Modeling Feasible and Culturally Optimal Relocation of Environmentally Displaced Persons

MCM/ICM 2020 Problem F

Team #2019289

Summary

In this paper, we analyze the issue of relocating Environmentally Displaced People (EDPs) and develop a model that guides the United Nations (UN) on when and how they should address this problem. This issue is complex and multifaceted, as it is not only related to relocation, but also timing factors and the risks of losing unique cultures through mass migration. The problem, in our interpretation, is of finding methods for which these EDPs can be displaced with minimal loss of cultural heritage. At the same time, it is important to quantify the viability of different absorbing countries as to ensure the optimal environment for both the refugees and the hosting nations.

To be able to formalize a solution to this immensely complex issue, we first limit ourselves to the EDPs from what we find to be the four most endangered island nations: Kiribati, Tuvalu, Maldives, and the Marshall Islands.

We view this as an optimization problem where we are trying to maximize both cultural preservation and practicality of relocation (encoded in the viability quantity). In the same light, we think of this problem as finding the optimal island-country pairings for these objectives. Since they are two distinct objectives, we divide our model into corresponding components. More specifically, we create the *Cultural Heritage Preservation Index (CHPI)* and the *Viability* function. We can then optimize their convex combination, essentially giving each island nation a time-dependent ranking of countries they should migrate to. At this point, we solve an assignment problem using the Kuhn—Munkres algorithm to give the UN the most thorough recommendation possible.

We take into account time factors by firstly considering CHPI as a function of time. We then also model how many refugees should emigrate in a given year in response to these two constraints: the urgency pertaining to sea level rise and the disruption to existing populations.

Contents

1 Introduction

In recent years, climate change has become an important topic of conversation. It is projected that rising sea levels will completely cover the Maldives, Tuvalu, Kiribati, and the Marshall Islands in water, leaving their inhabitants without land. In order to curtail the cultural and socio-economic damage this displacement will create, the UN has recently ruled that the Environmentally Displaced Persons (EDPs) may be considered as refugees. While considerable research has been done in regards to the scientific, economic and political implications of climate change, it is important to note that a unique aspect of these climate refugees is that they carry rich and distinct cultural heritage, not commonly found in any other community and at a risk of disappearing through mass migration to unfamiliar land. Their culture heritage is significant not only to promoting global cultural diversity and complexity in their own right, but also to preserving the identities of the island inhabitants as individuals and as a whole [9].

The given problem is then: when and how should the United Nations step in to settle to issue of EDPs, given that cultural preservation is a priority? As complex as it may already sound, the scope of the problem is influenced also by other facets such as refugee rights, viability of different countries to accommodate these EDPs, and the timescales at which the problem is escalating. Answering this question, we propose the following objective:

1.1 Our Objective

The rest of this report concerns an answer to this problem, while taking into account factors such as those listed above. It addresses the scope of this issue with regards to the number of people at risk and the risk of loss of culture; a possible policy to address these EDPs based on mathematical models, and an analysis of the potential impact of the proposed policy.

More specifically, we are looking to displace the four island nations of Maldives, Tuvalu, Kiribati, and Marshall Islands into other countries before their islands are lost. The goal of our model is to evaluate which countries are best fit to take these EDP's by comparing cultural similarities, countries' cultural acceptance, and countries' preexisting conditions which may affect their ability to host these EDPs. After formulating this model and testing different parameters, we wish to advise the UN on what steps should be taken in order to minimize damage for all parties involved.

2 Extent of the Problem

2.1 Our Interpretation of the Issue

According to "The 9 Most Endangered Islands in the World" due to climate change listed by Pacific Climate Change Portal and considering the accessibility of data [4], we begin by narrowing our scope from all EDPs to those coming from one of the four following island nations: The Marshall Islands, The Maldives, Tuvalu, and Kiribati. Though we agree that there are a vast number of reasons for displacement due to climate change, we reckon that most of these displacements will be due to unforeseeable disasters. Thus, we turn our focus to the completely foreseeable disaster of rising sea levels, specifically in regard to these four islands. Our interpretation of the question is of finding a method for which these EDPs can be displaced with minimal loss of cultural heritage. At the same time, it is important for this method to minimally disrupt the environment of the hosting country, as to allow them to accommodate the EDPs as best as they can.

2.1.1 Scope of the Problem

According to the National Oceanic and Atmospheric Administration of the U.S., sea level has risen 21-24 centimeters since 1880 and was 81 millimeters above the highest annual average from 1993 to present. The rate of sea level rise is accelerating as well: from 2006-2015, it has more than doubled from 1.4 millimeters/year throughout the last century to 3.6 millimeters/year from 2006-2015. Analyses show that even if the world followed the lowest greenhouse gas pathway possible, the global sea level would still rise at least 0.3 meters by 2100, putting coastal cities and island nations at risk and posing threats to homes of more than 300 million people [8]. In the worst case predicted by climate scientists, as many as 640 million people could be threatened by 2100, among which those from Tuvalu, the Marshall Islands, the Maldives and Kiribati are predicted to be the most endangered [4]. With the sea levels rising between 0.38m-1.8m and a total population over 610,000, the four island countries are predicted to sink entirely underwater by 2050 the earliest [11].

Aside from the humanistic need to save the lives of those island citizens, a unique culture heritage will be lost as the islands disappear underwater. While there may be a stated need to save their cultures in the debates of climate change, they are often overshadowed by the scientific, economic and political aspects of climate issues. However, to relocate those people without considering the preservation of culture is to declare the islands and their culture expendable in the pursuit of a global environmental purpose. Instead, in considering the threat of sea level rise, neither the island citizens nor their culture should be considered dispensable. Sea level rise in the four island nations, therefore, is as much an issue of preserving cultural heritage and diversity, as it is about environmental issues.

3 Approach

With all the faces of the issue in mind, our approach is to create pairings of refugee nations and absorbing nations such that we maximize culture heritage preservation for the refugee populations, as well as the viability of the absorbing nations. To explain the motivation behind this, consider, for instance, these factors when relocating a group of refugees:

- Will the refugees be able to assimilate to the new country? Will the absorbing country accommodate the refugees by being welcoming and embracing the cultural differences they bring?
- Does the absorbing nation have enough economic and geographic-specific resources to support these refugees?

- Will the geographic changes allow for cultural preservation by the refugees? For example, is it possible for the refugees to keep certain agricultural practices or access crops that are essential to their traditions?

It would solve some of the problems if we, for example, relocate refugees of the Maldives to India since climate and agriculture would be similar, but given an already high population density in India, coupled with a record high unemployment rate, India would unlikely be able to support this additional surge of migrants. As we can see, there would be no single solution which perfectly solves all the problems, but there could exist one which solves some set of the problems in a balanced way. This is the idea behind our approach.

To be more concrete, we identify three key factors contributing to some of the problems discussed above: 1) the compatibility between the refugee countries (denoted R_i hereon) and the absorbing countries (denoted A_j), 2) the acceptance of the absorbing country, and 3) the viability of the absorbing nations to support these refugees. To quantify these factors, we introduce the data-driven functions $Compatibility(R_i, A_j)$, $Acceptance(A_j; t)$, and $Viability(R_j)$. *Compatibility* and *Acceptance* combine to make the *Cultural Heritage Preservation Index (CHPI)*. Then, the pairing score evaluation for R_i and A_j is given as:

$$E(R_i, A_j; t) = \alpha \cdot CHPI(R_i, A_j; t) + (1 - \alpha) \cdot Viability(A_j).$$

We would then recommend that the UN relocate refugees from countries R_i to countries A_j whose pairing score between them are the highest. The functions that contribute to the model are discussed and explained in greater mathematical details in Sec. 4, but note that α can be tuned to how much we are optimizing for cultural preservation or the viability of the absorbing nation. If $\alpha = 1$, then we only care about preserving cultural heritage, et cetera. The problem of recommending pairs of countries can essentially be thought of as a matching or an assignment problem, to be discussed further in Sec. 4.4. Note also that this score can change over time, which we have made explicit by including the time parameter t in the function(s). When unambiguous, we drop the explicit notation though time-dependence is always implicitly implied.

In arriving at this approach, certain assumptions needed to be made:

3.1 Assumptions

1) Climate change, sea-level rise in particular, is irreversible in the following 100 years, and will inevitably lead to migration from island countries.

2) We assume sea-level rise as the main drive for migration in Tuvalu, the Marshall Islands, the Maldives and Kiribati.

3) It is preferable that the EDPs from the island countries move to countries that are less vulnerable to climate change as to not exacerbate the situation further.

4) The population in the island countries would not change significantly in the future compared to the size of migration.

5) The more the EDPs stay together in the countries to which they migrate, the better it is for their cultural preservation.

6) A country is only able to take on more refugees if its own people are doing well enough.

7) Compared to the urgency of migration driven by sea-level rise and the importance of preserving the cultural heritage, the distance between the island countries and the absorbing countries for migration is of less importance, thus is not incorporated into our model. Instead, we compare the latitude between those countries, which reflects not only the matter of distance, but also their geographically specific cultures.

4 Model

We began our model by using all Developed Countries (as defined by being a member of Organisation for Economic Co-operation and Development. This contains around 35 countries), since we have made an assumption that countries would be able to take refugees if they are already doing sufficiently well. As will be clear in the coming sections, our models are largely data-driven and so we limit ourselves to a subset of develop countries for which we can consistently collect data.

More specifically, our set of absorbing nations consist of the following countries: Australia, Germany, Japan, Netherlands, New Zealand, Poland, Russia, Singapore, Spain, Sweden, Ukraine, and United States.

We make a case for the UN to invest in more data and analysis in Sec. 6.

4.1 Modeling Cultural Heritage

We reckon that to best preserve cultural heritage, we need both the refugee country and the absorbing country to be compatible in various ways e.g. geographically and culturally ($Compatibility(R_i, A_j)$), and that the absorbing country is accepting of immigrants and what they may bring ($Acceptance(A_j; t)$). To this end, we create the *Cultural Heritage Preservation Index (CHPI)* to measure this aggregate quantity:

$$CHPI(R_i, A_j; t) = Average(Compatibility(R_i, A_j), Acceptance(A_j; t)). \tag{1}$$

Note that because attitudes towards immigrants can change and nationalism can rise over time (which is a concern in this problem), acceptance is a function of time, and we write this explicitly in the equation above.

To model compatibility between two countries, we look at the following variables:

1. **Geographic location (latitude)**: Many agricultural practices and ways of living are influenced by the type of climate in a given country, which in turn can be encoded by the latitude values. It is reasonable to expect that countries close together in (absolute) latitude can be similar in some ways.

2. **Religion composition**: If we limit the scope of the problem to the four islands listed in Sec. 2.1, then we find that each of these countries is composed almost exclusively of either

Christians or Muslims. We would expect that if a country has a large population of Christians or Muslims, then it could be more compatible with these islanders.

3. **Staple crops in common**: One way to quantify the culture of a nation is to look at the composition of products commonly used in it [7]. For example, nations that consume primarily potatoes could be rather different, culturally, than nations that mostly consume rice. Calculating commonalities in staple crops could give us another indicator of how compatible two nations might be.

Data is collected correspondingly (see Sec. 4.1.1) to calculate the compatibility. More formally,

$$Compatibility(R_i, A_j) = Average\left(Lat(i,j), Rel(i,j), Crops(i,j)\right), \tag{2}$$

with

$$Lat(i,j) : [-90, 90] \times [-90, 90] \mapsto [0,1] = \frac{|Latitude(R_i) - Latitude(A_j)|}{180};$$

$$Crops(i,j) = \frac{c_{R_i}^{\top} c_{A_j}}{173} \in [0,1]$$

where c_{R_i} is a length-173 indicator vector such that $(c_{R_i})_i = 1$ if R_i produces the crop i and 0 otherwise. Essentially, this is a dot product between two indicator vectors, and the value is higher if two nations have more staple crops in common. The values are scaled by 173 to make the range lie within [0,1] (the reason for using the factor 173 is made clearer in Sec. 4.1.1). $Rel(i,j)$ gives the proportion of people in A_j of religion that is the majority in country R_j. (For example, if Christians are the majority in R_j then $Rel(i,j)$ gives the proportion of Christians in A_j.)

To model the *Acceptance* of a country, we again employ data-driven methods. The World Values Survey (WVS) released questionnaires concerning attitudes of people towards certain issues such as whether they prefer not to have immigrants as their neighbors, or if jobs should be given to nation people rather than foreigners when they are scarce [2]. We use this time-series data (averaged between three different questions) to make a forecast for the acceptance value over time.

Both the *Compatibity* and *Acceptance* functions give a value between 0 and 1.

4.1.1 Data Collection and Analysis

The latitudes and religion compositions of different countries are widely available and easily obtained, thus we focus our attention to the staple crops data. We first collect crops statistics among different countries from the Food and Agriculture Organization of the United Nations (FAO). The FAO records data for 173 products such as potatoes, blueberries, and nuts. Then for each of the country that we analyze, we apply a geographic filter and convert this tabular dataset into an indicator vector with the i^{th} entry equal to 1 if the production of the i^{th} crop exceeds 100 tonnes per year in that country and 0 otherwise. The dot product as defined in $Crops(i,j)$ is then performed. (Note that an equivalent but more numerically efficient method is to perform inner table joins.)

For the acceptance servey data, we collect time-series responses to the following questions:

1. "On this list are various groups of people. Could you please mention any that you would not like as neighbors?" (Immigrants/foreign workers).

2. "On this list are various groups of people. Could you please mention any that you would not like as neighbors?" (People of a different race).

3. "When jobs are scarce, employers should give priority to people of this country over immigrants." (Agree/Neither/Disagree).

For Items 1 and 2, we collect the time-series percentage of people who did not mention. For Item 3, we collect the time-series percentage of people who disagree. Based on this time-series, we impute missing data using the backfill method and perform linear regression analyses to make a forecast of the acceptance indicator at a given time t. The acceptance value for a given country at a given time is the average between the predicted responses at that time.

4.2 Modeling Viability

Modeling *viability* is a shorthand way of describing the part of our model that involves a host country's ability (or inability) to take in these EDPs. Thus our function of viability is only related to the host country, as the specifics of who the EDPs are shouldn't be necessary. It is imperative to note that while our viability function is predicting the most viable countries to host our EDPs, it implies nothing about their willingness to host. Thus, when we talk about a country's viability, we are talking about its *potential* ability to host EDPs with no guarantee of fulfillment of that potential. That fulfillment is partially determined in the Modeling Cultural Heritage section, as well as something that we would recommend the UN to ensure (to be discussed in Sec. 6).

We model our viability with the following variables: GDP Per Capita, Population Density, Population Size, Employment Rate, Vulnerability to Climate Change.

We justify each component as follows.

1. **GDP Per Capita:** We figure that having a larger GDP Per Capita means a (generally) higher quality of living. As a result, a country with a higher GDP would have more resources and wealth with which to help the EDP's. We are not necessarily saying that any wealthy country would be *willing* to help EDP's. Rather, we are saying that a country with a higher GDP would have more opportunities in which they could help. Thus we want our GDP to be directly proportional to our Viability function value.

2. **Population Density and Population:** While these are technically two separate variables, they must be discussed within the same text as they are quite interconnected. In order to have the opportunity to take on refugees, a country must have room both in land and population. A higher population density clearly would not be the optimal country to be placed, as that would only increase the population density even more, thus we want population density to be inversely proportional to our Viability function value.

   Furthermore, our population can be seen as an overall buffering factor for the population density. A country with low population and population density means that it would take fewer immigrants to raise that population density. Thus we see that the factor of "room" is nothing but being inversely proportional to the population density and directly proportional to population itself.

3. **Employment Rate:** The employment rate of a given country relates to the quality of life in that country and more generally is indicative of the opportunities present for EDPs in that country. A more employed population implies that the migrant population would have more opportunities to be employed as well, thus a healthier symbiosis between groups. Thus employment rate is directly proportional to our Viability function.

4. **Vulnerability to Climate Change:** In order to fully model the viability of a given country to harbor refugees from an island destroyed by climate change, we must also consider its own degradation in regards to climate change. Clearly if both the island and hosting country's land is lost to climate change, this would not be a viable country for their residents to reside, let alone their residents and more EDP's. Thus we consider this as inversely proportional to our Viability function.

Now that our model's variables have been justified, we may look at the actual mathematics behind it. The Vulnerability to Climate Change variable is on a [0,1]-scale, and we leave it as is. For the other variables, however, we normalize our data using the min-max normalization (see Sec. 4.2.1) so as to limit the range of values to [0,1]. Our data fortunately does not contain any major outliers, thus we find it reasonable to use min-max as that is typically the biggest concern for this type of normalization. Our viability function is then as follows:

$$Viability : Country \mapsto [0, 1]$$

For a given country A_j we denote the GDP variable as g, population density as d, population as p, employment rate as e, and vulnerability to climate change as v. We construct our Viability equation:

$$Viability(x) = \alpha \cdot g + \beta \cdot p \cdot (1 - d) + \gamma \cdot e - \delta \cdot v \tag{3}$$

where α, β, γ and δ are coefficients that sum to 1.

In testing, we used varying coefficients to ascertain the importance of certain variables—this is explained more thoroughly in our Results and Analysis Section.

4.2.1 Data Collection and Analysis

Our data for the first four variables in our Viability model is collected from the data section of The World Bank. While these data are changing with respect to time, we felt as if the World Bank's data were enough to paint a general picture as to each country's respective variables, without concerning ourselves too much with their dependence on time (as we already have the *Acceptance* function based upon time). As stated earlier, we used min-max to normalize each of these values as none of the variables had particular outliers. This function is defined as follows:

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}}.$$

In order to ensure our normalization was reasonable, we actually computed "Robust Scaler" using the first and third quartile rather than min-max i.e.

$$x' = \frac{x - Q_1}{Q_3 - Q_1}.$$

We found the the numbers were nearly identical which helped us determine that minmax was safe to use as there weren't any outliers.

The data on our last variable, Vulnerability to Climate Change, is collected from ND-Gain (Notre Dame's Global Adaptation Initiative) [5]. The values for this variable was already scaled from 0 to 1 so our normalization was up to at most a coefficient factor.

4.3 The Overall Evaluation Model

The overall evaluation of a given island-country pairing is relatively simple once our sub-functions are defined. We define our overall evaluation of inhabitants R_i at country A_j at time t as follows:

$$E(R_i, A_j; t) = \alpha \cdot CHPI(R_i, A_j; t) + (1 - \alpha) \cdot Viability(A_j) \tag{4}$$

where $\alpha \in [0, 1]$ is the emphasis we place on preservation of cultural heritage. The advantage of breaking up our evaluation into different components is that it allows us greater control of what we are trying to model, but also now we can see how our evaluation might change based on how much we value cultural preservation. On one extreme, if $\alpha = 0$ then this is equivalent to only focusing on culture preservation (and forcing countries to take in refugees regardless of its viability). On the other extreme ($\alpha = 1$), the model gives a relocation recommendation that optimizes only for the viability of the host country. Later in our sensitivity analysis we will discuss different possible values of α and their impact on our model, but for now it is appropriate to think of $\alpha = 1/2$ for ease of discussion.

Fixing the refugee island R_j, the model $E(R_i, A_j; t)$ essentially gives us at any time t the ranking between the hosting countries on which one might be the best match given how much we want to focus on preserving country and on the viability of the migration. We would then propose to relocate the majority of the refugees from R_i to the k top ranked countries (allowing for some room for individual choice, of course).

4.3.1 Interpretation of the Score Model

As an example, consider the scenario in which the refugees from the Marshall Islands settle in France. If the data indicates that France has an open-minded attitude about immigrants and people of different race, the value for *Acceptance* would be high. But if it turns out to be unlikely that certain agricultural practices will be feasible in France, then *Compatibility* could take on an intermediate value within [0,1]. Given its large economy and physical land, $Viability$ score is likely to be high. These factors combine to give a pairing score between the Marshall Islands and France.

Once can see from Figure 1 that each country's overall rating is characterized by a line in $\mathbb{R}^2$ and thus the country ranking for each island stays relatively stable with respect to time (as each line can cross at most one time). However, it became imperative for us to look into the *when* of our original question with further analysis (see Sec. 4.5).

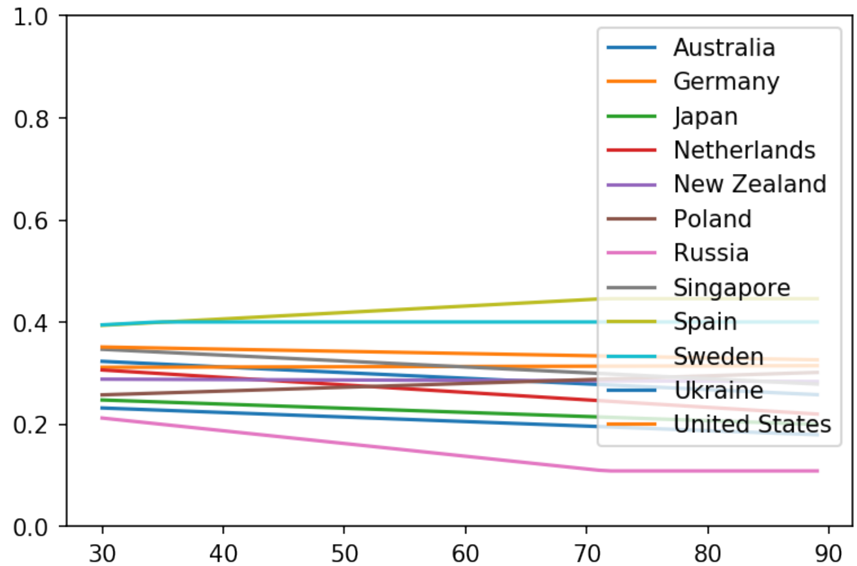


Figure 1: A view of Maldives country relations from 2020-2080

4.4 Matching Islands and Countries Using Evaluation Scores

In a naïve way, one could simply assign refugees from an island to a country whose evaluation score between the pair is the highest. (For example, we could recommend that the UN relocate all refugees from Kiribati to Spain). However, an issue arises when the islands have the same top k pairings with absorbing countries (see Fig. 3). In this case, the most optimal solution is to send all the refugees to one country that has the highest pairing score evaluation. For example, according to our evaluation in Fig. 3, instead of sending only refugees from Kiribati to Spain, we would be sending the refugees from all the other islands to Spain. But this is not feasible if we consider a case in which we extend this model to include not just these four islands but also possibly a billion EDPs. The question becomes, which refugees should go to which countries—given that we want the evaluation score to be highest—while taking into account feasibility? (By feasibility, we mean that it is not realistic that a country would absorb hundreds of thousands of refugees in one year).

Looking at it this way, we are essentially solving a matching or an assignment problem, where we are trying to find the perfect pairing (in the sense that everybody gets a good match, and not necessarily in the graph-theoretic sense of a perfect matching) by maximizing the evaluation score between the island-country pairs, thereby maximizing cultural heritage preservation and viability.

To formulate this as a matching problem, consider a complete bipartite graph $\mathcal{B}$ where one side consists of the refugee nations $\mathcal{R}$, and the other absorbing nations $\mathcal{A}$. Since $\mathcal{B}$ is complete, the edge set is $\mathcal{E} = R \times A$. Denote w_{ij} as the weight of the edge $(i, j) \in \mathcal{E}$ between $i \in \mathcal{R}$ and $j \in \mathcal{A}$. This weight is given by the evaluation score between a given refugee nation and an absorbing country. Define the matching $\mathcal{M}$ to be a set of $(i, j) \in \mathcal{E}$ where no vertices occur twice in the matching, and let x_{ij} be such that $x_{ij} = 1$ if $(i, j) \in \mathcal{M}$ and 0 otherwise. (See Fig. 2 for an illustration of this bipartite graph and matching construction.)

We then solve

$$
\begin{aligned}
\text{maximize} \quad & \sum_{(i,j)\in\mathcal{E}} w_{ij}x_{ij} \\
\text{subject to} \quad & \sum_{j\in\mathcal{A}} x_{ij} = 1 \quad \forall\, i \in \mathcal{R}, \\
& \sum_{i\in\mathcal{R}} x_{ij} = 1 \quad \forall\, j \in \mathcal{A} \\
& 0 \le x \le 1 \quad \forall\, (i,j) \in \mathcal{E} \\
& x_{ij} \in \mathbb{Z} \qquad \forall\, (i,j) \in \mathcal{E}.
\end{aligned}
$$

The first two constraints are so that each vertex is adjacent to only one edge incident. With this formulation, we have an integer linear programming problem, and minimizing the negative of the objective is the minimum-weight matching problem in bipartite graphs, also known as the linear sum assignment problem. There exist methods that can solve this bipartite matching problem in polynomial time, such as the Kuhn-Munkres algorithm, which we will employ.

Note that because the evaluation scores (the weights of the edges in this case) are a function of time, our matchings can also change over the years.

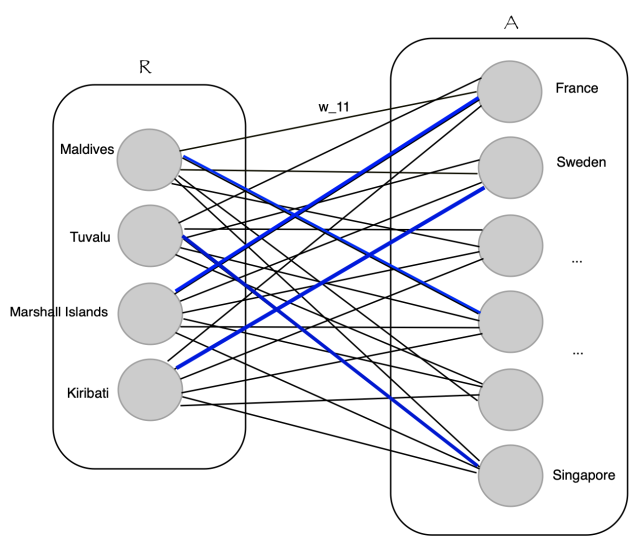


Figure 2: An illustration of the construction of our complete bipartite graph with an example matching between refugee nations and absorbing countries (in blue).

4.5 Creating a timeline for the migration model

Now that we have *where* our EDPs should go at a given time t, it is logical to next look at *when* it is optimal for these EDP's to uproot. Obviously no time is perfect, however we claim that the number of emigrants leaving a given island at a given time t is best modeled as follows:

$$f(t) = \frac{P_0}{\sqrt{t}} \quad s.t. \quad \sum_{1}^{n} f(t) = P \tag{5}$$

for a constant P_0 as the number of emmigrants in the first year, P as the total population of the given island, and n as the number of years until everyone must be evacuated.

Obviously our restriction of $\sum_1^n f(t) = P$ comes from the fact that everyone must be evacuated in n years. P_0 can be found through computation to be the first year's worth of emigrants, though no other year will have as high of a number as the first. Lastly, we leave n unspecified for now as it allows for more versatility in modeling EDPs outside the scope of our islands.

To arrive at (5), we first considered the idea that logistically, immigration would be easiest if every year we send the same number of emmigrants i.e. $f(t) = \frac{P}{n}$. While this made our model most agreeable with the hosting countries, it did not allow for much nuance, and frankly was underwhelming.

We then moved to the idea of an inversely proportional relationship of t and $f(t)$, as we think it would be better to frontload our migration of EDPs. Though sea-levels rising is relatively predictable, we know that climate change as a whole is not, and thus went with the age-old adage of "rather safe than sorry", we chose the inversely proportional time dependence. After attempting a $\dfrac{1}{t}$ relationship with $f(t)$, we realized that our model would not allow for such frontloading as our P_0 was too high. At time $t = 0$, Maldives would have to emigrate over 100,000 people in one year. While this model was more intricate than our constant model, it left much to be desired in terms of realism.

Balancing the idea of practicality and exponential sea level growth, we decided to model our function using a factor of $\frac{1}{\sqrt{t}}$. This allowed for the sense of "urgency" that our $f(t) = \frac{P}{n}$ model could not account for and a sense of logistical ease that our $f(t) = \frac{1}{t}$ was lacking.

5 Results and Analysis

5.1 Results

Our Evaluation Model gave us results regarding the overall "score" any country-island pair has. We now look to see how this score can be transformed into more useful data.

As one can see from Fig. 3, our general model results do not vary too much between islands but do vary a considerable amount from country to country. We expect that this is due to the island nations having generally most attributes in common, but our countries vary in everything from religion to latitude. The fact that our island of choice doesn't wildly affect the model will become of much importance to us later when discussing recommendations for the UN (see Sec. 6). The top four countries are generally Spain, Sweden, United States and Australia, with the only exception of The Maldives switching Sweden and Spain's positions and having Singapore as its fourth choice as opposed to Australia. Some of this can partially be explained by the fact that these countries generally have good economy and some resources (high viability), but also they tend to be more open-minded to other cultures (high acceptance).

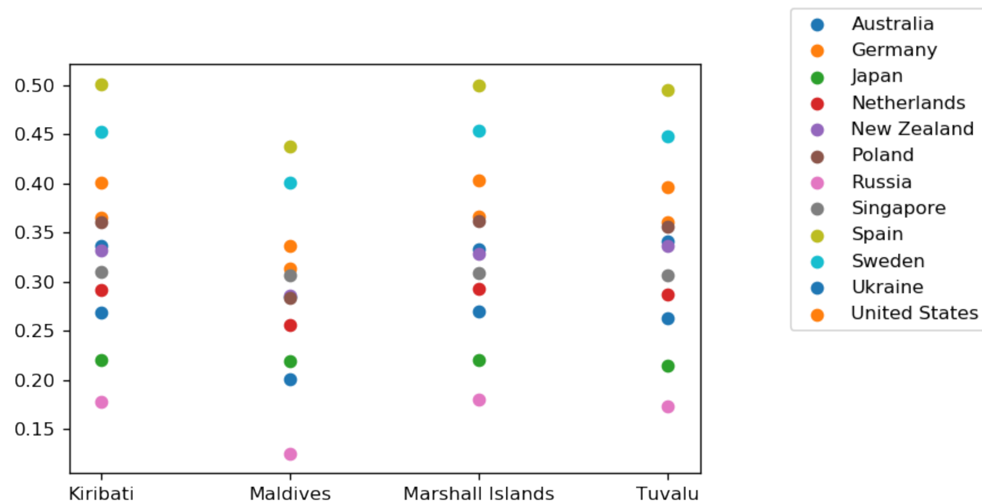
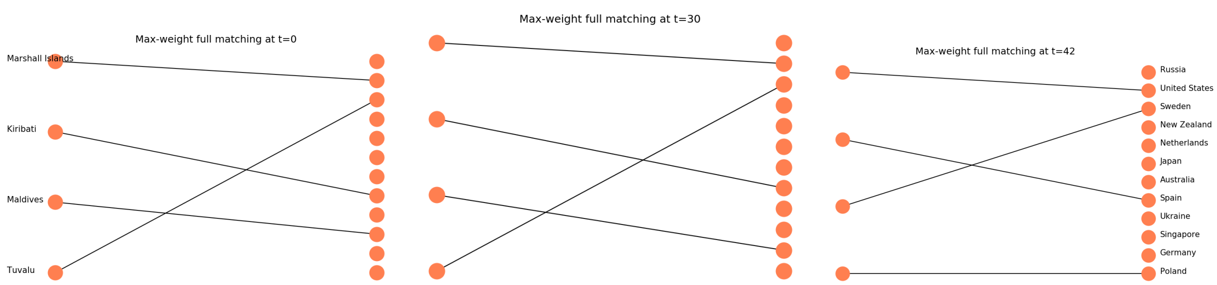


Figure 3: Island-country evaluation at a time slice $t = 30$.

The results that the matching algorithm gives us are illustrated in Fig. 4. In particular, for some number of years, we should relocate some number of refugees from the Marshall Islands to United States, the Maldives to Singapore, Kiribati to Spain, and Tuvalu to Sweden as to maximize cultural heritage preservation and viability. This optimal matching changes over time, as can be seen in Fig. 4.



(a) $t = 0$ (b) $t = 30$ (c) $t = 42$

Figure 4: Max-weight full matching at different time slices. The four vertices on the left are the islands, and the vertices on the left are the absorbing countries

5.2 Sensitivity Analysis

In terms of sensitivity analysis, there were a lot of simplifying assumptions made, so making sure to test many different coefficients was important to the credibility of our model.

We began by checking the sensitivity of our model with regards to the weights on the Evaluation function i.e. the α in

$$E(R_i, A_j; t) = \alpha \cdot CHPI(R_i, A_j; t) + (1 - \alpha) \cdot Viability(A_j)$$

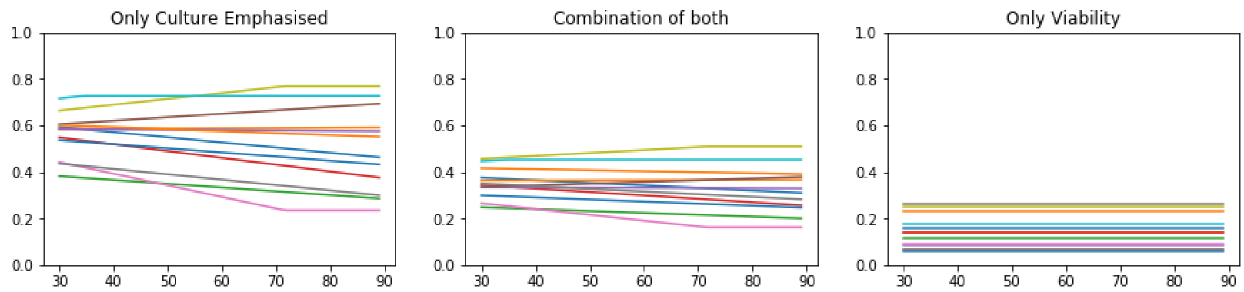


Figure 5: A view of Tuvalu's sensitivity to culture preservation and viability factors

As seen in Fig. 5, this brings considerable change about our model. We decided to look at the two extremes of the spectrum when it comes to Cultural Heritage Preservation and Viability of a host country. If we only focus on the Cultural Heritage Preservation, we note that the overall ranking of each country is generally the same as our model's, but the overall Evaluation score is higher. On the other hand, if we look only at the most Viable countries, we note that the ranking is considerably different than our model's, but the Evaluation scores are lower in value.

While normally this drastic difference in the Evaluation function would be alarming, we note that we are not very concerned because our model is best used to generate the *relative rankings* of these countries, not their specific scores. Thus our sensitivity analysis was neutral in regards to differences in Cultural vs. Viable interests. While it may have made an impact to put a higher weighting on the Viability function, most linear combinations of the two functions leave the same top four ideal countries in tact so we consider our model to be reasonably successful in this aspect.

We now turn our sensitivity analysis to the Viability function and the four coefficients inside of it. Unlike the overall Evaluation function, which was left in terms of α to allow for a more customizable answer based upon the user's personal interest in Cultural Heritage and Viability, our Viability function assumed to have equally weighted coefficients. The assumption is that the UN may want to have a say in the quality of Cultural Preservation they're looking to maintain, but would care less about the exact amount by which the GDP variable would increase the viability. As such, we are not concerned with the coefficients in front of our Viability factors, as it would be nearly impossible to ascertain what values which variables should be given. Saying that GDP is twice as important than employment rate seems rather arbitrary. Thus we consider all variables just as important to the overall Viability.

6 Recommendation to UN

After presenting our model and analyses, we now proceed to advise the UN on how they should be involved in order to mitigate the issue.

First, because our model and analyses are heavily driven by data, what we have discovered is that data can be a very powerful tool for planning for and mitigating the effects of climate change on environmental displacement. Yet another thing that we have realized is that the model would be improved with better and more consistent data. Some of the data points used in the time-series analysis and linear regression in Sec. 4.1 were missing for some countries, a challenge which we overcame using interpolation methods. As our model can serve as a solution framework as the situation worsens over time, we recommend that the UN invest in more data and analysis, as to best prepare for analyzing a large number of EDPs to be taken care of in the near future.

We recommend a 60 year plan for the UN in order to fully evacuate these island nations with minimal damage done to both the islands cultural heritage and the hosting countries. This means that between 2020 and 2080, the UN will step in to facilitate and oversee the relocation of refugees from the concerned islands to the countries we have mentioned thus far in this report. Doing so will likely lead to an optimal balance between cultural heritage preservation, viability, and feasibility.

To be more specific, according to the model described in Sec 4.5, we would be relocating about 850 refugees from Tuvalu, 32,000 refugees from the Maldives, 3,800 refugees from the Marshall Islands, and 8,250 refugees from Kiribati in the first year. These numbers, specific to each island, will be denoted P_0. The number of migrants would change with a scaling factor of $\frac{1}{\sqrt{t}}$ each year, and most of the populations from these islands would be evacuated within 30 years from now and completely evacuated by 2080.

Starting with t = 0 for 2020, each year of this period would have approximately $\dfrac{P_0}{\sqrt{t}}$ people from each country emigrate to their respective new homes.

As described in Section 4.4, we consider the first epoch from 2020 to 2050 as the brunt of the relocation. For this time, we have that Tuvalu would go to Sweden, Maldives to Singapore, Kiribati to Spain, and Marshall Islands to United States. The second epoch (years 2051 to 2061) would have the islands emigrate as follows: Tuvalu to Sweden, Maldives to Germany, Kiribati to Spain, and Marshall Islands to United States. Lastly, our third epoch (2061 to 2080) would have the islands emigrate as follows: Tuvalu to Poland, Maldives to Sweden, Kiribati to Spain, and Marshall Islands to United States.

The primary role of the UN would be to ensure that the absorbing nations, selected by the matching algorithm, indeed have adequate policies in place to take these refugees. For example, these nations should provide the refugees with some kind of special visas, as well as basic civil rights to buy properties, work, and vote.

7 Conclusion

In this conclusion, we give a brief analysis of the strengths and weaknesses for our model, as well as provide possible directions for future works. We then end with a summary of this report.

7.1 Strengths and Weaknesses

7.1.1 Strengths

1) We provide a quantitative model on preserving cultural heritage in response to EDP migration, enriching the research on climate change that usually emphasizes the scientific, economic and political aspects.

2) In modeling the compatibility between origin and absorbing countries, our definition of $Acceptance(A_j;t)$ as a function of time meets the reality that the absorbing countries' attitudes and policies toward refugees might change.

3) In deciding which countries are the best place to migrate, we consider a balance between compatibility, acceptance and viability, analyzing the refugee and absorbing countries separately then considering their interactions, which is a rather comprehensive approach.

7.1.2 Weaknesses

1) Countries such as Lagos, Yemen and Manila are also suffering from the effects of climate change, including severe drought, floods and hurricanes. However, we have not taken into account the climate refugees from these countries.

2) It is difficult to quantify the intangible aspects of culture, thus certain parts of cultural heritage might be missing from our model.

3) In our model, we have not considered other factors that might play into the relationship between climate change and migration, such as family and social networks, age distribution of the population, political instability and conflict in the refugee countries.

4) Our model cannot deal with the possible population overflow caused by the refugees in the absorbing countries.

7.2 Future Works and Improvements

As the timing for this contest is short, there is reasonably a lot of room for future works and improvements. As a courtesy to all, we will limit ourselves to a few of the more important ones.

The most important future work would be that of allowing a wider range of countries in terms of displacement. Climate change displacement is an incredibly complex topic, and it would be nearly impossible to create a singular model (or a singular MCM paper) regarding all possible manners of displacement. Moreover, any model that did would lose the nuances that make a more specific model work well. With that in mind, however, we would be very interested in creating models for different types of EDPs and possibly looking at ways in which they were similar.

Another important feature we would be interested in expanding upon in future works is the number of hosting countries. As it stands, we had twelve possible countries to be hosting refugees. While these counties were all on the more likely side of being countries to take these EDPs, this is obviously not representative of the entire world. This would be greatly impacted by more data available on countries.

Lastly are our improvements. What we would like to improve on most is our time-dependent modeling. Though having any time-dependency in a model allows it to be considerably more robust, it would be more preferable to do more in relation to the rate at which the island populations must emigrate. Creating an optimization problem regarding the urgency of migration versus the logistics of migration would be an interesting question to look into.

7.3 Conclusion

To conclude, we limit the scope of the issue to certain island nations that are at greatest risk of disappearing due to sea levels rising and to developed countries who could absorb some of these refugees. We then break down this issue of environmental displacement by considering what factors contribute to cultural heritage preservation (compatibility and acceptance), as well as those that contribute to viability of a country to accept refugees. The optimal plan to relocate these refugees would consider and optimize for both of these aspects. Given these factors and using data-driven methods, we create mathematical models to rank which countries would be the best match for which refugee populations. By breaking the problem down into different components, we have greater flexibility in modeling choices and greater control over different parameters. Then, borrowing methods from graph-theoretic matching, we solve an assignment problem and match different island nations with absorbing countries so as to maximize the overall evaluation scores. We recommend that the UN step in to facilitate the relocation of these refugees according to the forecasts made by our models, and that it invest more resources into data and analysis. We provide directions for future works and areas to improve in Sec. 7.2. While simplifying assumptions were made and the scope of the problem was limited, our model could serve as a solution framework as the situation worsens and more refugees need to be relocated.

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