frontiers | Frontiers in Climate

TYPE Original Research
PUBLISHED 06 August 2025
DOI 10.3389/fclim.2025.1603446

A fair-for-all perspective for climate migrants and destinations

Buket Cilali[1], Kash Barker[1]*, Andrés D. González[1] and Chie Noyori-Corbett[2]

[1]School of Industrial and Systems Engineering, University of Oklahoma, Norman, OK, United States,
[2]School of Social Work, University of Oklahoma, Norman, OK, United States

OPEN ACCESS

EDITED BY
Kelsea Best,
The Ohio State University, United States

REVIEWED BY
Avidan Kent,
University of East Anglia, United Kingdom
Medani Bhandari,
Akamai University, United States
Dev Sen Gupta,
Defence Terrain Research Laboratory (DRDO), India

*CORRESPONDENCE
Kash Barker
✉ kashbarker@ou.edu

RECEIVED 31 March 2025
ACCEPTED 11 July 2025
PUBLISHED 06 August 2025

CITATION
Cilali B, Barker K, González AD and Noyori-Corbett C (2025) A fair-for-all perspective for climate migrants and destinations.
Front. Clim. 7:1603446.
doi: 10.3389/fclim.2025.1603446

Climate change is already upon us. Millions of people are expected to be displaced due to the severe and slow-onset impacts. These displacements will lead to large-scale movements from high-risk and less resilient areas to safer or more resilient areas, creating a relocation problem: where people should go and when. This complex problem involves factors such as the source and extent of relocation demand, identification and capacity of destinations, movements from origins to destinations, and the well-being and dignity of both the displaced and receiving communities. We intend to solve the resulting relocation problem at different levels, starting with high-level decisions about which destinations to choose and how many people to send there. This will facilitate early preparations, such as infrastructure and service planning, at these destinations, ensuring timely action without delays. But in such a complicated problem, what could be the measure of the success of certain relocation decisions compared to others? We consider it requisite that the level of social integration at the destination locations and the fairness of the flow decisions are pivotal to a successful relocation plan and should be thoroughly analyzed. The moral imperative of fairness in these decisions cannot be overstated. That is why our study focuses on the fairness of movements within the context of a relocation problem: how many people from each origin should go to each climate destination in a way that is fair for both climate migrants and receiving communities. To this end, we formulate an optimization model such that the objectives and constraints reflect the key aspects of the relocation problem to assign the number of people to be relocated from each origin to each destination. The model incorporates multiple fairness metrics into objectives representing the perspectives of different stakeholders. These metrics are then analyzed and compared to evaluate trade-offs in the results.

KEYWORDS

climate change displacement, relocation planning, fairness, humanitarian operations research, multi-objective optimization

1 Introduction

Climate change, distinguished by its destabilizing and cascading effects, is becoming more and more recognized as a prominent driver of forced displacement, both independently and in conjunction with other socioeconomic and environmental factors (Wallace-Wells, 2019). Studies indicate that a substantial number of individuals are at a high risk of being forced to leave their homes or will be forced to move due to adverse climate change impacts even before the end of the first half of the 21st century. The 2020 Ecological Threat Register, published by the Institute for Economics and Peace, estimates that 1.2 billion individuals are at risk of displacement by the year 2050 due to inadequate social resilience in the face of high ecological threat levels (Institute for Economics and Peace, 2020). While the exact locations and scale of the displacement remain uncertain, the exceptionally high levels of anticipated displacement cited across various studies suggest that climate change constitutes the most serious risk of leading to a forced displacement crisis that might overshadow all former refugee crises (Biermann and Boas, 2012). Moreover, unlike the former crisis, where sudden displacements were caused by a conflict or an acute natural disaster event, displacement driven by slow-onset climate change impacts occurs over an extended period, resulting in large-scale movements from high-risk, less resilient areas to safer or more resilient destinations. This complexity is further compounded by the fact that displacement due to climate change impacts is not an isolated phenomenon but is interconnected with other environmental and societal stressors. These include, on one hand, water security issues, and on the other hand, climate impacts like sea level rise (Ohenhen et al., 2024; Hijma et al., 2025). Together, these factors intensify vulnerability in both origin and destination regions and create additional pressures for relocation.

The anticipation of these movements presents us with the challenge of managing large-scale relocation without disrupting regional and global stability, but also the opportunity to plan and prepare in advance. Alleviating the most destabilizing aftermath of large-scale displacements and movements requires knowledge of where people are likely to move and when (Lustgarten, 2020). The informed responses to these questions require a systematic approach to relocation planning, one that accounts for the source and extent of relocation demand, the identification and capacity of destination locations, and the well-being and dignity of displaced populations and receiving communities. Therefore, when movements are inevitable, planned relocation presents itself as one of the most viable adaptation solutions to address the challenges posed by climate change. In relocation planning, the complex and high-risk nature of climate change displacement necessitates proactive strategies, while the inequitable distribution of vulnerabilities and resources between regions funding relocation and regions where migrants will originate (e.g., the Global North and Global South, respectively) calls for international support (Biermann and Boas, 2012; IPCC, 2022). As a result, relocation planning provides an international blueprint of movements at the tactical level and can be used by authorities to make informed and proactive decisions and preparations at the strategic level.

However, designing an effective relocation plan is not simply a logistical or capacity-driven problem; it is also a deeply ethical one. Successful relocation efforts must ensure not only efficiency but also fairness, both for those being displaced and for the host communities receiving them. But what constitutes a “fair” relocation plan? Should fairness be defined by equitable burdens on receiving communities, equal treatment of displaced individuals, or broader principles of social justice? This question begs another fundamental question of “integration” between migrants and existing host community members. There should be a point of agreement between two parties allowing them to co-exist in a community with the feeling of fairness on both sides. The sense of fairness of host community members is as important as the sense of fairness of migrants for the purpose of successful integration, thus reducing the likelihood of conflicts between them (Breslawski, 2024). Having pre-planned matching systems that are stable and efficient between migrants and receiving states is inevitable in the current era of mass relocations (Jones and Teytelboym, 2017). However, how we conceptualize fairness, especially through both migrants and host communities, is a daunting task when considering numerous factors that influence the sense of fairness. The agreed-upon state of fairness sensed by both parties for better integration of a community eventually needs to be reflected in a migration policy that allows enhancement of their capabilities to contribute to a community and peacefully manage the flow of these climate migrants into the state and individual communities (International Organization for Migration, n.d.).

The inclusion of fairness in optimization models is becoming increasingly commonplace across a variety of applications (Xinying Chen and Hooker, 2023), particularly within the sphere of humanitarian operations research by its very nature. This integration is essential in situations where limited resources or burdensome responsibilities need to be allocated equitably. Nonetheless, the definition of fairness within each specific application context presents a considerable challenge. It requires not only a mathematical representation of fairness but also the management of trade-offs between competing interests. This challenge calls for a sophisticated approach to ensure that optimization models effectively balance efficiency with equity.

In the context of humanitarian logistics, fairness is a significant concern, as scarce resources are distributed among various entities. A thorough examination of fairness in humanitarian logistics, intersecting with the domains of facility relocation, resource distribution, and transportation, by Donmez et al. (2025) demonstrates the importance and functioning of equitable allocations during disaster situations. Their work highlights the diverse interpretations of fairness across different problem settings, identifies critical gaps in existing mathematical models, and outlines key research directions for incorporating fairness more systematically and contextually.

In the context of relocation driven by forced displacement, fairness can be pursued from different perspectives for different stakeholders. It involves the equitable distribution of resources and opportunities to those in need, ensuring that diverse communities with different geographical, social, cultural, and economic backgrounds are treated equitably. At the same time, fairness also entails the equitable distribution of the costs and efforts associated with the relocation process and related humanitarian efforts, ensuring that the burden is shared equitably. A balanced approach to relocation must account for both the needs of displaced people and the capacities of receiving communities, fostering cooperation and sustainable integration. Yet, achieving it in practice is complex. Defining fairness in this context is challenging, as it involves balancing multiple, sometimes conflicting, perspectives and criteria.

Recently, a growing body of research has sought to incorporate fairness principles into refugee resettlement and relocation planning. These studies explore various aspects, including the equitable distribution of displaced populations and associated responsibilities, the prioritization of vulnerable groups, and ensuring integration at final destinations by centering fairness in decision-making. For example, Ericson and Zeager (2022) investigate coordination mechanisms for fair burden-sharing in receiving non-homogeneous refugee populations among host countries, balancing humanitarian obligations with their capacities. Their method builds on fair division theories and is specifically adapted to reduce manipulation and ensure proportional burden-sharing. On the other hand, Freund et al. (2023) study how fairness, based explicitly on employment likelihoods, can be operationalized in dynamic refugee assignments, ensuring equitable treatment across different refugee subgroups over time. They develop two bid-price control algorithms that incorporate fairness for disadvantaged groups without significantly compromising overall employment outcomes. Looking at it from a different angle, Cilali (2024) examines the sensitivity of fairness in relocation planning to its definition by conducting a comparative analysis across various stakeholder perspectives, evaluation criteria, and measurement approaches. Their findings support the need for a trade-off analysis between efficiency and not one but several fairness measures.

These studies illustrate applications of fairness in optimization and decision-making models, particularly in relocation planning. They highlight the importance of defining and implementing fairness to address the unique and contextual challenges. The profound impact the definition and quantification of fairness can have on relocation outcomes emphasizes the need for careful consideration in designing equitable resettlement strategies. However, despite their respective contributions, existing studies are restricted by the level of decisions, limited definitions of fairness, or the amount of information required at the time of decisions. Studies from relevant research can also yield insight into planning where and when people should be relocated. For example, while fairness in relocation planning first brings to mind the populations that are displaced, fairness for the receiving populations or at the destinations is also crucial for a sustainable relocation plan. For example, recent studies on infrastructure requirements of displaced people at the destinations (Xinying Chen and Hooker, 2023; Donmez et al., 2025) analyze the relationship between the number of displaced people, the perception of infrastructure alternatives provided for them, and the public's willingness to cover the corresponding costs, revealing the critical role of equitable cost distribution in fostering public support and ensuring the long-term success of relocation efforts.

Ultimately, fairness is a very broad and hard-to-define term with so many conceptual and technical aspects to consider. By integrating a careful selection of these diverse perspectives, we aim to develop a more comprehensive approach to fairness in relocation planning. This will allow us to examine trade-offs between different fairness objectives while promoting both efficiency and equity.

Fairness considerations add further layers of complexity to an already difficult problem of relocation planning for climate change-induced forced displacement. This study aims to address these challenges by focusing on the fairness of relocation movements. Specifically, we investigate how many people from each origin should be relocated to each destination in a way that is fair according to different perspectives and various fairness principles. We compare multiple fairness metrics and analyze their implications for relocation decision-making, aiming to identify solutions that balance equity, efficiency, and long-term social integration. By doing so, we not only contribute to the literature on climate change adaptation and relocation planning but also provide practical insights for policymakers and humanitarian organizations preparing for large-scale climate displacement.

We note that the distinction between "refugee" and "migrant" is not always clear, even in traditional contexts (United Nations High Commissioner for Refugees, 2016; United Nations High Commissioner for Refugees, n.d.). The 1951 Refugee Convention (United Nations High Commissioner for Refugees, 2010) defines refugees as those fleeing persecution across international borders, whereas migrants generally move voluntarily for various reasons. However, displacement due to climate change challenges this binary classification, as it is neither a direct result of persecution nor entirely voluntary. Terms such as "climate refugees" (Climate Refugees, n.d.) and "environmental migrants" (Kälin and Weerasinghe, 2017) have been used to describe those affected, but no globally recognized legal definition exists. Therefore, we adopt the term "climate migrants" to represent those displaced by the effects of climate.

The rest of this paper is structured as follows. Section 3 presents the mathematical optimization model for relocation planning, detailing how fairness considerations are integrated into the framework. Section 4 introduces the illustrative example used to demonstrate the implementation of the model. Section 5 analyzes and compares the results under different fairness perspectives, highlighting their implications for relocation decisions. Finally, Section 6 provides concluding remarks, discussing key insights, limitations, and potential directions for future research.

2 Methodology

This section presents the mathematical optimization model developed to support fair and effective relocation planning for climate change-induced displacement. First, we describe the base relocation model, which captures the core components of the relocation planning problem. Next, we introduce fairness-related objectives and constraints, which ensure equitable treatment of climate migrants and receiving communities. Since these fairness constraints introduce computational complexities, we then present their reformulations. Finally, we discuss the solution approach, detailing how the multi-objective nature of the problem is addressed.

2.1 Base relocation model

Relocation planning for displaced populations is a complex multi-period decision-making problem where authorities must determine where to relocate displaced populations, how many individuals to relocate from each origin to each destination, when relocation should take place over a long-term planning horizon, and how to balance resource constraints at destination locations. To address these challenges, the base model is formulated as a multi-period mathematical optimization model that accounts for key factors such as demand at origin locations (the number of individuals requiring relocation), capacity at destination locations (limits on how many people can be accommodated at different times), budgetary and resource constraints (e.g., infrastructure investments, financial support required), and dynamic relocation decisions (movement of individuals over time). The model captures real-world constraints such as capacity availability, resource allocation, and relocation feasibility, ensuring that decisions are both operationally viable and strategically sound. The main objective is to maximize relocation decisions while others focus on minimizing cultural distances and financial burdens.

The sets, parameters, and decision variables of the base relocation model are presented in Tables 1–3.

The base relocation model comprises three objectives. The first objective function in Equation 1 represents the main purpose of the relocation problem, aiming to maximize the total number of relocation assignments between all origin–destination pairs over the planning horizon. The second objective function, presented in Equation 2, aims

TABLE 1 Sets and indices.

Notation	Definition
I	Set of origin locations, indexed by i
J	Set of destinations, indexed by j
T	Set of periods indexed by t

TABLE 2 Parameters.

Notation	Definition
d_i^t	Relocation demand forecasted to arise for origin $i \in I$ at period $t \in T$
d_{ij}^{CD}	Cultural distance based on partition between origin $i \in I$ and destination $j \in J$
c_j^e	Unit cost of capacity expansion for destination $j \in J$
α	Policy-determined lower bound percentage tying financial support to the cost of expanding capacity
β	Policy-determined upper bound percentage tying financial support to the cost of expanding capacity

TABLE 3 Decision variables.

Notation	Definition
x_{ij}^t	Relocation flow assigned from origin $i \in I$ to destination $j \in J$ at period $t \in T$
s_i^t	Unmet relocation demand at origin $i \in I$ at period $t \in T$
Π_j	Financial support provided to destination $j \in J$
cap_j^t	Relocation capacity of the destination $j \in J$ at period $t \in T$
$\text{cap}\Delta_j^t$	Relocation capacity expansion for the destination $j \in J$ at period $t \in T \setminus \{1\}$

to minimize the total cultural distance between relocated and receiving communities, ensuring social integration at the destinations. The third objective function, provided in Equation 3, aims to minimize the total amount of financial support allocated to the destinations from the central funds, addressing the limited availability of humanitarian funds compared to humanitarian needs (United Nations Office for the Coordination of Humanitarian Affairs, 2024).

$$\max \sum_{t\in T}\sum_{j\in J}\sum_{i\in I} x_{ij}^t \tag{1}$$

$$\min \sum_{t\in T}\sum_{j\in J}\sum_{i\in I} d_{ij}^{CD} \times x_{ij}^t \tag{2}$$

$$\min \sum_{j\in J} \Pi_j \tag{3}$$

The base relocation model imposes various constraints regarding flow balance, capacity, and funding restrictions. The first group of constraints in Equations 4, 5 ensures the balance between outflows, unmet demand, and emerging demand of the origins for the first and subsequent periods, respectively. The second group of constraints presented in Equation 6 restricts the maximum level of inflow that a destination can receive based on its current level of available capacity. The third group of constraints presented in Equations 7, 8 ensures the balance between inflows, available capacity, and capacity expansion of the destinations for the first and subsequent periods, respectively. Finally, the fourth group of constraints presented in Equations 9, 10 establishes a condition on the minimum and maximum financial support that each destination may receive based on its capacity expansion expenditures, respectively.

$$\sum_{j\in J} x_{ij}^1 + s_i^1 = d_i^1 \quad \forall i \in I \tag{4}$$

$$\sum_{j\in J} x_{ij}^t + s_i^t = s_i^{t-1} + d_i^t \quad \forall i \in I, t \in T \setminus \{1\} \tag{5}$$

$$\sum_{i\in I} x_{ij}^t \le \text{cap}_j^t \quad \forall j \in J, t \in T \tag{6}$$

$$\text{cap}_j^1 = \text{cap}\Delta_j^1 \quad \forall j \in J \tag{7}$$

$$\text{cap}_j^t = \text{cap}_j^{t-1} - \sum_{i\in I} x_{ij}^{t-1} + \text{cap}\Delta_j^t \quad \forall j \in J, t \in T \setminus \{1\} \tag{8}$$

$$\alpha \times \sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t \le \Pi_j \quad \forall j \in J \tag{9}$$

$$\beta \times \sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t \ge \Pi_j \quad \forall j \in J \tag{10}$$

2.2 Inclusion of fairness

To incorporate fairness, we employ the Gini index to define fairness measures to be minimized as an indicator of inequality in the distribution of relocation flows and funds from the perspectives of displaced people and receiving communities, respectively.

The Gini index is an index extensively used in economics to assess the inequality of distribution income, where an index value of 0 indicates perfect equality and closer to 1 indicates greater inequality. There are a variety of other measures to quantify fairness (Farris, 2010), but we select the Gini index due to its simplicity and popularity. We use the following mathematical definition of the Gini index (Ceriani and Verme, 2012) provided in Equation 11, where n is the number of elements and x_i is the value of the ith element.

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|x_i - x_j\right|}{2n\sum_{i=1}^{n} x_i} \tag{11}$$

Objectives given in Equations 12, 13 ensure fairness from the perspectives of origins and destinations, respectively, by minimizing levels of inequality by using the corresponding Gini indices.

$$\min G^{\text{orig}} \tag{12}$$

$$\min G^{\text{dest}} \tag{13}$$

The calculation of these objectives is provided in Equations 14, 15. Equation 14 defines fairness based on the average unmet demand of origin populations proportional to their current total demand over the planning horizon. Alternatively, Equation 15 defines fairness based on the funding of destinations proportional to their total capacity expansion expenditures.

$$G^{\text{orig}} = \frac{\sum_{i\in I}\sum_{i'\in I}\left|\frac{\sum_{t\in T}\frac{s_i^t}{\sum_{t'=1}^{t} d_i^{t'}}}{|T|} - \frac{\sum_{t\in T}\frac{s_{i'}^t}{\sum_{t'=1}^{t} d_{i'}^{t'}}}{|T|}\right|}{2\times|I|\times\sum_{i\in I}\frac{\sum_{t\in T}\frac{s_i^t}{\sum_{t'=1}^{t} d_i^{t'}}}{|T|}} \tag{14}$$

$$G^{\text{dest}} = \frac{\sum_{j\in J}\sum_{j'\in J}\left|\frac{\Pi_j}{\sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t} - \frac{\Pi_{j'}}{\sum_{t\in T} c_{j'}^e \times \text{cap}\Delta_{j'}^t}\right|}{2\times|J|\times\sum_{j\in J}\frac{\Pi_j}{\sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t}} \tag{15}$$

2.3 Reformulations

Naturally, the nonlinearity of Equations 14, 15 pose difficulties for typical optimization solvers. Especially the use of absolute values in the Gini index formulation is a significant issue for an optimization solver. To reduce the resulting nonlinearities and transform the mathematical formulation into a more solver-friendly form, we first define two groups of auxiliary variables

$$A_{ii'} = \left|\frac{\sum_{t\in T}\frac{s_i^t}{\sum_{t'=1}^{t} d_i^{t'}}}{|T|} - \frac{\sum_{t\in T}\frac{s_{i'}^t}{\sum_{t'=1}^{t} d_{i'}^{t'}}}{|T|}\right| \quad \forall i,i'\in I \quad \text{and}$$

$$A_{jj'} = \left|\frac{\Pi_j}{\sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t} - \frac{\Pi_{j'}}{\sum_{t\in T} c_{j'}^e \times \text{cap}\Delta_{j'}^t}\right| \quad \forall j,j'\in J$$ as also adopted in Braik et al. (2025). Then, we replace Equation 14 with Equations 16–18 and Equation 15 with Equations 19–21.

$$A_{ii'} \geq \frac{\sum_{t\in T}\frac{s_i^t}{\sum_{t'=1}^{t} d_i^{t'}}}{|T|} - \frac{\sum_{t\in T}\frac{s_{i'}^t}{\sum_{t'=1}^{t} d_{i'}^{t'}}}{|T|} \quad \forall i,i'\in I \tag{16}$$

$$A_{ii'} \geq -\left[\frac{\sum_{t\in T}\frac{s_i^t}{\sum_{t'=1}^{t} d_i^{t'}}}{|T|} - \frac{\sum_{t\in T}\frac{s_{i'}^t}{\sum_{t'=1}^{t} d_{i'}^{t'}}}{|T|}\right] \quad \forall i,i'\in I \tag{17}$$

$$G^{\text{orig}} \times 2n_I \sum_{i\in I}\frac{\sum_{t\in T}\frac{s_i^t}{\sum_{t'=1}^{t} d_i^{t'}}}{|T|} = \sum_{i\in I}\sum_{i'\in I} A_{ii'} \tag{18}$$

$$A_{jj'} \geq \frac{\Pi_j}{\sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t} - \frac{\Pi_{j'}}{\sum_{t\in T} c_{j'}^e \times \text{cap}\Delta_{j'}^t} \quad \forall j,j'\in J \tag{19}$$

$$A_{jj'} \geq -\left(\frac{\Pi_j}{\sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t} - \frac{\Pi_{j'}}{\sum_{t\in T} c_{j'}^e \times \text{cap}\Delta_{j'}^t}\right) \quad \forall i,i'\in I \tag{20}$$

$$G^{dest} \times 2n_J \sum_{j\in J}\frac{\Pi_j}{\sum_{t\in T} c_j^e \times \text{cap}\Delta_j^t} = \sum_{j\in J}\sum_{j'\in J} A_{jj'} \tag{21}$$

2.4 Solution approach

As we have a multi-objective formulation, we use the ϵ-constraint method (Chankong and Haimes, 2008) to generate noninferior solutions for the fair relocation model. To do so, we transform our multi-objective problem such that we only optimize the primary objective function while incorporating other objective functions as constraints. As a result, we maximize f_1 subject to $f_2 \leq \epsilon_2$, $f_3 \leq \epsilon_3$, $f_4 \leq \epsilon_4$, $f_5 \leq \epsilon_5$ where f_1, f_2, f_3, f_4, and f_5 are the objectives given in Equations 1–3, respectively. Then, we obtain the noninferior solutions by solving the resulting problem for the varying values of ϵ_2, ϵ_3, ϵ_4 and ϵ_5.

3 Illustrative example

In the absence of comprehensive and reliable data on long-term climate-induced displacement, we base our analysis on synthetic data grounded in publicly available sources and plausible assumptions. While the proposed model can, in principle, be applied at various levels of spatial granularity, including internal migration setting, we focus here on cross-border relocation between origin and destination countries. This decision reflects contexts where internal relocation may not be viable (e.g., small island states facing existential threats). To demonstrate the implementation of our model, we draw on the illustrative example introduced by Cilali et al. (n.d.) for another multi-period relocation planning study. The assumptions and parameter construction logic used in this example are outlined as follows:

- Relocation demands were estimated using exposure projections from the Climate Mobility Dashboard developed by IOM's Global Data Institute, focusing on heatwave data under high warming (RCP 6.0) and regional rivalry (SSP3) scenarios.
- Ten origin countries with the highest number of vulnerable individuals exposed were selected based on the demand data.
- Four destination countries were chosen considering climate risk, institutional readiness, and regional diversity, though left unnamed to avoid speculation.
- Unit cost of capacity expansion was proxied using social expenditure as a percentage of GDP divided by the total population.
- Cultural partition distances between country pairs were estimated using ethnic, linguistic, and religious fractionalization indices.
- Funding policy percentages (10% minimum, 90% maximum) were uniformly assigned to all destination countries to observe the effects of the existence of funding restrictions.

For the complete rationale, step-by-step methodology, and related resources, see Cilali et al. (n.d.).

4 Analysis

In this section, we present and compare the model outputs from two main perspectives: (i) Pareto-optimal solutions, trade-offs, and the relationships between multiple objectives, and (ii) the price of fairness.

We start our analysis with Pareto-optimal solutions, trade-offs, and the relationships between multiple objectives, where the multiple objectives are abbreviated as follows:

- f_1: total relocation flow,
- f_2: total cultural distance,
- f_3: total financial support,
- f_4: Gini index for origins (inequality level of the distribution of proportional unmet demand),
- f_5: Gini index for destinations (inequality level of the distribution of proportional financial support).

Figure 1 illustrates the correlation matrix between multiple objectives. As shown in the heatmap, there is a strong positive correlation between total relocation flow (f_1) and total cultural distance (f_2), which can be attributed to the fact that each relocation assignment contributes to the total cultural distance. Notably, total financial support (f_3) also has a strong positive correlation with both

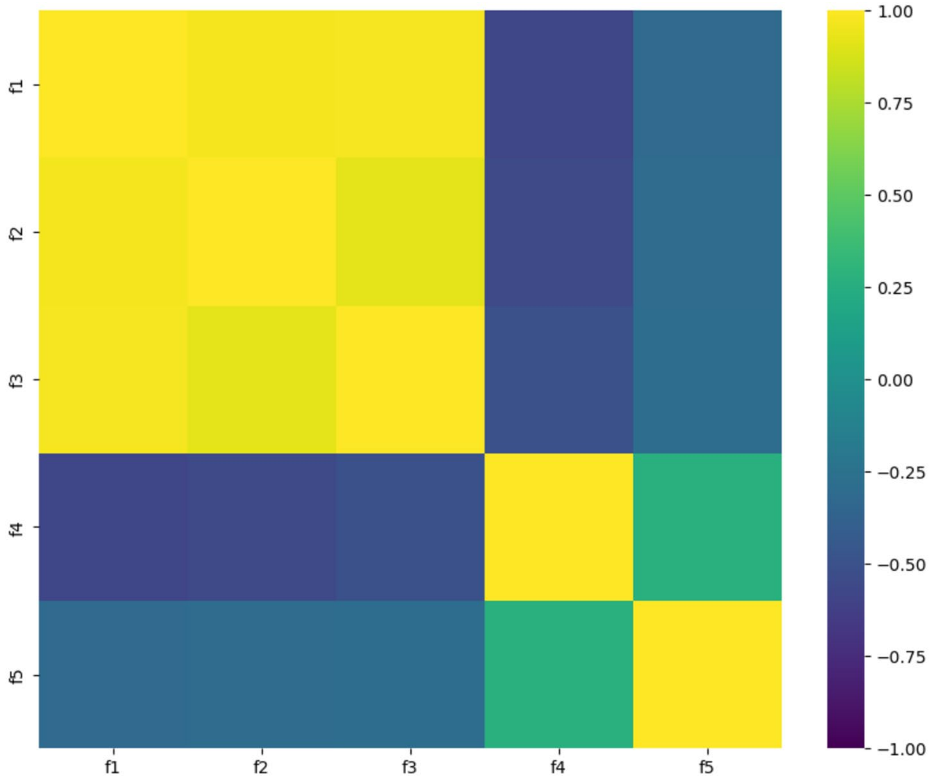

FIGURE 1
Correlation matrix of objectives.

f_1 and f_2, reflecting that higher relocation activity and greater cultural distance typically require more financial resources. In contrast, f_1, f_2 and f_3 all show negative correlations with the fairness objectives, particularly from the perspectives of origins (f_4). This highlights the trade-offs between efficiency and equity, emphasizing the importance of explicitly incorporating fairness into the model objectives.

Figure 2 is a 3D projection of the Pareto-optimal solutions and the clusters they form in relation to total relocation flow (f_1) and fairness objectives (f_4 and f_5), while total cultural distance (f_2) is represented by the size of the markers. Similarly, Figure 3 is a 2D projection of the same solution clusters in relation to fairness for origins (f_4) and fairness for destinations (f_5). Pareto-optimal frontiers reveal distinct patterns among clusters, highlighting trade-offs between relocation efficiency and fairness. Cluster 1 consists of solutions with almost no relocation activity, which most of the time results in minimum inequality, particularly for the destinations, but offers no practical relocation outcomes. Cluster 2 includes high-relocation solutions that come at the cost of higher cultural distances, as seen in the larger marker sizes. It can be inferred that higher relocation helps with inequality issues upto a point, especially for the origins, as it decreases the source of inequality for origins. However, the relationship between relocating more people and being fair to all origins is not a simple one as it can be seen from Cluster 0. Cluster 0 achieves lower inequalities for origins only for moderate levels of relocation.

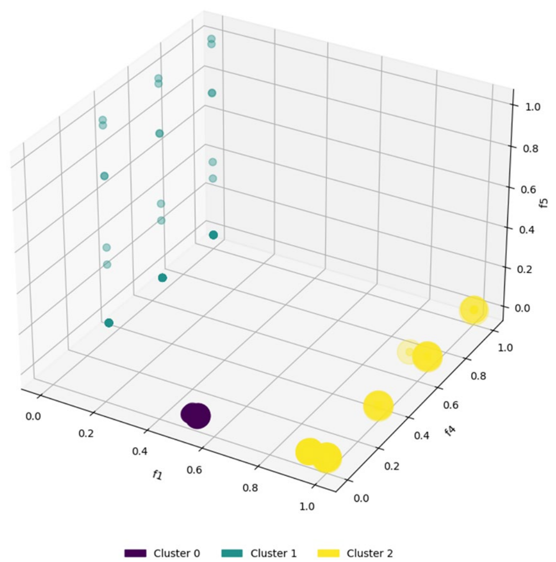

FIGURE 2
3D Pareto frontier with clusters.

Figure 4 demonstrates two box plots displaying the distribution of the fairness objectives, f_4 (Gini Index for Origins) and f_5 (Gini Index for Destinations). Fairness at origins (f_4) exhibits considerable variation across the solution space, indicating differing levels of unmet demand inequality. In contrast, fairness at destinations (f_5) is generally at or near perfect equality, with some outliers. This accumulation around zero for f_5 can be attributed to the way financial support is structured since fairness at destinations is measured based on the total funding received proportional to the total expenditures, and the imposed conditions on support allocation inherently promote more balanced outcomes.

Another important aspect of the fairness analysis is the Price of Fairness (PoF), which represents the relative reduction in the utility under the fair solution compared to the utilitarian solution (Bertsimas et al., 2011). It can also be described as the relative loss of efficiency for the sake of equity.

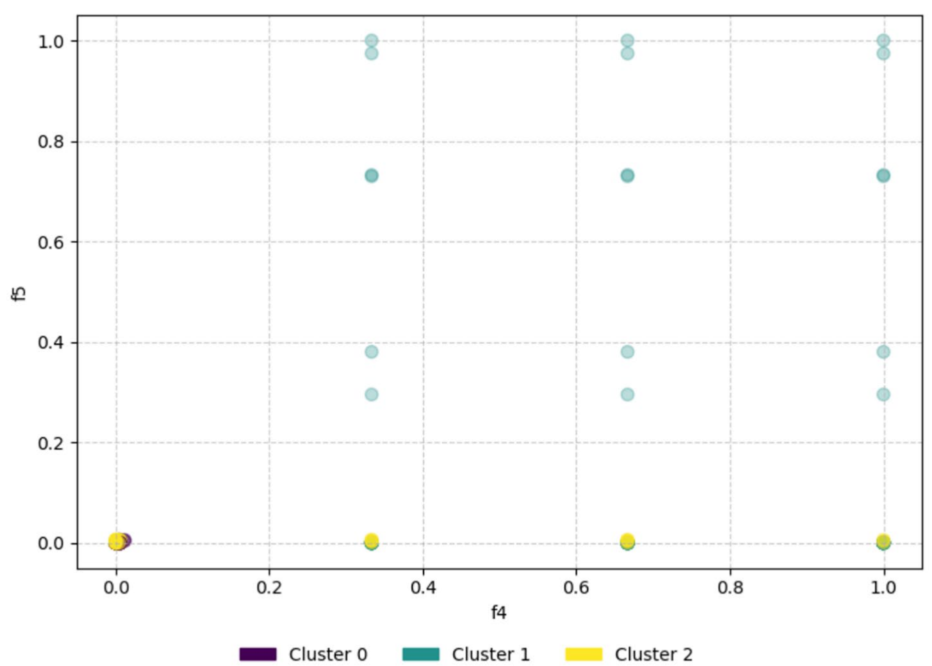

FIGURE 3
2D Pareto frontier with clusters.

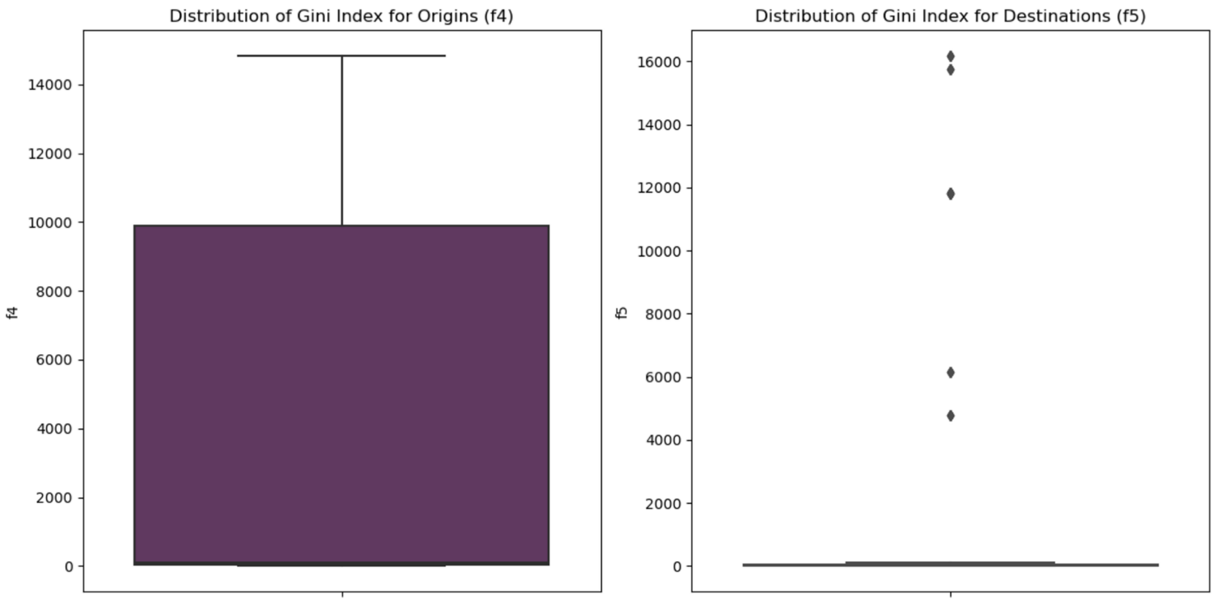

FIGURE 4
Distributions of fairness objectives.

In this study, we evaluate PoF for two stakeholder perspectives (origins and destinations), for each perspective, by comparing social welfare outcomes of two versions of the multiobjective relocation model: one incorporating the fairness objective (referred to as the fair model) and one replacing that fairness objective with corresponding utilitarian social welfare objective (referred to as the utilitarian model). While both models are solved using the υ-constraint method, their respective formulations differ in how they treat fairness and social welfare: the fair model minimizes inequality across groups (measured by Gini indices), whereas the utilitarian model minimizes the average proportional burden experienced by each group (measured by social welfare metrics).

We define two separate social welfare metrics aligned with the fairness perspectives: (i) for origins, the average ratio of unmet demand to current total demand across all origins and periods; (ii) for destinations, the average ratio of financial support received to total capacity-building expenditures across all destinations. These social welfare objectives are minimized in the utilitarian version and tracked but not optimized in the fair version for comparison.

Due to the multi-objective nature of the problem and the corresponding usage of ϵ -constraint method, we solve a series of instances for both versions. However, for PoF analysis, we optimize the fairness measure for the fair model and optimize the social welfare metric for the utilitarian model while incorporating base model objectives as epsilon constraints with varying thresholds on total relocation, cultural distance and total financial support (i.e., ϵ_1, ϵ_2 and ϵ_3). We then extract the corresponding social welfare values for each combination of ϵ_1 - ϵ_2 - ϵ_3 .

Finally, a series of PoF values is calculated for each stakeholder perspective as the relative increase in average burden under fairness as quantified in Equations 22, 23 (noting the sign convention due to the minimization of social welfare):

$$PoF_{orig} = -\frac{SW_{orig}^{util} - SW_{orig}^{fair}}{SW_{orig}^{util}} \tag{22}$$

$$PoF_{dest} = -\frac{SW_{dest}^{util} - SW_{dest}^{fair}}{SW_{dest}^{util}} \tag{23}$$

This approach enables a stakeholder-specific evaluation of how much efficiency is sacrificed in pursuit of equity by quantifying the tradeoff between them.

Figures 5, 6 demonstrate the 3D plot of the PoF across ϵ_1 - ϵ_2 - ϵ_3 grid for origins and destinations, respectively. As seen in Figure 5, PoF for origins is always negative and becomes more pronounced as the efficiency constraints tighten for total relocation and loosen for total cultural distance and total financial support. It means that incorporating fairness not only reduces inequality among origins but also leads to a better overall outcome for them. On the contrary, as seen in Figure 6, PoF for destinations is always positive

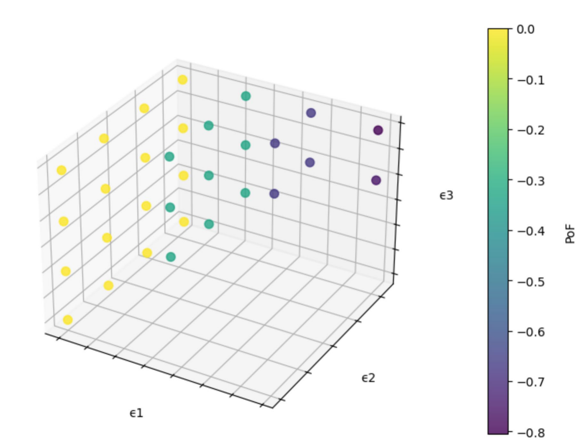

FIGURE 5
PoF for origins.

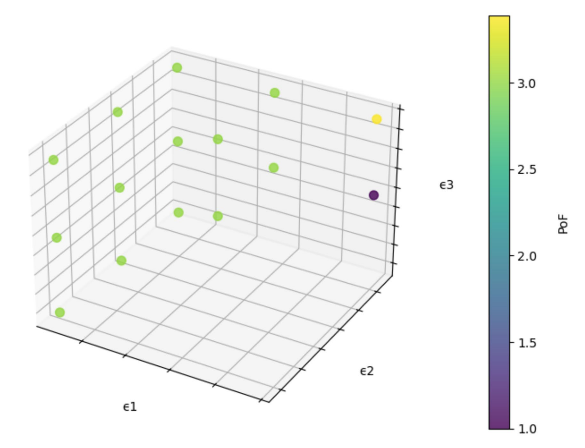

FIGURE 6
PoF for destinations.

and very high nearly all the time, suggesting that prioritizing fairness at destinations results in higher average financial burden.

Together, these plots reveal that the price of promoting fairness is not uniform across stakeholders. Achieving origin fairness is more sensitive to resource allocation constraints, whereas destination fairness consistently incurs a higher cost. This asymmetry highlights the necessity for customized fairness strategies in multi-stakeholder systems.

5 Conclusion

This study addresses the complex problem of planning large-scale, climate change-induced relocations in a way that is both operationally feasible and ethically sound. Specifically, it investigates how to assign relocation flows from vulnerable origin populations to safer destinations while considering multiple competing objectives such as efficiency, social integration, and fairness. The problem is formalized as a multi-period, multi-objective optimization model, incorporating relocation demand, destination capacity, cultural distance, and financial constraints, with fairness explicitly measured through Gini indices from both origin and destination perspectives.

By integrating fairness as a central component of the model, this work contributes to the literature on both humanitarian operations research and climate change adaptation policy. A key contribution of the study lies in its comparative analysis of fairness objectives, offering insights into the trade-offs between efficiency and equity across stakeholders.

The results of this study offer practical implications for both policymakers and researchers working on climate-induced migration. By quantifying trade-offs between fairness and efficiency, the model provides a transparent way to support evidence-based decisions about who should be relocated, where, and when. This can guide the development of policies that are not only operationally feasible but also viewed as legitimate and fair by stakeholders. Additionally, this modeling approach can be adapted by interdisciplinary teams, including economists, sociologists, and legal scholars, to examine how fairness considerations intersect with other aspects of climate change or human mobility governance.

While incorporating fairness through the Gini Index is a valuable contribution, it offers a limited view of many dimensions of fairness. Future research should explore additional fairness measures to capture broader aspects of justice. Moreover, analyzing more scenarios from stakeholder-specific perspectives could deepen understanding. Integrating such perspectives would enable models to guide not only more just outcomes but also more legitimate, accepted, and sustainable relocation strategies. Future work will explore different perspectives of fairness and how fairness can be more effectively integrated into the decision process, including across decision-making bodies (e.g., host countries and regions), across migrants, and across time periods (e.g., "it will all work out in the end" versus "we are in this together from the start"). Further considerations of fairness, especially for decision-makers, will address not only resources expended (e.g., humanitarian aid resources) but also risk (e.g., security concerns), as the perception of fairness across decision-makers may improve willingness to participate in finding solutions to this important problem with global consequences.

Ultimately, this study underscores the importance of embedding fairness in the early design of relocation planning, ensuring that climate change adaptation efforts are not only effective but also just.

Data availability statement

The raw data supporting the conclusions this article will be made available by the authors, without undue reservation.

Author contributions

BC: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. KB: Formal analysis, Funding acquisition, Supervision, Writing – review & editing. AG: Conceptualization, Writing – review & editing. CN-C: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was funded in part by a grant from the Army Research Office through its Minerva Initiative (award W911NF-24-1-0177).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

References

Bertsimas, D., Farias, V. F., and Trichakis, N. (2011). The Price of fairness. *Oper. Res.* 59, 17–31. doi: 10.1287/opre.1100.0865

Biermann, F., and Boas, I. (2012). "Climate change and human migration: towards a global governance system to protect climate Refugees" in Climate change, human security and violent conflict: Challenges for societal stability. eds. J. Scheffran, M. Brzoska, H. G. Brauch, P. M. Link and J. Schilling (Berlin, Heidelberg: Springer Berlin Heidelberg), 291–300.

Braik, A. M., Sen Gupta, H., Koliou, M., and González, A. D. (2025). Multi-hazard probabilistic risk assessment and equitable multi-objective optimization of building retrofit strategies in hurricane-vulnerable communities. *Comput. Aided Civ. Inf. Eng.* 40, 2074–2097. doi: 10.1111/mice.13445

Breslawski, J. (2024). Who deserves aid? Perceptions of fairness in contexts of forced displacement. *World Dev.* 183:106710. doi: 10.1016/j.worlddev.2024.106710

Ceriani, L., and Verme, P. (2012). The origins of the Gini index: extracts from Variabilità e Mutabilità (1912) by Corrado Gini. *J. Econ. Inequal.* Mineola, NY: Courier Dover Publications. 10, 421–443. doi: 10.1007/s10888-011-9188-x

Chankong, V., and Haimes, Y. Y. (2008). Multiobjective decision making: Theory and methodology: Courier Dover Publications.

Cilali, B. (2024). Planning for climate change-induced displacement: Social integration, uncertainty, decentralization, adaptability, and fairness, Oklahoma, US.

Cilali, B., Barker, K., González, A. D., Hemmati, S., and Salo, A. "Consensus-driven decentralized optimization for global relocation planning in the context of climate change," Submitted. Available at: https://www.climate-refugees.org/why. (Accessed July 18, 2025)

Climate Refugees. "Climate Refugees." Mineola, NY: Courier Dover Publications 2074–2097.

Donmez, Z., Saldanha-da-Gama, F., Karsu, S., Kara, B. Y., Ayyildiz, M., and Uslu, B. (2025). Humanitarian Logistics: How fair is fairness? *SSRN Electron. J.* doi: 10.2139/ssrn.4396254

Ericson, R. E., and Zeager, L. A. (2022). Coordination and fair division in refugee responsibility sharing. *J. Confl. Resolut.* 66, 1263–1291. doi: 10.1177/00220027221080985

Farris, F. A. (2010). The gini index and measures of inequality. *Am. Math. Mon.* 117:851. doi: 10.4169/000298910x523344

Freund, D., Lykouris, T., Paulson, E., Sturt, B., and Weng, W. (2023). "Group fairness in dynamic refugee assignment," January.

Hijma, M. P., Bradley, S. L., Cohen, K. M., van der Wal, W., Barlow, N. L. M., Blank, B., et al. (2025). Global Sea-level rise in the early Holocene revealed from North Sea peats. *Nature* 639, 652–657. doi: 10.1038/s41586-025-08769-7

Institute for Economics and Peace. (2020). Ecological threat register 2020: understanding ecological threats, resilience and peace. Institute for Economics & Peace, Sydney, Australia, Sep. 2020. Available at: https://www.iom.int/migrant-integration (Accessed July 18, 2025).

International Organization for Migration. Migrant integration.

IPCC (2022). "Summary for policymakers" in eds. H. -O. Pörtner, D. C. Roberts, E. S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Climate change 2022: Impacts, adaptation and vulnerability (Cambridge, UK and New York, NY, USA: Cambridge University Press), 3–33. doi: 10.1017/9781009325844.001

Jones, W., and Teytelboym, A. (2017). Matching systems for refugees. *J. Migr. Hum. Secur.* 5, 667–681. doi: 10.1177/233150241700500306

Kälin, W., and Weerasinghe, S. (2017) "Environmental migrants and global governance: facts, policies and practices," Geneva.

Lustgarten, A. (2020). "Where will everyone go?," *ProPublica*

Ohenhen, L. O., Shirzaei, M., Ojha, C., Sherpa, S. F., and Nicholls, R. J. (2024). Disappearing cities on US coasts. *Nature* 627, 108–115. doi: 10.1038/s41586-024-07038-3

United Nations High Commissioner for Refugees. (2010). Convention and protocol relating to the status of Refugees. Geneva.

United Nations High Commissioner for Refugees (2016). 'Refugees' and 'migrants' – frequently asked questions

United Nations High Commissioner for Refugees. Refugees and migrants – definitions. Available at: https://refugeesmigrants.un.org/definitions (Accessed July 18, 2025).

United Nations Office for the Coordination of Humanitarian Affairs. (2024), "Global humanitarian overview 2025," December.

Wallace-Wells, D. (2019). The uninhabitable earth: Life after warming. *1st* Edn. New York, NY, USA: Tim Duggan Books.

Xinying Chen, V., and Hooker, J. N. (2023). A guide to formulating fairness in an optimization model. *Ann. Oper. Res.* 326, 581–619. doi: 10.1007/s10479-023-05264-y