time, intermodal routes, and transportation capacity. Looking at medical rescue, Zhang et al. (2019) propose a two-stage model considering the collaboration of helicopters and ambulances based on a covering location model to maximise coverage and minimise costs. Ozkapici et al. (2016) introduce a model for intermodal relief transportation in humanitarian logistics considering sea and road transportation based on the seabasing concept. The formulation aims to minimise the total transportation time of operations considering seaports as transhipment points. Yang et al. (2018) propose a Method of Successive Average (MSA)-based sequential optimisation algorithm minimising evacuation time. Lin et al. (2019) look at the potential of meeting market demand without spoilage in instances caused by disruptions. The algorithm considers a stochastic logistics network with time windows to evaluate network reliability and the probability of meeting market demand. Kavlak et al. (2021) explore the use of intermodal transportation in humanitarian logistics using a capacitated multi-period formulation minimising operative costs. They conclude that intermodal transportation is beneficial when demand is in consecutive periods, reducing response time and the number of vehicles involved. Enhancing the reliability of the transportation network after disruptions, Uddin and Huynh (2019) consider a reduced number of network links, nodes, and facility capacity. Their formulation minimises total costs by using random link and terminal capacity through chance-constraint programming. Hosseini and Al Khaled (2021) propose an intermodal formulation considering congestion to determine traffic flow whilst minimising total costs. The model can re-route traffic to a residual network to overcome the disruptions caused by disasters, making the network more resilient. This idea of the resilience of critical infrastructure is put forward by Zimmerman et al. (2015), who consider that transportation alternatives for evacuation and supplies are essential in emergencies. Ertem et al. (2022) introduce a capacitated dynamic multicommodity intermodal network flow model with three echelons (origin, transhipment point, and destination). The model minimises response time with penalties for unmet demand. Their findings show the value of intermodal transportation for large-scale disasters and instances with extremely damaged infrastructure. However, the number of articles looking at intermodal transportation in humanitarian logistics is still limited, as pointed out by Ertem et al. (2017) in their review of intermodal formulations in the area. That opens an opportunity for further formulations in the area, especially since the models presented do not consider the environmental impact of humanitarian operations.

2.2 Carbon footprint reduction in humanitarian logistics

The level of destruction, the large amounts of relief flowing into the affected area, and the nature of the emergent operations implemented to deliver relief to disaster victims inevitably produce waste and have an impact on the environment (Fuli et al., 2020). Considering the impact of human activities on sustainability and pollution (Chowdhury et al., 2022a; Jammeli et al., 2021) and the evidence of the global decline in efficiency regarding greenhouse emissions in many countries (Lu et al., 2022), the literature has called for the introduction of sustainable practices in humanitarian operations (Kunz & Gold, 2017; Peretti et al., 2015), leading to some studies looking into sustainability in the field (Chen et al., 2020).

Hamdan and Cheaitou (2017) provide a tool for supplier selection and order allocation including green criteria and accounting for shortages. The tool is integrated in three steps: the Technique for Order of Preference by Similarity to Idea Solution (TOPSIS) method, the analytic hierarchy process (AHP), and the multiplication product of the criteria category and value is added to costs to select the best suppliers. The non-linear bi-objective model maximises the preference (sum of green and traditional criteria) and minimises costs. Cao et al. (2018) explore the inclusion of sustainability in disaster operations from the point of view of equity and service. They propose a multi-objective non-linear formulation maximising the lowest satisfaction level, minimising the maximum difference in satisfaction among areas, and minimising the maximum difference in satisfaction across stages. Zhang et al. (2018) introduce environmental considerations into a multi-depot routing model for emergency facilities under uncertain information. The objectives of the formulation are to minimise costs, travel time and emissions produced based on the travel distance and the CO_2 emission per km. Kaur and Singh (2019) propose a non-linear mixed-integer deterministic optimisation model to reduce carbon emissions in procurement and transportation based on the cap-and-trade strategy. The model accounts for multiple suppliers and multiple carriers aiming to minimise costs, including carbon costs. Boostani et al. (2020) propose a stochastic model for facility location, resource allocation and procurement using a multi-objective model. The model minimises costs, maximises fairness and minimises the environmental impact of operations. The article highlights the importance of considering emissions beyond transportation, such as the emissions generated in operative activities. Fuli et al. (2020) focus on strategies to reduce carbon emissions accounting for the influence law of customer carbon sensitivity coefficient and carbon trading prices. They propose a two-stage non-cooperative game formulation focused on profit, which is used to conclude that the choice of strategies relies on two factors: carbon trading prices and fixed emission reduction targets. Cao et al. (2022) tackle the three dimensions of sustainability by proposing a multi-objective formulation aimed at minimising carbon emissions and potential risks and maximising economic benefits for reverse logistics of medical waste. The formulation supports decisions about the location and transportation of medical waste considering the emissions produced by transportation.

It is noteworthy that several of the articles presented in this section introduce multi-objective approaches to considering environmental concerns as a prominent aspect. However, the findings of this review support comments from Laguna-Salvadó et al. (2019). They recognise the existence of few solutions considering sustainability measures in humanitarian operations, which are aligned with arguments about the neglect of environmentally-friendly practices in mathematical models in the field (Fuli et al., 2020).

2.3 Intermodal transportation and carbon emission reduction

Considering the environmental impact of relief operations combined with the need for efficient and effective operations, it is important to investigate the intersection of intermodal operations and carbon emission reductions. There is evidence that intermodal transportation can help reduce CO_2 emissions (Rossi et al., 2021), which is why the European Union has focused on the use of that approach (Bask & Rajahonka, 2017). Although no papers in the field of humanitarian logistics combine both aspects, their importance has been explored in commercial logistics. Craig et al. (2013) provide an interesting approach to estimating CO_2 production for intermodal freight transportation. They compare the results of intermodal transportation with land transportation alone, highlighting the importance of accounting for CO_2 emissions in intermodal transportation and demonstrating the average carbon savings compared to truckload transportation. Qu et al. (2016) introduce a model for intermodal freight transportation with greenhouse emission considerations extending the capacitated multicommodity network design problem. The model minimises transportation costs considering transportation emissions. They show the potential of obtaining cost-efficient and emission-efficient solutions. Agbo et al. (2017) design a bi-objective formulation for transportation from marine port terminals to inland port terminals. The model aims to minimise cost and transit time by imposing limits on carbon emissions to reduce the environmental impact of the operations. Resat and Turkay (2019) propose a bi-objective model to manage intermodal logistics with environmental considerations. The article considers ports as starting points for the flow of relief. The objectives of the model are to minimise transportation costs and carbon dioxide emissions from transportation. Demir et al. (2019) analyse the current state of green logistics using multiple modes for freight transportation and propose a bi-objective mathematical formulation of the green intermodal service network design problem. They highlight that compromise on costs to reduce carbon emissions is not needed. Maiyar and Thakkar (2020) consider procurement uncertainty, greenhouse gas emissions and potential disruptions to design a robust formulation for facility location and transportation of food grains. The p-hub median problem minimises the relative regret associated with cost. Rossi et al. (2021) propose a travelling stock model combining intermodal transport and the hub-and-spoke network for perishable food. Their analysis shows that intermodal transportation can be environmentally and economically sustainable. Overall, the articles presented agree that intermodal transportation can be integrated with carbon reduction measures to improve the sustainable performance of transportation without sacrificing cost. However, less is known about the impact of environmental considerations in the priorities of humanitarian logistics.

3 Research gap

The review presented highlights the value of intermodal transportation to improve the efficiency of operations and the value of integrating carbon reduction measures to reduce the environmental impact of humanitarian operations. Although both fields have been combined in commercial operations before, less is known in the context of humanitarian operations. The following gaps have been found in the review:

- The combination of intermodality and carbon reduction measures has shown improvements in commercial supply chains, but more information is needed to identify its advantages for the humanitarian setting considering the specific conditions and interconnectedness found in these operations, especially since topics such as carbon emissions have yet to gain traction in OR/MS research (Romero-Silva & de Leeuw, 2021).
- The articles incorporating intermodality and carbon reduction measures in the literature focus on transportation emissions. Facility operation produces carbon emissions as well (Li & Hai, 2019; Mogale et al., 2020). As relief transportation is often studied in conjunction with facility location in humanitarian logistics, emissions need to be investigated not only in transportation but also in facilities for the design of models for humanitarian logistics.
- There is evidence of the potential of including carbon emission reduction measures in commercial logistics without negative impacts on costs (Demir et al., 2019). Nevertheless, humanitarian operations need to balance efficiency and effectiveness (Beamon & Balcik, 2008). Thus, it is important to analyse the impact of introducing carbon reduction measures on the service provided in humanitarian operations as well.

This article tackles these gaps by introducing a novel multi-objective programming formulation incorporating intermodality and carbon reduction emissions for humanitarian logistics. The formulation is used to test the benefits and impact of these aspects in the level of cost and satisfaction of demand using information from a real case study in Mexico.

4 Methodology

4.1 Methodological approach

This article is based on the decision theory view (Easterby-Smith et al., 2012), which involves the use of an analytical approach to optimise decisions. This approach was chosen because of the repercussions of logistics decisions in operations surrounded by chaotic conditions. Operational Research has proven to be valuable for designing solutions for emergency response and humanitarian logistics (Altay & Green, 2006; Galindo & Batta, 2013). Techniques such as AHP, game theory, probability and statistics, graph theory, optimisation, and simulation have the potential to provide solutions for different logistics activities.

Modelling is a common research method in supply chain management because it allows the key aspects of the situation to aid decision-making (Kotzab et al., 2005) to be captured. Models are a representation of reality and can be descriptive, prescriptive or predictive (Souza, 2014). Descriptive models analyse the current situation to explain what is happening in the system (Albright & Winston, 2009), whereas predictive models leverage past data to identify trends and give predictions of what will happen (Souza, 2014). Given the need for measurable and quantifiable features of the event to identify and propose a solution, this article is based on the idea of prescriptive models. These models deliver a course of action (i.e., an 'optimal' policy) based on information and context (Albright & Winston, 2009). This approach is widely used in humanitarian logistics (Altay & Green, 2006; Galindo & Batta, 2013), as it can model real objects (Klein & Hirschheim, 1987) and explain and predict an objective, tangible and fragmentable reality (Mentzer & Kahn, 1995).

Optimisation modelling is particularly useful in this area because it allows the features of different decisions affecting supply chains to be captured to find the optimal value of the performance measures (Caunhye et al., 2012). Optimisation models maximise or minimise one or more objectives to provide the best combination of decisions based on the conditions of the problem. One of the main advantages of optimisation is the possibility to perform a 'what if' analysis (Albright & Winston, 2009), identify the best combination for a set of conditions, structure the thought process, increase objectivity and formulate complex problems tractably (Lee-Post, 2003).

The use of optimisation modelling is a natural fit for the problem at hand. It incorporates the key aspects of humanitarian supply chains, their constraints, and their resources to find the most suitable combination of decisions according to defined metrics. Hence, this research will propose an optimisation model to support disaster management in humanitarian operations. Specifically, this research uses stochastic mixed-integer programming. It uses binary variables for selection decisions along with integer variables for the other decisions involving units that cannot be easily divided (e.g., people, trucks, products). Uncertainty in demand is captured in the model as well.

4.2 Context of the situation

The population in areas affected by disasters require the delivery of products and the provision of services for survival. Given the impact of the first 72 h after an event in survival and suffering (Wassenhove, 2006), this article focuses on supporting decisions before (i.e., preparedness) and immediately after the disaster (i.e., response). The literature review has shown the use of optimisation models for intermodal transportation in supply chains (e.g. Demir et al., 2019; Ertem et al., 2022; Kavlak et al., 2021; Resat & Turkay, 2019). This research assumes four tiers: points of origin, transhipment points, local distribution centres and shelters. The purpose is to select facilities, allocate human and material resources and enable the flow of products from the points of origin to the points of demand.

Initially, the model defines the level of demand. Members of the local population who are displaced from their homes are transferred from the affected communities to safe areas, defined here as shelters. Beneficiaries in shelters represent the demand to be served, as seen in previous formulations (Rodríguez-Espíndola et al., 2020). To reach the beneficiaries, the relief is shipped from different points of origin (e.g., suppliers, national warehouses, stockpiles). These products go through the tiers of the supply chain, changing mode in the transhipment points without being manipulated (Bilegan et al., 2022; Ertem et al., 2017) and reaching the distribution centres to be prepared for distribution to shelters. Each of the transhipment points and distribution centres selected requires staff to operate it. Transhipment points and local distribution centres need personnel to receive, store, handle and ship the relief, whereas shelters require employees for management, safety and providing living services. It is assumed the relief is shipped in containers through the most convenient transportation mode at the point of origin as seen in previous literature (Ertem et al., 2022), and the model allows switching the transportation mode of containers at transhipment points if a better option exists or the current mode is unusable. Next, the containers arrive at local distribution centres, where the items are removed from the containers and prepared for shipment based on the requirements of the shelters. Finally, the items are deployed using the most convenient or available mode of transportation to reach the beneficiaries. Decisions about location and transportation are based on traditional measures such as distance (translated into the cost), coverage, and accessibility, but with the addition of the level of carbon emissions produced. The emissions considered are transportation emissions (Kaur & Singh, 2019) and facility emissions (Li & Hai, 2019; Mogale et al., 2020), including the use of electricity for operation and activities for the change of mode. The representation of the system can be seen in Fig. 1.

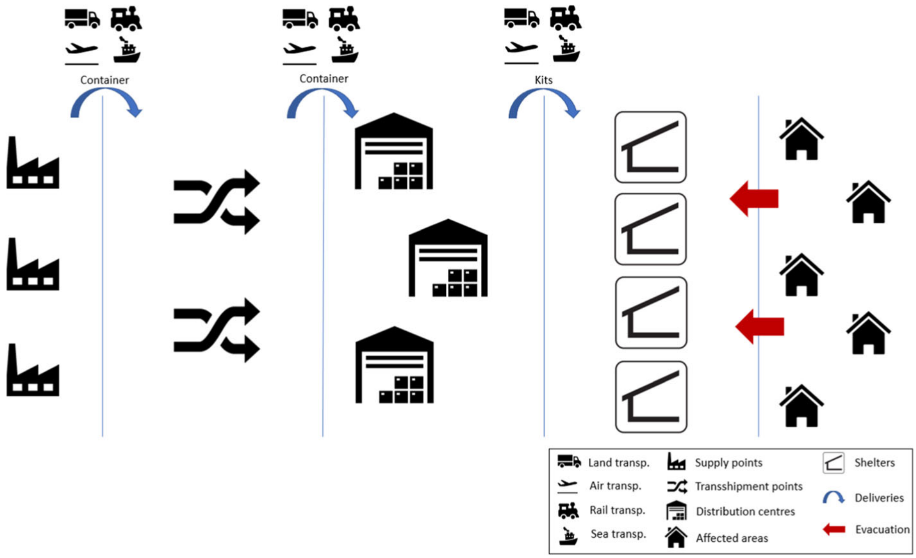

Fig. 1 Supply network represented in the model

Capturing the need for efficiency and effectiveness using single performance measures is complicated (Beamon & Balcik, 2008). Multiple-criteria decision-making is useful in dealing with decisions when multiple conflicting criteria need to be considered to make more informed decisions (Jayaraman et al., 2015). That is why it has grown considerably in the area of green logistics (Argoubi et al., 2020). The model proposed in this article balances objective functions related to efficiency and effectiveness. It addresses effectiveness by pursuing the minimisation of costs (including the cost of emissions to add the environmental dimension) and the minimisation of shortage of relief at the shelters. Therefore, the objective of the formulation is to deliver a set of optimal solutions called the Pareto frontier.

4.3 Model assumptions

The optimisation model proposed is underpinned by the following main assumptions:

- Public donations are collected and managed for post-disaster distribution. As the model focuses on the immediate response, gathering and delivering these is beyond the planning horizon of the model (Torabi et al., 2018).
- Information and resources from every participating organisation are shared with a disaster management coordinator and resources are ready to be shipped. Based on the centralised decision-making systems used in different countries (Alexander, 2015), an overarching decision-maker can manage the resources efficiently and effectively.
- Contracts and conditions of supply with potential suppliers are pre-arranged. It is important to have clear agreements with suppliers to have certainty about the supply and enable quick response (See Balcik & Ak, 2014).
- There are enough vehicles to transport relief between facilities. The analysis considers the possibility of using resources from the organisations involved or private providers.

- People are informed before an evacuation of their allocated shelter. Pre-disaster evacuation procedures are in place (Rodríguez-Espíndola et al., 2020).

4.4 Model formulation

Notation
Sets

i	Supply facilities
j	Transhipment nodes
k	Shelters
l	Regions affected
m	Transport mode
o	Container
q	Distribution Centre
s	Scenario

Parameters

α_o	Number of items provided per container o
$\beta_{i,j,m}$	Transportation cost from origin i to transhipment point j per mode m
bravo_q	Number of employees required to operate DC q
γ_j	Cost of activating transhipment point j
δ_{ls}	Number of people needing refuge at region l during scenario s
ε_o	Cost of procurement of container o
ζ_q	Capacity of DC q
η_j	Capacity of containers per transhipment point j
$\theta_{i,o}$	Container o at origin point i
$\iota_{j,q,m}$	Transportation cost from transhipment node to local DC q by mode m
$\kappa_{i,j,m,s}$	Availability of transport mode m from source i to transhipment point j in scenario s
$\lambda_{j,q,m,s}$	Availability of transport mode m from transhipment point j to DC q in scenario s
μ_k	Number of people that can be sheltered on shelter k
ν_k	Cost of activating shelter k
ξ_m	Number of employees required to transport one container per mode m
$\mathrm{o}_{l,k}$	Coverage of affected area l by shelter k
π_s	Probability of scenario s
ρ	Number of employees available
σ_j	Emissions produced by operating transhipment point j
τ	Conversion factor per product (e.g., if 1 food kit feeds 4 people, the value is 4)
$\upsilon_{i,j,m}$	Carbon emissions produced by the transportation of one container from origin i to the transhipment point j by mode m
φ_j	Number of employees required per transhipment point j
$\chi_{j,q,m}$	Carbon emissions produced by the transportation of one container from transhipment point j to DC q by mode m
ψ_j	Emissions produced by the operations to change mode in transhipment point j
ω_k	Emissions produced by electricity of managing shelter k
EM	Cost per kg of CO_2 produced

eco_q	Emissions produced by electricity used at DC q
vec_m	Capacity of vehicle m
$CT_{q,k,m}$	Transportation cost from local DC q to shelter k by mode m
$COV_{q,k,m,s}$	Availability of transport mode m from DC q to shelter k in scenario s
$ET_{q,k,m}$	Carbon emissions produced by trip from DC q to shelter k by mode m
$WAGE$	Employee wage per period
VOL	Volume of the items shipped
WEI	Weight per product
CDC_q	Cost of opening DC q
$MD_{i,j,m}$	Availability of mode m between transhipment point j and DC q
$ND_{j,q,m}$	Availability of mode m between origin i and transhipment point j
$FD_{q,k,m}$	Availability of mode m between DC q and shelter k
$RA_{i,j,m,s}$	Reliability of path between origin i and transhipment point j per mode m on scenario s
$RB_{j,q,m,s}$	Reliability of path between transhipment point j and DC q per mode m on scenario s
$RC_{q,k,m,s}$	Reliability of path between DC q and shelter k per mode m on scenario s
M	Very large number

where

$$\kappa_{i,j,m,s} = MD_{i,j,m} * RA_{i,j,m,s}, \forall \text{ i, j, m, s}$$

$$\lambda_{j,q,m,s} = ND_{j,q,m} * RB_{j,q,m,s}, \forall \text{ j, q, m, s}$$

$$COV_{q,k,m,s} = FD_{q,k,m} * RC_{q,k,m,s}, \forall \text{ q, k, m, s}$$

Variables

First-stage variables

C_i	Number of employees allocated at origin i for distribution
A_j	Employees available in transhipment point j for operation
F_j	Number of employees allocated at transhipment point j for distribution
V_q	Number of employees allocated to DC q
EDC_q	Number of employees required for distribution in DC q
W_j	It has a value of 1 if transhipment point j is used, 0 otherwise
T_k	It has a value of 1 if shelter k is used, 0 otherwise
G_q	It has a value of 1 if DC q is used, 0 otherwise
$X_{i,j,m,o,s}$	It has a value of 1 if arc *i-j* is used by container o in mode m at scenario s, 0 otherwise

Second-stage variables

$Y_{j,q,m,o,s}$	It has a value of 1 if arc *j-k* is used by container o in mode m at scenario s, 0 otherwise
$H_{q,k,m,s}$	Number of items shipped from DC q to shelter k by mode m at scenario s
$P_{q,k,m,s}$	Number of trips required from DC q to shelter k by mode m at scenario s
$B_{k,s}$	Number of people allocated per shelter k at scenario s
$U_{k,s}$	Number of items not delivered per shelter k at scenario s
$R_{k,s}$	Excess of items delivered to shelter k at scenario s
$N_{q,s}$	Inventory leftover at facility q at scenario s

$E_{l,k,s}$ Intermediate variable for the transfer of disaster victims from area l to shelter k at scenario s

$Z_{j,o,s}$ It has a value of 1 if change of mode is required for container o in transhipment point j at scenario s, 0 otherwise

$D_{j,m,o,s}$ Dummy for change of mode to avoid negative values

$Du_{j,m,o,s}$ Dummy for change of mode to equal zero

Objective functions

$$\begin{aligned} minCost = & \sum_j \left(\gamma_j * W_j + EM * \sigma_j * W_j\right) + \sum_k (\nu_k * T_k + EM * \omega_k * T_k) \\ & + \sum_q \left(CDC_q * G_q + EM * ecco_q * G_q\right) \\ & + WAGE * \left(\sum_i C_i + \sum_j A_j + \sum_j F_j + \sum_q V_q + \sum_q EDC_q\right) \\ & + \sum_s \pi_s * \Bigg(\left(\sum_i \sum_j \sum_m \sum_o \beta_{i,j,m} * X_{i,j,m,o,s} + EM * \upsilon_{i,j,m} * X_{i,j,m,o,s}\right) \\ & \qquad + \sum_j \sum_q \sum_m \sum_o (\iota_{j,q,m} * Y_{j,q,m,o,s} + EM * \chi_{j,q,m} * Y_{j,q,m,o,s} + \varepsilon_o * Y_{j,k,m,o,s} \Bigg) \\ & + \sum_q \sum_k \sum_m \Bigg(CT_{q,k,m} * P_{q,k,m,s} + EM * ET_{q,k,m} * P_{q,k,m,s)} + \sum_j \sum_o \left(EM * \psi_j * Z_{j,o,s}\right) \Bigg) \end{aligned} \tag{1}$$

$$minShortage = \sum_s \sum_k \pi_s * U_{k,s} \tag{2}$$

Constraints

$$\delta_{ls} = \sum_k o_{l,k} * E_{l,k,s} \quad \forall \text{l, s} \tag{3}$$

$$B_{k,s} = \sum_l E_{l,k,s} \quad \forall \text{k, s} \tag{4}$$

$$\sum_j \sum_m X_{i,j,m,o,s} \le \theta_{i,o} \quad \forall \text{i, o, s} \tag{5}$$

$$\sum_i \sum_m \sum_o X_{i,j,m,o,s} \le \eta_j * W_j \quad \forall \text{j, s} \tag{6}$$

$$B_{k,s} \le \mu_k * T_k \quad \forall \text{k, s} \tag{7}$$

$$\sum_j \sum_m \sum_o Y_{j,q,m,o,s} * \alpha_o * VOL \le \zeta_q * G_q \quad \forall \text{q, s} \tag{8}$$

$$\varphi_j * W_j = A_j \quad \forall \text{j} \tag{9}$$

$$G_q * bravo_q = V_q \quad \forall \text{q} \tag{10}$$

$$\sum_j \sum_m \sum_o \xi_m * X_{i,j,m,o,s} \le C_i \quad \forall \text{i, s} \tag{11}$$

$$\sum_q \sum_m \sum_o \xi_m * Y_{j,q,m,o,s} \le F_j \quad \forall \text{j, s} \tag{12}$$

$$\sum_k \sum_m \xi_m * P_{q,k,m,s} \le EDC_q \quad \forall \text{q, s} \tag{13}$$

$$\sum_{i} C_i + \sum_{j} A_j + \sum_{j} F_j + \sum_{q} V_q + \sum_{q} EDC_q \le \rho \tag{14}$$

$$X_{i,j,m,o,s} \le \kappa_{i,j,m,s} \quad \forall \text{i, j, m, o, s} \tag{15}$$

$$\sum_{i} \sum_{m} X_{i,j,m,o,s} = \sum_{q} \sum_{m} Y_{j,q,m,o,s} \quad \forall \text{j, o, s} \tag{16}$$

$$\sum_{i} X_{i,j,m,o,s} - \sum_{q} Y_{j,q,m,o,s} + Du_{j,m,o,s} = D_{j,m,o,s} \quad \forall \text{j, m, o, s} \tag{17}$$

$$Z_{j,o,s} \ge \sum_{m} D_{j,m,o,s} \quad \forall \text{j, o, s} \tag{18}$$

$$Y_{j,q,m,o,s} \le \lambda_{j,q,m,s} \quad \forall \text{j, q, m, o, s} \tag{19}$$

$$\sum_{j} \sum_{m} \sum_{o} Y_{j,q,m,o,s} * \alpha_o = \sum_{k} \sum_{m} H_{q,k,m,s} + N_{q,s} \quad \forall \text{q, s} \tag{20}$$

$$B_{k,s} = \tau * \left(\sum_{q} \sum_{m} H_{q,k,m,s} + U_{k,s} - R_{k,s} \right) \quad \forall \text{k, s} \tag{21}$$

$$P_{q,k,m,s} * vec_m \ge H_{q,k,m,s} * weight \quad \forall \text{q, k, m, s} \tag{22}$$

$$P_{q,k,m,s} \le M * COV_{q,k,m,s} \quad \forall \text{q, k, m, s} \tag{23}$$

$$W_j, X_{i,j,m,o,s}, Y_{j,q,m,o,s}, Z_{j,o,s}, D_{j,m,o,s}, T_k, G_q \in [0, 1]$$

$$H_{q,k,m,s}, P_{q,k,m,s}, C_i, A_j, F_j, E_{l,k,s}, U_{k,s}, R_{k,s}, B_{k,s}, Du_{j,m,o,s}, V_q, EDC_q, N_{q,s} \in Z^+$$

Equation 1 minimises the costs of activating facilities, transportation, CO_2 emissions, transhipment operations, and wages from employees. The model reduces the use of resources whilst considering the service provided through the second objective function. Equation 2 minimises unmet demand weighted by the probability of occurrence. This measure focuses on providing a higher level of service to people affected by ensuring the highest level of satisfaction possible within the resources available. Expression (3) enters the people affected into the system, and Eq. (4) allocates them to shelters. Constraint (5) ensures that only containers existent at origin points can be sent, whereas Expression (6) ensures that transhipment points activated are not handling more containers than their capacity. The capacity of people in shelters is controlled by Constraint (7), and Expression (8) ensures the capacity of DCs is respected. Equation (9) calculates the number of employees required at transhipment points, whereas Expression (10) determines the number of employees required at DCs. Constraints (11), (12) and (13) estimate the number of employees needed for distribution from origin to transhipment point, from transhipment point to DCs, and from DCs to shelters, respectively. The maximum number of employees available is controlled by Expression (14). Constraint (15) ensures that only available transportation links are used from supply points to transhipment points. Equation (16) makes sure transhipment points are only used as temporary hubs and that no items are stored there. Equation (17) defines changes of mode at the transhipment point, which are recorded in Expression (18). Constraint (19) ensures that only available transportation links are used from transhipment points to DCs. Equation (20) determines the number of individual products delivered at DCs, Constraint (21) calculates the number of people without relief, Expression (22) determines the number of trips required and Constraint (23) ensures that only available links are used for distribution from DCs to shelters.

4.5 Model solution

The proposed model provides a set of efficient solutions forming the Pareto frontier. The points in the Pareto frontier represent a trade-off between the two objectives, in which one dimension can be further improved only by worsening the value of the other variable. This article proposes the use of the traditional ε-constraint method for the solution. This a posteriori method can determine the Pareto frontier by transforming the multi-objective structure of the model. The modified structure has a single objective, whereas the other objective(s) are turned into constraint(s) (Mavrotas, 2009). That way, the model is solved by focusing on a single objective for several iterations in a range defined by the objective turned into a constraint (Rodríguez-Espíndola, 2022).

Following this method, the individual ideals for both objective functions are calculated to create a matrix. In this case, the cost objective function is turned into a constraint. The shortage objective function is optimised several times, changing the maximum value of the cost function to create the Pareto frontier, including the trade-off between objectives to select the most suitable solution based on decision-maker preferences (See Kunze et al., 2022).

The model can be programmed on the General Algebraic Modelling System (GAMS) using the ε-constraint method to find the set of efficient solutions. Ramos et al. (2010) provide a comparison between programming models on common languages (C + + , Java and Visual Basic, among others), numeric analysis languages (MATLAB, MAPLE and Mathematica, among others) and algebraic languages (GAMS, AMPL and XPRESS-MP, among others) for optimisation models. The findings suggest algebraic languages are the most powerful alternatives combining flexibility for changes on the model, simpler maintenance and easier detection of errors. A popular software using algebraic language is GAMS, as evidenced by the number of applications in articles focused on disaster management (e.g. Duran et al., 2011; Mete & Zabinsky, 2010; Salmeron & Apte, 2010; Tirado et al., 2014). Therefore, GAMS was selected along with Cplex as the solver, a common combination in the literature.

5 Case study

A case study is "*an empirical exercise based on gathering information from multiple sources to analyse one instance within a real context*" (Host et al., 2012). The use of a case study for modelling purposes allows the representation of real conditions for testing the performance of the system. Using historical disaster situations is useful in analysing that performance under real-world conditions and drawing conclusions. Resources such as money, people, and materials can be quantified and used to assess the situation and the behaviour of the system designed.

5.1 Region

Mexico was chosen as the region for analysis because it has high hazard exposure and vulnerability. Mexico is one of the countries in the Americas most affected by disasters, just behind the United States (Guha-Sapir, 2017). The country experiences an average occurrence of four large-scale disasters per year. In 2021 alone, the country recorded 11 events, which made it one of the ten most affected countries globally in the year (CRED, 2021). Hurricanes and tropical storms are a significant problem, as shown by the 58 disasters caused by storms from 2000–2018 (EM-DAT, 2019).

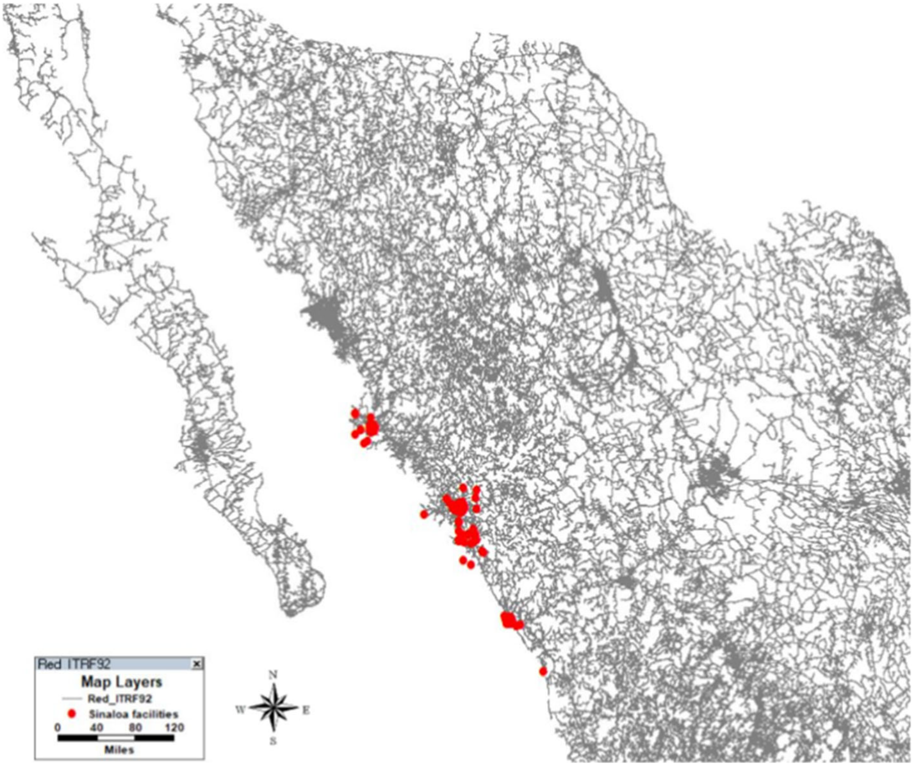

Fig. 2 Regions analysed in the case study

Using the emergency declarations that required relief distribution in the country in recent years (SINAPROC, 2013), it was evident that Hurricane Manuel had a major impact on the country. Around mid-September 2013, it closed in on the Pacific coast and caused 123 deaths in the country, along with flooding and landslides (Pasch & Zelinsky, 2014) because of severe rainfall. It has been one of the worst disasters experienced in Mexico over the last 20 years, with over 300,000 people affected.

One of the coastal states that are vulnerable to the impact of these events is Sinaloa. Sinaloa is located on the west side of the country, and the hurricane passed very close to its coastline, which caused extraordinary rain in many communities (Pasch & Zelinsky, 2014) and the overflow of the Culiacán River and minor rivers, leaving 15 communities cut off from communication (Mexican_Senate, 2013). The impact was nearly MNX $3,039 million in damages in the state (CENAPRED, 2020). Over time, it has suffered the impact of devastating hurricanes including Hurricane Manuel in 2013. Considering that context, this article tests the model using a case study in three of the main areas affected by the hurricane in Sinaloa: Ahome, Culiacán and Mazatlán, shown in Fig. 2.

5.2 Data collection

The data for the case were obtained using a combination of publicly available data, freedom of information requests to disaster management authorities and geographical information accessible through INEGI. This section outlines the sources of the data included in the analysis.

5.2.1 Facilities considered

Details of the three types of facilities were required for analysis. Data from the Communications and Transport Secretariat (SCT) were used to identify the main ports, railway stations and airports in each city, which were considered the main transhipment points. Warehousing facilities from Diconsa were used as distribution centres. The facilities were geo-localised and included in GIS for analysis. GIS is useful for sustainable planning because it allows consideration of the uses of the land, its cover and the topography for analysis (Çetin, 2015). The costs of opening these facilities were obtained through the size of the facility and the cost per m^2 of professional preparation services.

Shelters were obtained directly from the official list of civil protection shelters in Sinaloa. The document includes the capacity of each facility and its location, which was used to geo-localise each of the facilities for analysis with GIS. The shelters were in the areas of Ahome, Culiacán and Mazatlán. The costs of opening these facilities included the cleaning costs and the assumption of basic items for survival from Mexican regulations including mattresses, blankets, flashlights, raincoats, water containers and baby bathtubs.

The number of employees available for operating facilities and handling distribution was obtained from the branch of the military in charge of disaster relief operations (SEDENA), along with the number of people required for transportation. Their wages were determined using the salary of civil protection officials (Mazatlán_municipality, 2020).

5.2.2 Relief products

The products that can be charged to FONDEN (Mexico's natural disasters fund) for disaster response and their characteristics are included in regulations (SEGOB, 2012). The products considered for analysis were food kits. The number of pre-positioned items and their location were obtained from a freedom of information request addressed to Diconsa, the organisation in charge of procuring and handling the products included in the food kit. This information was used to set up the supply points and define the number of units available at each origin, along with the number of products per unit.

5.2.3 Transportation modes

For the analysis, the different transportation modes in the country were simplified into four basic groups: road transportation (including trucks, trailers and cars, among others), railway transportation (trains for freight transportation), water freight (including ships and boats, among others) and air transportation (including small planes and helicopters). The availability of these different modes was based on previous disaster reports from the Secretariat of Security and Civilian Protection for land and air transportation, Diconsa for water freight, and the SCT for railway transportation. The transportation costs per mode were obtained from Panteia (2020).

5.2.4 Carbon emissions

Three types of CO_2 emissions are considered in the model: transportation emissions, emissions because of operations in transhipment points, and emissions from the use of electricity in facilities.

Carbon emissions from transportation were based on distances. The distances were estimated using the geographical layers of the facilities, which were entered into TransCAD® software to calculate road and direct distances. The distances were multiplied by the CO_2 emissions of standard vehicles available (Sims et al., 2014). Emissions because of electricity consumption were obtained using the report about the electric consumption by building type in Mexico by Lorentzen and McNeil (2019), assuming four days for initial response. That value was multiplied by the conversion factor (Carbon_Trust, 2020).

The cost of operations inside transhipment facilities was calculated by multiplying diesel consumption for forklifts by an average time of 9.5 h of operation, obtained from Pashkevich et al. (2019), and the capacity per day to process containers was based on the parameters provided by the same source. These emissions were multiplied by the cost of CO_2 in Mexico published by the OECD (2019).

5.2.5 Scenario development

The scenarios were based on historical information on the disasters affecting the region of Sinaloa. Information on disasters and the number of people affected was obtained from a report about disasters in Mexico from 2000 to 2015 (CENAPRED, 2017). This document contains details about the time of the disaster, the communities affected, and the number of people affected, among others. Using the variation of the impact of the disaster on demand for the development of scenarios as previous papers have done (See Balcik & Ak, 2014; Falasca & Zobel, 2011), three levels of disasters were defined based on the findings. The events were classified as low impact (less than 10,000 people), medium impact (more than 10,000 but less than 100,000 people) and high impact (more than 100,000 people). The three categories in three regions were combined to design an experiment with 3^3 scenarios $= 27$ scenarios. The probabilities were obtained by dividing the frequency of occurrence of each scenario by the total occurrence of scenarios.

Demand was calculated using information from authorities about real events, considering both conditions. The highest value for each category was used to estimate the demand in each area based on the proportion of people in that area compared to the number of people in the state, available from the Mexican National Institute of Statistics and Geography (INEGI, 2020b). The number of people living in each area was obtained from INEGI (2020a) and their location was obtained from the geographical layers from INEGI (2021).

6 Analysis of results

6.1 Case study

The purpose of this section is to test the potential of the system to handle real-world networks to provide solutions for decision-makers. The model was tested using data from the case study to provide insights about its performance in realistic conditions. As the model has two objective functions, the case was solved using the ε-constraint method. This method allows

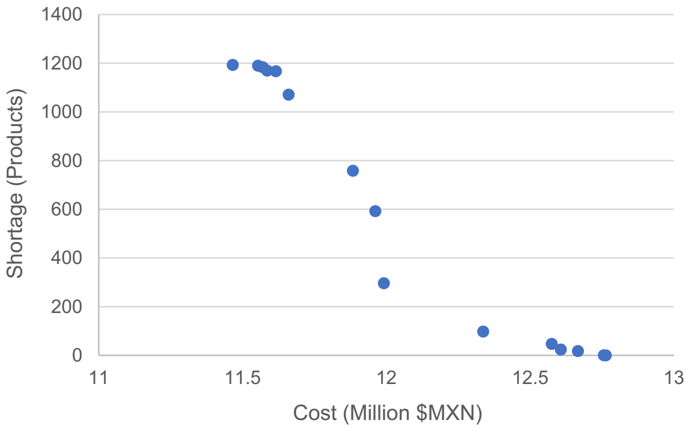

Fig. 3 Pareto frontier of the case study

the optimisation of one objective for several values of the second objective (ε). The shortage function was optimised using the cost function as a constraint. The model and the solution approach were programmed in GAMS using Cplex as the solver. To get a good range of solutions, a total of 100 iterations were run with epsilon values ranging from the ideal to anti-ideal values obtained in the payoff matrix. The stopping criteria were a maximum time of one hour per solution and a relative gap of 0. After running the 100 iterations, the system delivered 15 non-dominated solutions. This means these solutions are not improved in both performance measures (i.e., cost and shortage) by any other solutions in the feasible space. The solutions from the Pareto frontier are shown in Fig. 3 below and reflect the conflict between the costs of the operations and the level of shortage of food kits in the affected areas. The figure shows that the level of shortage can be improved by an increase in costs and vice versa, which can allow the decision-maker to select a solution based on her/his preferences.

Each of the points in the figure contains a policy with a set of decisions for the variables of the problem. To clarify the differences between policies, Table 1 introduces a more detailed summary of the results, showing the variations between solutions. The difference between cost-efficient results with a low level of fulfilment and the solution delivering all the products (i.e., no shortage) is nearly MXN $1.3 million, which represents over 10% of the cost of most of the solutions. Therefore, appropriate management of the resources can make a significant difference in the level of shortage. In some cases, a small change in cost makes a significant difference in the number of people served. For instance, between ND6 and ND7, investing nearly 2% more in the cost of ND6 (MXN $223,438.10) leads to a steep change of nearly 30% in the number of items delivered. Conversely, a larger increase between ND10 and ND11 (MXN $238,612.81) has far less impact on the level of shortage (around 50 products). The Pareto frontier allows the decision-maker to perceive these differences and find the most appropriate solution based on their priorities and the resources available. Focusing on the facilities, one of the hard constraints in the system is to ensure that everyone can reach a shelter. The effect of that constraint can be seen in the table, where the number of shelters is high in all the solutions, affecting the cost even in cost-efficient solutions. Distribution centres and transhipment points, however, rely on the budget available and the products to be distributed. Although both increase in service-oriented solutions, the effect on shelters is worth noticing. Depending on the facilities selected, the number and location of shelters

Table 1 Summary of the results of the Pareto frontier

ID	Cost	Shortage	Employees	Facilities			Containers	
				Transhipment points	DCs	Shelters	Maximum	Total
ND1	11,466,302	1,192.84	0	0	0	40	0	0
ND2	11,554,455	1,189.33	57	1	1	50	1	1
ND3	11,570,801	1,183.45	67	1	1	47	1	1
ND4	11,586,314	1,169.25	56	1	1	32	1	2
ND5	11,616,555	1,166.98	75	1	1	41	1	3
ND6	11,660,741	1,070.70	80	1	1	48	1	6
ND7	11,884,179	758.17	172	1	1	23	1	11
ND8	11,962,182	592.13	145	1	2	23	2	18
ND9	11,992,183	295.68	129	1	1	28	1	19
ND10	12,337,185	97.46	227	1	2	45	2	32
ND11	12,575,798	46.93	333	2	2	28	2	39
ND12	12,607,115	23.40	415	3	3	33	3	36
ND13	12,666,621	17.34	380	3	3	34	3	43
ND14	12,757,120	0.23	401	2	4	37	4	47
ND15	12,763,426	0.00	396	2	3	40	3	47

vary. This means that sheltering decisions are influenced by the relief network proposed to facilitate responsiveness and accessibility and shows the importance of the connection between shelters and relief facilities, which are often selected at different stages in other formulations. Additionally, service-oriented solutions require more products (i.e., containers) to distribute to disaster victims, which requires more employees for facility operation and relief distribution.

6.2 Experimentation

The case study was used to solve the research questions. Particularly looking at intermodality and carbon reduction measures, this section introduces an experiment looking at their impact and contrasts the results from the case study with alternatives disregarding these aspects. The comparison is made using a benchmark model disregarding intermodality and carbon reduction measures. This is achieved by eliminating the possibility of making transhipments at the transhipment points and deleting the variables focused on environmental emissions from the benchmark model. The benchmark model was run under the same conditions as the case study (100 iterations with a time limit of one hour per solution and a relative gap of 0). The analysis delivered 17 non-dominated solutions used for comparison.

Figure 4 compares the Pareto frontier of the case study and the Pareto frontier of the benchmark model. The points show the range of cost-oriented and service-oriented solutions in both cases. Interestingly, findings suggest that including sustainability and intermodality does not negatively affect the service or the cost of the solutions. Some solutions from the benchmark model are dominated by the results from the model, especially in service-oriented policies. Intermodality can add flexibility to these solutions to reduce transportation costs and facilitate reaching more areas. At the same time, the result shows that carbon emission reduction measures are not detrimental to disaster response efforts. This is valuable because, during disaster management, carbon emission considerations are often put aside because of the urgency of providing support for the victims.

The value of intermodality is related to its potential to facilitate operations. Having more alternatives for transportation can help reach isolated areas and reduce transportation costs. As shown by Hosseini and Al Khaled (2021), this approach can help adapt the flow of resources to available links in disrupted networks. In that case, different intermodal segments can be

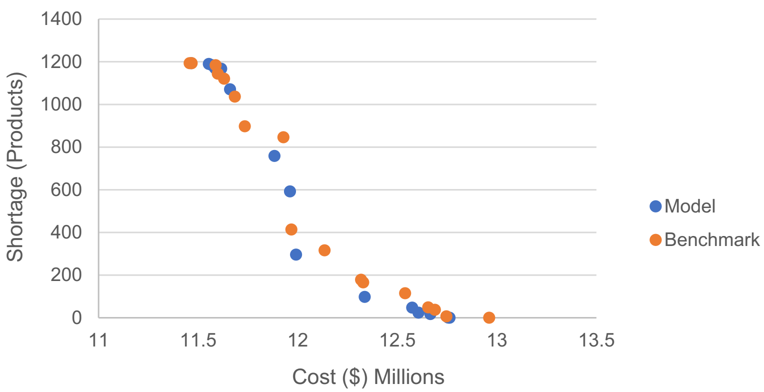

Fig. 4 Comparison of the Pareto frontier of the benchmarking model and the proposed model

Table 2 Intermodal changes

Solution	Containers	Transhipments	Solution	Containers	Transhipments
ND1	0	0	*ND9*	19	13
ND2	1	1	*ND10*	32	16
ND3	1	0	*ND11*	39	35
ND4	2	0	*ND12*	36	27
ND5	3	1	*ND13*	43	22
ND6	6	2	*ND14*	47	22
ND7	11	0	*ND15*	47	32
ND8	18	6			

used to ensure the reliability of the transportation network (Uddin & Huynh, 2019). To clarify the impact of intermodality on the case study, Table 2 shows the total number of transhipments across scenarios and the number of containers transported. Most of the solutions used intermodality as a feasible alternative to minimise both objective functions. Especially in the most service-oriented solutions, an increase in the number of containers is accompanied by more transhipments. For instance, in ND15, up to 68% of the total number of containers shipped had a change of mode along the way. The percentage of transhipments increases dramatically from ND9 onwards, which is the point where the solutions of the model start to dominate the solutions from the benchmark model. The reason is that intermodality allowed the system to combine the transportation modes and balance the solutions among them, with most of the solutions using land transportation and sea transportation to reach transhipment points and land and air transportation to get to the distribution centres. This helps facilitate transportation when accessibility is reduced, and it allows satisfying the requirements of the customers at the same time as costs and carbon emissions are balanced. Conversely, the model disregarding intermodality only used two transportation modes throughout the entire system (air and land transportation) rather than all the transportation modes. This becomes problematic because these channels can become congested or have few vehicles available, affecting the delivery times of essential products.

The other major aspect studied in the article revolves around sustainability. Once the fact that incorporating carbon emission factors in the model does not worsen the solution is known, it is important to see its influence on the results. This part explores that impact by looking at the level of emissions produced by the activities involved in both the solutions of the model and the benchmark formulation in Table 3. The results suggest that the difference in environmental impact is significant, especially in service-oriented solutions. The table shows that solutions with similar levels of service and cost consistently produce higher levels of carbon emissions in the benchmark model. This means that to reach a similar level of service, the solutions from the benchmarking model incur considerably more carbon emissions than the result of the model proposed in this research. For instance, solutions ND3 from both models have similar values of shortage, but the solution from the benchmarking model produces more than three times the level of carbon emissions generated by the solution from the model. Similarly, looking at the solutions satisfying the demand completely, the effect of disregarding carbon emissions in the benchmark model represents more than twice the level of emissions produced by the equivalent solution in the proposed model. Therefore, the inclusion of carbon emission

Table 3 Comparison of carbon emissions

Model proposed				Benchmark model			
Solution	Cost	Shortage	Emissions	Solution	Cost	Shortage	Emissions
ND1	11,466,302	1,192.84	13,880.75	*ND1*	11,457,932	1,192.94	13,881.63
ND2	11,554,455	1,189.33	15,992.57	*ND2*	11,468,036	1,192.87	19,816.53
ND3	11,570,801	1,183.45	17,791.05	*ND3*	11,589,018	1,183.44	53,731.22
ND4	11,586,314	1,169.25	20,279.38	*ND4*	11,599,552	1,144.05	27,027.13
ND5	11,616,555	1,166.98	27,795.73	*ND5*	11,631,142	1,119.92	410,554.41
ND6	11,660,741	1,070.70	66,349.28	*ND6*	11,684,880	1,036.37	174,300.25
ND7	11,884,179	758.17	119,362.16	*ND7*	11,734,993	896.87	300,521.60
ND8	11,962,182	592.13	230,059.56	*ND8*	11,928,886	845.69	997,857.39
ND9	11,992,183	295.68	861,744.84	*ND9*	11,968,879	413.09	820,438.49
ND10	12,337,185	97.46	873,267.83	*ND10*	12,135,777	315.99	1,225,310.32
ND11	12,575,798	46.93	403,261.98	*ND11*	12,318,783	178.02	904,415.29
ND12	12,607,115	23.40	416,380.29	*ND12*	12,329,643	165.77	840,816.23
ND13	12,666,621	17.34	482,025.03	*ND13*	12,539,777	114.39	1,816,674.78
ND14	12,757,120	0.23	490,337.03	*ND14*	12,655,869	48.45	1,086,660.79
ND15	12,763,426	0.00	807,183.46	*ND15*	12,689,804	36.90	1,158,335.50
				ND16	12,747,560	6.68	1,454,077.89
				ND17	12,962,445	0.00	2,245,108.91

measures can make humanitarian operations more environmentally friendly without affecting their performance.

Understanding the type of emissions produced can help identify the key activities to reduce the environmental impact of operations. Looking more closely at the solutions with the lowest level of shortage, Table 4 provides information about the types of emissions produced in each solution. Understandably, the model proposed increases emissions produced by incorporating intermodal changes because of the need for operations in transhipment points. However, that small value has a significant effect on transportation and facilities. Emissions because of facilities are slightly lower in the solutions proposed by the model. The addition of the emissions because of intermodal operations and emissions at the facilities from the solutions of the proposed model are lower than the emissions in facilities from the benchmarking model. The major difference, however, can be noticed in transportation. The maximum value of transport emissions produced by solutions from the model proposed is lower than half of

Table 4 Maximum emissions produced per category

	Emissions facilities	Emissions transport	Emissions intermodality
Maximum model	21,991.28	857,107.70	4.66
Maximum benchmark	22,923.37	2,222,185.54	0

the maximum emissions from the benchmark model. Considering that transport emissions represent over 90% of the level of emissions in most solutions (except the most cost-effective solutions), the reduction of this value is crucial to mitigate the environmental impact of humanitarian operations. The findings suggest that appropriate planning can help reduce the environmental impact of humanitarian operations.

These results support the argument that intermodality and carbon reduction measures can be successfully implemented in humanitarian logistics models to provide operational and environmental advantages. Overall, the results obtained suggest that incorporating intermodality and environmental considerations can provide flexibility in transportation and allow the use of different combinations of transportation modes while simultaneously significantly reducing carbon emissions.

7 Discussion

Despite examples in the commercial logistics literature about the potential benefits of including intermodality and carbon emission reduction (Maiyar & Thakkar, 2020; Qu et al., 2016; Resat & Turkay, 2019), the area of humanitarian operations is yet to investigate these aspects. This is understandable because humanitarian operations have the overarching objective of helping victims, which often means disregarding other aspects such as efficiency and environmental concerns (Chen et al., 2020). However, the evidence is not conclusive that these aspects negatively affect the service provided to disaster victims. Following calls for evidence about the sustainable benefits of intermodal transportation (Bask & Rajahonka, 2017), this article has investigated the inclusion of both considerations and their impact on the service provided to victims.

The first research question focuses on the inclusion of intermodality and carbon reduction measures in a humanitarian logistics model. It is essential to reflect on the conflicting objectives found in humanitarian operations (Beamon & Balcik, 2008). The proposed model achieves this by leveraging the advantages of multi-objective optimisation. The resulting model was tested using information from a case study looking at the impact of hurricanes on the cities of Ahome, Culiacán and Mazatlán. Hurricane Manuel heavily affected these cities in 2013 (Mexican_Senate, 2013). Another interesting aspect is that because of the geographical location of the state, these cities share different communication channels (Panteia, 2020), which allows for investigation of the impact of intermodality considering different transportation modes. Most solutions found in the experimentation include intermodal transportation, which is consistent with previous findings in the literature (Ertem et al., 2022; Strawderman & Eksioglu, 2009). In our study, intermodality increases noticeably in service-oriented solutions for multiple reasons. Damaged or inadequate infrastructure is a common condition faced by humanitarian operations (Kovacs & Spens, 2009) and can prevent the use of delivery channels at certain legs of the journey. Intermodality allows the leverage of different channels to find good combinations to reach areas that would be difficult to serve otherwise. Additionally, it allows the adaption of the distribution plan to the vehicles available at the facilities and the use of all the transportation modes available. The purpose is to reduce the pressure on the most widely used modes, which in turn avoids excessive congestion and delays (Roso, 2013), which are major problems in humanitarian operations (Yang et al., 2018). This finding has significant implications because it provides analytical evidence of the impact of intermodality on achieving more efficient, effective, and responsible disaster operations. It shows that intermodality introduces a degree of flexibility that can benefit both authorities and victims.

Humanitarian operations have a relevant impact on the environment (Kunz & Gold, 2017), making it necessary to start devising strategies to ensure that humanitarian operations can help victims effectively at the same time the environmental effect is reduced. As part of the second research question, this article has explored the effects of disregarding this aspect. The results of the comparison with a benchmark model suggest that introducing environmental concerns into the formulation does not negatively affect the service provided to victims. The results show that cost-oriented solutions deliver similar results, and the benchmark model is slightly dominated by the model proposed in this research. This is expected because service-oriented solutions require delivering more products to the victims. The model combining intermodality and carbon reduction measures outperforms the benchmarking model in these solutions because of the flexibility added by using intermodal transportation. Combining alternatives for transportation with a focus on reducing the level of emissions allows the system to use transportation paths that are unavailable for the model without intermodality. The result is relevant because it demonstrates that effectiveness and responsibility are not necessarily in conflict, giving confidence to managers about the added value of incorporating carbon emission reduction measures to make humanitarian operations more sustainable.

A key finding of this study is that adding intermodality and carbon reduction measures in the formulation can reduce the level of emissions by more than half of the CO_2 produced without compromising the level of service provided to the victims. This is evidence that including carbon reduction measures is feasible even in humanitarian contexts, as the minimum level of shortage can be achieved without extra investment. This finding is the initial step towards a greater understanding of the value of sustainability to support humanitarian operations. Hence, the inclusion of carbon emission reduction measures in mathematical models for humanitarian logistics should be promoted to reduce the environmental impact of these operations.

This article extends findings in the literature (e.g., Demir et al., 2019; Qu et al., 2016) showing that the combination of intermodality and carbon emissions reduction can positively affect overall performance in humanitarian supply chains. The combination of the flexibility provided by intermodal transportation and considerations about carbon emissions in transportation, facilities and operations allows the system to select the best possible combination for cost, level of service, and environmental impact. Therefore, we can conclude that it is possible to obtain simultaneously cost-efficient and emission-efficient solutions. This is consistent with the carbon savings on transportation found by Craig et al. (2013), Qu et al. (2016) and Resat and Turkay (2019). Additionally, our analysis suggests carbon savings can be achieved in facility operation even after considering the carbon cost of intermodal changes.

8 Conclusions

This article introduces a novel multi-objective programming formulation using intermodality for humanitarian logistics operations considering carbon reduction measures. It determines the optimal combination of transportation channels based on the possibility of moving containers at transhipment points to reach the distribution centres to create and distribute the relief kits sent to victims. At the same time, it optimises the use of resources whilst considering carbon emissions in planning for the allocation of evacuees to shelters. This is achieved by minimising the costs of emissions as part of the cost objective function. On the other hand, intermodality has been added by using transhipment points to change the mode of transportation of the container before reaching local distribution centres for distribution.

The article extends knowledge in the areas of humanitarian supply chains and sustainability. It introduces a novel multi-objective formulation for humanitarian logistics incorporating intermodal transportation and carbon reduction measures to reduce the shortage of relief items provided to victims. The results of the experimentation show the value of introducing intermodality to provide flexibility for logistics plans and the potential to use it to reduce the level of emissions produced by these operations. Additionally, the experimentation provides evidence of the impact humanitarian operations can have on the environment and the effect of introducing carbon reduction measures to minimise that impact. This article has shown that carbon reduction measures in humanitarian logistics models can make a massive difference in the level of emissions without compromising the level of service provided to victims or the cost of the operations.

The study can be used to inform decision-makers about ways to manage logistics decisions, direct the organisations involved and explore alternatives for the transportation of relief to avoid congestion in the distribution channels. It can also provide benchmarks for planning operations and testing scenarios for more robust disaster response.

This article opens multiple avenues for research. The research shows the value of carbon reduction measures for disaster preparedness and immediate response. A similar formulation looking at multiple periods could provide information about the impact of these measures in an extended operation and into the recovery stage. Similarly, it would be worth looking at analyses using different operational research techniques to contrast their results with the findings of this article. It can also be used to look more closely at the types of emissions produced and the waste generated by humanitarian operations to support sustainable humanitarian operations, especially in the long term. Finally, following the findings about the value of intermodality for humanitarian logistics, the development of further models considering strategies for intermodality could be useful, especially looking at international suppliers and international aid to enable the efficient flow of resources into the affected areas.

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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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