2016 Mathematical Contest in Modeling (MCM)
Team Control Number: 52852
Problem Chosen: F

As crises in the Middle East escalates, the influx of fleeing refugees to overburdened, resource-shorted European countries have produced a similar crisis. To help alleviate the situation, we build a computational model to simulate refugee flow among six migratory routes (Western Mediterranean, Central Mediterranean, Eastern Mediterranean, West Balkans, Eastern Borders, and Albania to Greece) into the 15 most affected countries. We then optimize these flow rates by iterating our model. We also investigate crisis dynamics by introducing various other factors into the model, including resource allocation, the effect of exogenous events, and scalability of our model to larger scenarios. Our results are summarized in policy recommendations for the UN to address the crisis.

To optimize the flow of refugee movement among our network of 6 entry routes and 15 countries, we apply two optimization methods: Dijkstra's Algorithm and a custom Genetic Algorithm. By combining the two results, we find that asylum-seekers should not take the two routes through the West Balkans and Albania to Greece; they should instead distribute themselves roughly evenly among the other four. This was suggested by our model as the most efficient and safest for all people.

We then use this distribution of flow rates to determine the areas of Europe in greatest need of resources to support and protect asylum-seekers. We suggest allocating governmental resources to the entry points of Spain, Italy, Greece, and Hungary; we also suggest allocating additional non-governmental organization resources to the most popular paths across country borders. These include Northern Africa, the sea passage between Libya and Malta/Italy, and Ukraine.

To determine the effect of exogenous events, we test two different types of shocks (concentrated and diffused) in two different locations (France and Germany). We determined that in the case of a shock in France, refugees should shift from western and central routes to eastern routes. In the case of Germany, the refugees are shifted in reverse. The scale of this redirection is dependent on the scale of the shock's impact on the region.

The scope of our solution can also be maintained without significantly detracting from refugee welfare, aside from increased relocation, through exogenous events and on a larger scale. When the volume of refugees emigrating from the Middle East was increased from the project number by a factor of 10, the solution was maintained without significant backlog of asylum application processing. If the volume of resources can be scaled accordingly, our solution system for refugee distribution across the six routes can be maintained despite parameter changes.

Computational Modeling and Dijkstra's Algorithm/Genetic Algorithm Optimization of the European Refugee Crisis Resolution

MCM/ICM Problem F

Team 52852

February 2016

Dear UN Commission,

In light of recent events in the Middle East, skyrocketing populations of refugees are fleeing to safe-haven countries in Europe in search of peace and stability. We understand the resource burden this places on European countries, and we are aware of the controversy over how to best relocate and resettle this ever-growing group of people in need. Thus, we have developed a set of mathematical models to simulate the European Refugee Crisis. Our hope is that this provides more understanding on how the crisis functions and how it may be alleviated.

Our first policy recommendation is a quota system in which every country is required to accept a certain number of refugees. This will dramatically reduce the pressure from small, overburdened coastal countries such as Greece and will allow refugees to integrate into their new homes more evenly throughout Europe. In our model, we use a system based on that suggested by the European Commission for relocation [9]. Due to feasibility and time constraints, we only consider the top 15 countries, but we recommend extending this system to all European countries in practice.

Given these quotas, we then provide a plan for optimally distributing asylum-seekers so that they reach their destinations with minimal resource needs. Our suggestions are sending:

- 28% of all people each along the Central Mediterranean and Eastern Mediterranean routes, as we find these to be the most efficient and/or safe according to our optimization algorithms;
- 26% of people along the Eastern Borders route, as this was next most efficient and/or safe;
- 18% of people along the Western Mediterranean route;
- and no one through either the Western Balkans or Albania to Greece route. These do not offer the most desirable implementation of resources (cost, time) to get refugees to the same destination; instead, they encourage unnecessary travel through unsafe non-European countries.

In terms of resources, we have identified areas that process the most number of asylum applications and thus require the most supplies. Our model also reports areas where large numbers of refugees die due to starvation and poor health. Governments should send resources to the main entry points in Spain, Italy, Greece, and Hungary. NGOs should send resources in the form of food and shelter along Northern Africa (Morroco, Algeria, Libya), initiate search and rescue missions along the dangerous sea passage from Libya and Malta, and across the Ukraine in the form of food and shelter.

In the case of exogenous events, we provide adjusted refugee flow rates to maximize safety and health. If a shock were to happen in France, we recommend transferring people from the Western and Central Mediterranean routes to more eastern paths, as in this case it is safer to access Europe from the east. In contrast, were a shock to happen in Germany, it would be safer for refugees to shift from eastern routes to more western routes.

We hope that our suggested policies and preventive measures, backed by our model, offer valuable insights that may alleviate the tragic European Refugee Crisis.

ICM-RUN
Team 52852

1 Introduction

1.1 Background

With recent and ongoing events in the Middle East, we have seen, in the past year, a massive flood of refugees fleeing the Middle East in search of political stability, shelter, safety, and peace. Most emigrants travel through the Mediterranean before crossing into countries in Europe and Asia including Italy, Greece, Germany, and Hungary. More than a million migrants and refugees entered Europe in 2015, and already over 50,000 have arrived since the new year [1].

The European Refugee Crisis poses great challenges to the EU and necessitates careful implementation of effective refugee policies and guidelines. Safe-haven countries struggle to provide adequate resources while disputing how to best relocate and resettle their ever-growing influxes of people. Refugees will take many routes depending on a host of factors, such as safety, accessibility, transportation availability, and resource capacity of destinations. All of these play out with legal, political, humanitarian, and economic consequences, positioning the crisis as a dilemma of global magnitude.

1.2 Problem Restatement and Analysis

In light of worsening situations in both Europe and the Middle East, we mathematically model the European Refugee Crisis to help the UN better understand how the crisis functions and how it may be alleviated. We aim to address the following tasks:

1. What factors enable and/or inhibit safe and efficient movement of refugees? We develop a set of measures and parameters to include in our analysis.
2. What are optimal distributions of refugee flow across the six major travel routes (West Mediterranean, Central Mediterranean, Eastern Mediterranean, West Balkans, Eastern Borders, and Albania to Greece)? Section 2.1 contains a map of these routes.
3. How do environmental factors and crisis dynamics change over time? Specifically:
   (a) How can resources be allocated most fairly?
   (b) What resources need priority?
   (c) How do the roles and resources of non-government agencies (NGOs) affect the crisis?
   (d) How does the inclusion of refugee destinations outside of Europe impact the crisis?
4. What types of immigration policies ensure such optimal refugee flow (Task 2), prioritizing the health and safety of all people?
5. How do exogenous events impact crisis dynamics? What types of immigration policies will be resilient to these events?
6. How do crisis dynamics change when the scope of the problem is increased? How do issues such as disease control, childbirth, and education come into play?

2 Preliminary Model Considerations

Before we begin, we first lay the foundation for our model and report all assumptions, definitions, and variables. We also gather and analyze refugee migration statistics to later parametrize our model.

2.1 Definitions

In our model:

- We define *refugees* to be individuals who have received positive asylum decisions, including refugee status, subsidiary protection, Geneva Convention status, and humanitarian reasons. We define *asylum-seekers* to be all other individuals en route or awaiting their decisions.

2.2 Assumptions

In our model, we assume that:

- *All asylum-seekers from the Middle East take one of the six paths and end up in one of the 15 countries described in 2.4.* This is due to the limited scope of our problem and lack of data on less traversed routes and less popular destinations.

- *Every country continuously accepts refugees until it reaches its quota*, i.e. countries will not reject asylum-seekers as long as their quotas are not reached. In practice, countries have no reason to make arbitrary asylum application decisions.

- *Asylum-seekers excludes those migrants who have family in an EU member state or who arrive with a visa or permanent residence permit already in hand.* These individuals constitute very small proportions of the total refugee population and place less burden on the ability of the EU to provide basic resources such as shelter.

- *Asylum-seekers travel at rates of 40 km/day over land and 200 km/day over water.* We base this on average walking and boat speeds, taking into account the fatigued states of asylum-seekers and the poor conditions of most smuggling boats [2, 3].

- *Asylum-seekers begin with full health and no hunger.* We set the health and hunger meters of all refugees to be 100, each, at the beginnings of their journeys. This allows us to most accurately measure the effects of the paths themselves, and subsequently the distribution of resources, on the health of the refugees.

2.3 Variables

In our model, we define the following variables, some of which were statistics which we explain in section 2.5:

- f_r = the fraction of asylum-seekers fleeing the Middle East along route r, where $r = 1, 2, \ldots$ 6 as numbered in section 2.4. Note that $\sum_{r=1}^{6} f_r = 1$ based on our first assumption.

- s_r = the survival rate along route r, where $r = 1, 2, \ldots$ 6 as numbered in section 2.4.

- Q_c = the refugee quota for country c, where $c = 1, 2, \ldots$ 15 as numbered in section 2.4.

- R_c = the number of refugees accepted by country c at any time, where $c = 1, 2, ... 15$. Note that $R_c \leq Q_c$ always.
- p_e = the preference value assigned to entry point e. We further explain this in section 3.1.
- w_e = the number of asylum-seekers awaiting decisions and currently residing at entry point e.

2.4 Geography of the Crisis

We consider six main migratory routes from the Middle East into EU member states [4] as illustrated in Fig. 1 and numbered below.

1. West Mediterranean (blue), which constitutes the sea passage from Northwestern Africa to Spain.
2. Central Mediterranean (red), which is defined as the route from Northern Africa (usually Libya) across the Mediterranean into Malta and then Italy.
3. Eastern Mediterranean (green), which refers to the passage from Turkey to Greece.
4. West Balkans (purple), which constitutes the route through the West Balkan states into Hungary, from either Asia or the West Balkans themselves.
5. Eastern Borders (orange), which describes the passage from Ukraine into mainly Hungary.
6. Albania to Greece (gray), which refers to the circular route across the Albania-Greece border.

Figure 1: Six major migratory routes into the EU. Adapted from [5].

After arriving, asylum-seekers and refugees then spread to the rest of Europe. Though all EU member states encounter asylum-seekers, we only consider those who received a significant number of applications (over 0.8% of all applications) in 2014 [6]. These countries are numbered and listed below in Table 1.

	Country	Applications	% of Total
1.	Germany	202645	30.6
2.	Sweden	81180	12.3
3.	Italy	64625	9.76
4.	France	62735	9.71
5.	Hungary	42775	6.46
6.	Austria	28035	4.23
7.	Netherlands	26210	3.70
8.	Switzerland	23555	3.56
9.	Belgium	22710	3.43
10.	Denmark	14680	2.22
11.	Norway	13205	1.72
12.	Bulgaria	11080	1.67
13.	Greece	9430	1.42
14.	Poland	8020	1.21
15.	Spain	5615	0.85

Table 1: Total asylum applications received by EU member states in 2014.

2.5 Metric and Factors to Consider (Task 1)

After thorough reading on mass migrations and the European Refugee Crisis in particular, we determine that factors that enable safe and efficient refugee flow include:

- *Short, safe, and legal travel routes*, which increase the likelihood of asylum-seekers successfully arriving in EU member countries.
- *Multiple entry points*, which allow for faster processing of applications and more even spread of resources.
- *Fair, streamlined, and efficient asylum granting procedures*, which accelerate refugee assimilation into Europe and prevent uneven use of resources.
- *Safe transportation methods (e.g. large, sturdy ships)*, which increase the likelihood of asylum-seekers surviving the passage to Europe.
- *Search-and-rescue operations undertaken by European governments*, such as Italy's former Operation Mare Nostrum, which save lives at sea and aid asylum-seekers in successfully crossing the passage into Europe.
- *High resource availability in destination countries*, which increases the capacity and ability of the EU to house, feed, and protect the general refugee population.

In contrast, factors that inhibit safe and efficient refugee flow include:

- *Long or hazardous travel routes*, which decrease the likelihood of asylum-seekers successfully arriving in EU member countries.
- *Single or limited entry points*, which cause backlogging, overcrowding, rapid depletion of resources, and high volumes of applications in one area - all of which hinder the progress of refugees.

- *Unsafe, inadequate, or overcrowded transportation methods*, which decrease the likelihood of asylum-seekers surviving the passage to Europe.
- *Low resource availability in destination countries*, which decreases the ability of the EU to house, feed, and protect the refugee population.
- *Blockades, in which countries refuse to accept immigrants*, which forces asylum-seekers to take further routes and seek other destinations.

2.6 Refugee Migration Statistics

To parametrize our model, we collect data, from multiple sources [2, 4-11], on the EU refugee population and asylum application process.

2.6.1 Survival Rates s_r

Each of the six migratory routes was assigned an s_r value that represented its inherent danger. This was defined according to Equation 1 below.

$$s_r = 1 - \frac{\text{number of missing/dead along route } r}{\text{total refugees taking route } r} \tag{1}$$

where numbers were taken from 2014 records by the Missing Migrants Project [7] and the EU external border force Frontex [4]. Survival rates are calculated in Table 2 below.

r	Route	Missing/dead	Total	s_r
1	Western Mediterranean	104	7842	0.987
2	Central Mediterranean	2919	170664	0.983
3	Eastern Mediterranean	789	50834	0.984
4	West Balkans	93	43357	0.998
5	Eastern Borders	16	1275	0.987
6	Albania to Greece	2	8841	0.999

Table 2: Survival rates s_r by route.

2.6.2 Refugee Quotas Q_c

In September 2015, the EU announced a quota system to relocate 120,000 refugees from overburdened member states (Greece, Italy, and Hungary) throughout the rest of Europe. These quotas were assigned through a distribution key proposed by the European Commission [8] [9]. This key is based on population size (all other things being equal, larger states should take in more refugees), GDP (wealthier states should take in more), asylum applications received in the last four years (negligent states should take in more), and unemployment (less unemployed states should take in more).

We propose a similar quota system, not for relocation, but for overall refugee acceptances per country. This is the first step in optimizing refugee movement and ensuring that no single country is overburdened, providing the groundwork for later determining the fairest distribution of resources.

We base our quota system on the European Commission's relocation scheme; our only modifications are adjusting the key among our fifteen countries, scaling up to account for the 3 million refugees predicted for 2016 [10], and manually calculating values for Switzerland and Norway, as they are not EU member states and thus were not included in the key. To do so, we took their population sizes, GDPs, asylum application numbers, and unemployment rates relative to all other countries [6, 11, 12, 13]. Our calculated quotas are shown in Table 3 below.

c	Country	Key	Adjusted Key	Q_c
1	Germany	15.43%	21.62%	648728
2	Sweden	2.46%	3.44%	103216
3	Italy	9.94%	13.94%	418121
4	France	11.87%	16.64%	499264
5	Hungary	1.53%	2.15%	64536
6	Austria	2.22%	3.11%	93336
7	Netherlands	3.66%	5.15%	153878
8	Switzerland	*2.60%	3.64%	109313
9	Belgium	2.45%	3.43%	103006
10	Denmark	1.73%	2.42%	72525
11	Norway	*2.21%	3.10%	92916
12	Bulgaria	1.08%	1.51%	45407
13	Greece	1.61%	2.26%	67900
14	Poland	4.81%	6.74%	202228
15	Spain	7.75%	10.85%	325625
	Total	71.36%	100%	3000000

Table 3: Refugee quotas Q_c by country.

where we calculated the last two columns as:

$$\text{Adjusted Key} = \frac{\text{Key}}{\text{Total} = 71.36\%}$$

and

$$Q_c = \frac{\text{Adjusted Key}}{100\%} \times 3000000$$

3 Model Description

We construct a visual model in NetLogo, an open-source agent programming environment [14].

3.1 NetLogo Methods

In our model, asylum-seekers move along predefined path on a map of the Mediterranean area. These paths include the six migratory routes as well as links between destination countries (which are traversed during relocation). Each moving NetLogo turtle (agent) represents 1000 refugees, and every two ticks (time steps) signifies the passage of one day. Asylum-seekers disappear from the model when they become refugees, to avoid cluttering the interface. They appear (spawn) at a source location in the Middle East at a steady rate of 41 turtles every 10 ticks, equivalent to 41,000 new individuals every 5 days. This reflects a uniform distribution of 3 million refugees over the entire course of 2016.

From the Middle East, asylum-seekers travel along one of the six routes to an entry point. They move over water at a rate of 5 steps/tick and over land at a rate of 1 step/tick (see assumptions in section 2.2). Every entry point e owns (keeps track of) W_e, the number of people waiting for their decisions. Every entry point also has access to Q_c, the quota of the country it belongs to, and R_c, the current number of refugees accepted to the country it belongs to. Larger countries have multiple entry points, as this speeds up refugee progress.

Asylum-seekers choose their destinations based on a preference value p_e assigned to every entry point e. They will travel to the neighboring entry point with the highest p_e value, considering that – all other things being equal – countries with more open spaces $(Q_c - R_c - W_e)$, higher survival rates, smaller travel distances, and/or less overcrowding and backlog (proportional to the number of asylum-seekers W_e already there) are more preferred. Thus, we define preference values according to Equation 2 below.

$$p_e = \frac{(Q_c - R_c - W_e)(s_r)}{\text{distance} \times W_e} \tag{2}$$

Because our model is dynamic to simulate the crisis in real-time, R_c, W_e, and p_c constantly change with every tick.

By the Dublin Regulation, [19], asylum-seekers must apply for asylum at the first entry point they reach. While awaiting their decisions, they consume resources and reside at the entry point. In our model, the wait time is greater if there are a large number of asylum-seekers W_e also waiting at the same entry point. This simulates the real problem of overcrowding and backlogging at asylum shelters and application processing centers.

After waiting, if the asylum-seekers are denied from the entry point because the quota is filled, they use the preference values to decide which country to apply to next. They continue doing so until they are accepted.

Our goal is to find the optimal flow of refugee movement. We define *optimal* to be the set of f_r values that minimizes the time required for all asylum-seekers to be safely relocated and successfully deemed refugees. Thus, the performance of a particular solution is measured by its run time in ticks.

3.2 Dijkstra's Algorithm

First, we use a variation of Dijkstra's algorithm for the shortest paths between nodes to determine optimal refugee flow across the six migratory routes. Dijkstra's algorithm considers a given source node and calculates the shortest-path tree from the source node to all other potential nodes in the network by assigning arbitrary values to each node. As such, it is ideal for creating network routing protocols and, by extension, modeling the European Refugee Crisis.

Our model interface is shown in Figure 2. We consider six sub-networks that correspond to the six paths of movement from the Middle East to safe countries in Europe. The six sub-networks are each connected to the "source" area of the map from which asylum-seekers originate. Asylum-seekers then move throughout the six networks–but never between networks–to one of six entry points. To build the six sub-networks, we create intermediate stopping points and entry points amongst our 15 countries. The first stopping point of each sub-network is designated as a *source node* and each entry point as an *end node.* We also assign links (paths) to logically connect specific points. Each point is then assigned a preference value p_e based on Equation 2 as well as an arbitrary Dijkstra's

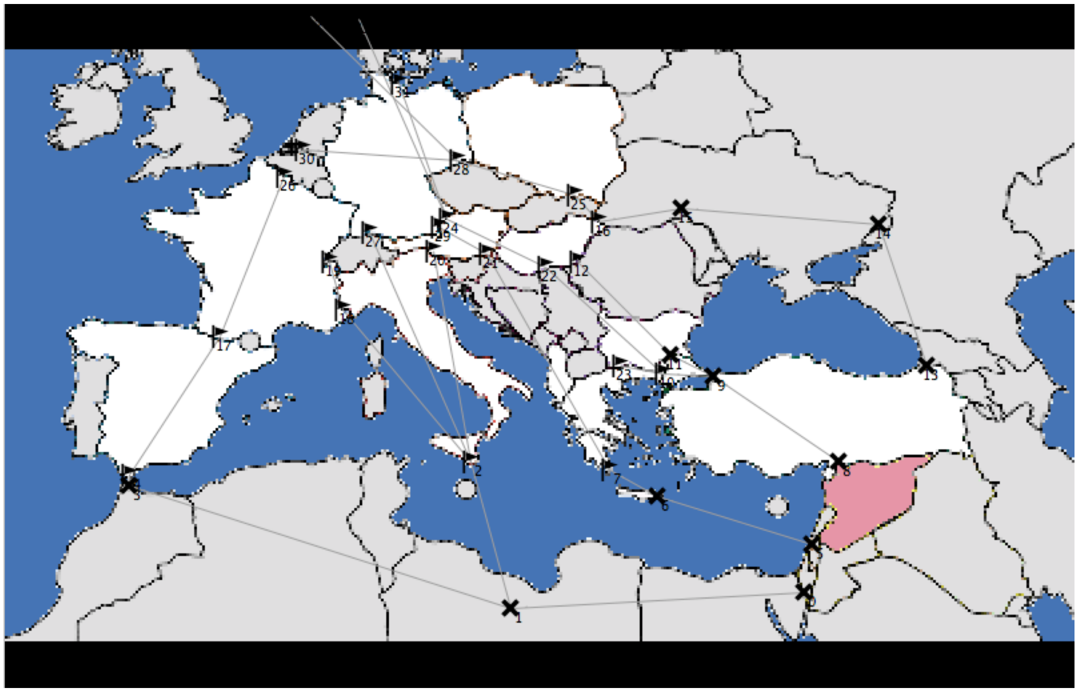

Figure 2: Network created with Dijkstra's Algorithm. The source area is colored pink and destination countries are white.

number D_n, whose value is calculated according to Equation 3 below. Due to the directionality of the links, we can identify *out-links* as points that refugees travel out of and *in-links* as those that refugees travel into. Note that a point can potentially be both an out-link and an in-link, depending on the link in question.

$$D_n = \sum (p_e)_{out-link} \tag{3}$$

Thus, end nodes have low D_n values and source nodes have high ones.

Asylum-seekers move across the network, taking paths that are determined individually by the D_n values of each node along the path. Because higher p_e values indicate more preferable entry points, asylum-seekers first into the source node (of the six starting points) with the *highest* D_n value and continued north through the path of highest D_n. As they move into different stopping points and entry points, however, p_r values are altered, and D_n values are adjusted accordingly. Thus, preference for each path fluctuates with every tick.

By maintaining a dynamic model, updated for every movement made by every refugee across the entire system of sub-networks to continuously maintain the most optimal path of movement, we observe a real-time movement and distribution of refugees across the network of changing preference.

Given the nature of Dijkstra's algorithm, we can consistently determine the optimal distribution of refugees across the six paths with good confidence.

3.3 Genetic Algorithm

We also implement a Genetic Algorithm (GA) to optimize the flow rate (f_r) of the refugees across each of the six routes. Our interface is shown in Figure 3. GAs work by using principles of natural selection and genetics over successive generations to find optimal distributions of certain parameters - in our case, the flow of refugees across each of the six migratory routes. Because GAs are more robust for unconstrained optimization problems than for conventional AI systems, they are well suited to our model [15].

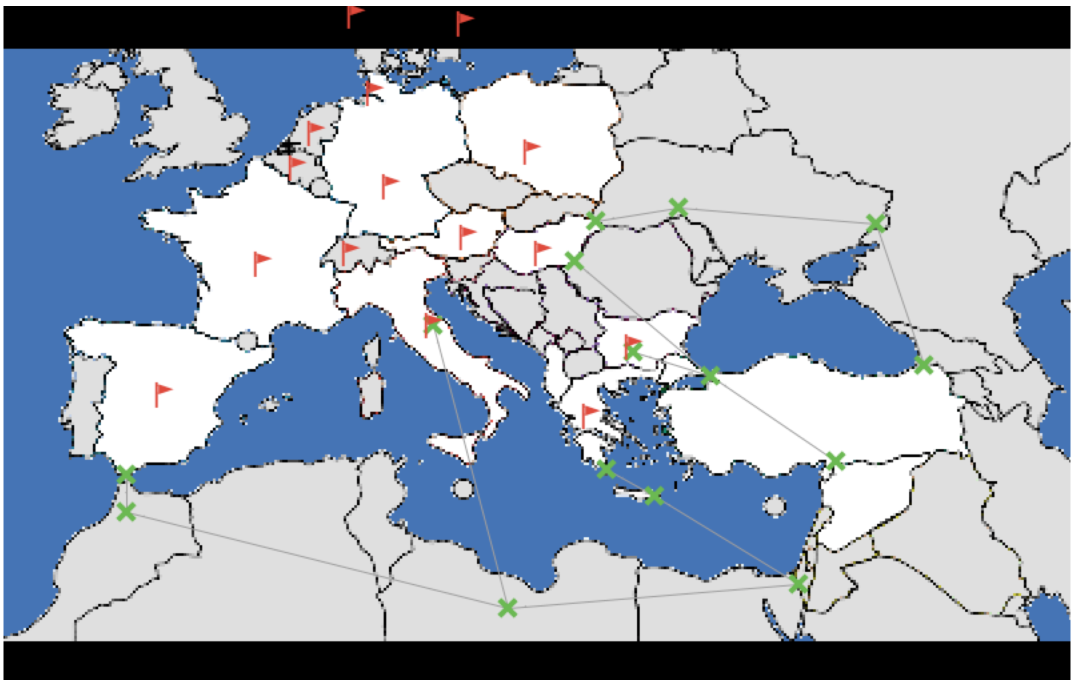

Figure 3: The model interface for each iteration of the Genetic Algorithm. Each country owns a red flag for the people to go to. This is run for each individual to produce a fitness score.

To run the GA, we represent every set of f_r values as an "individual" with a fitness level corresponding to how well that set of f_r values performs. Performance is measured by the total run time according to our metric. We aim to "breed" the most fit individual, which will be our solution.

We start with a generation of 10 individuals with randomly generated f_r values. To produce each "offspring", we randomly select individuals and "mutate" them with probability 0.5. The population size and mutation rate were chosen based on optimal results out of different parameter combinations. Individuals that are more fit have a higher chance of being selected and thus passing on their desirable "genes" to offspring, as is with actual natural selection. We repeat this process 10 times to build a new generation of 10 individuals.

Successive generations are made by iterating this selection process. To determine our solution, we monitor the fittest individual over many generations and use its f_r values.

3.4 Considering Resources and Crisis Dynamics

Using our optimized flow rates reported in section 4.1, we incorporate resources into our model. We do so by adding hunger and health bars to each turtle. Both are on a scale from 0 to 100, with 0 representing death from starvation/disease and 100 representing full health/no hunger.

As time progresses, people's health and hunger values fluctuate according to the resources available in their immediate surroundings. For asylum-seekers en-route to their safe country's entry point, health decreases by 0.4 units per tick on land (calculated from the median number of ticks needed to reach the source country) and 2.0 units per tick on water (scaled due to the lack of shelter and sanitation). Hunger decreases 0.4 units on land and 0.8 units on water (scaled due to an inability to replenish resources while on water) per tick. At entry points and intermediate ports, both health and hunger are replenished by 10 units per tick. By monitoring locations of death due to hunger and/or health, we can determine areas of most resource need.

3.5 Exogenous Events

In our model, we also account for exogenous events that can violently alter refugee crisis dynamics, such as major terrorist attacks. We consider two types of exogenous events: concentrated and diffused shocks. When shocks occurs, the preferences p_e for origin countries decreases by a factor of 10, and p_e for adjacent countries halves. Diffused shocks additionally halve the preference of that country's surrounding entry points. This scale takes into consideration the decreased preferences of asylum-seekers towards affected areas. Other metrics, particularly the area's quota, are not taken into consideration because they do not immediately impact the flow of refugees [16].

Altering p_r values changes how the people choose their destinations and thus the routes that they take. We test the effects of shocking France and Germany because they are most prone to terrorist attacks terror, as they have many entry points. France is representative of a more isolated safe country (with limited and directed paths of travel), and Germany is representative of a central, safe country (with fewer travel limitations). We then monitor the changes in the flow rates f_r of our model.

3.6 Scaling Up

We test the scalability of our model, and thus the scope of the solution, by increasing the total asylum-seeker population by a factor of 10. This new refugee population of 30,000,000 is generated and considered in two scenarios:

1. constant time frame (1 year)
2. constant emigration rate (41 asylum-seekers every 5 days)

We similarly scale refugee quotas Q_c by 10 to accommodate projected populations, and use Dijkstra's algorithm to re-calculate optimal f_r distributions for refugee movement along the six routes.

4 Solution Description

4.1 Optimal Refugee Flow (Task 2)

Through our model, we obtain two sets of f_r - one solution each from the results of Dijkstra's Algorithm and a Genetic Algorithm. With the GA, we find a solution after 33 generations because fitness begins to plateau there, as shown in Figure 4. Our two solutions are very close, as shown in

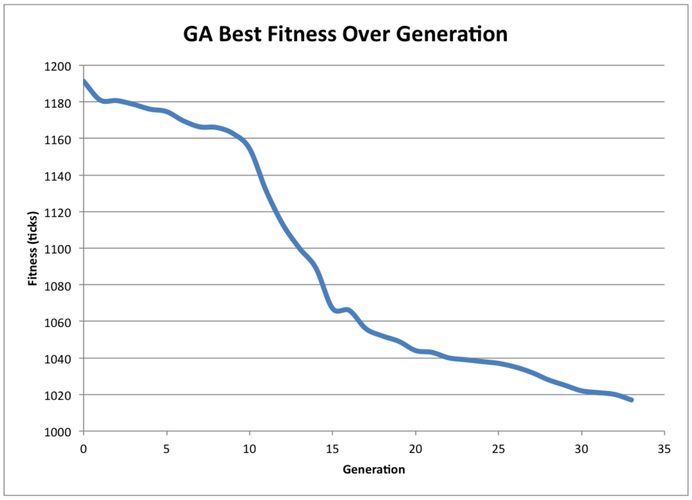

Figure 4: Most fit individual of each generation in our GA.

Figure 5, thereby supporting the validity of our results. We decide to average f_r values from both methods to determine final values.

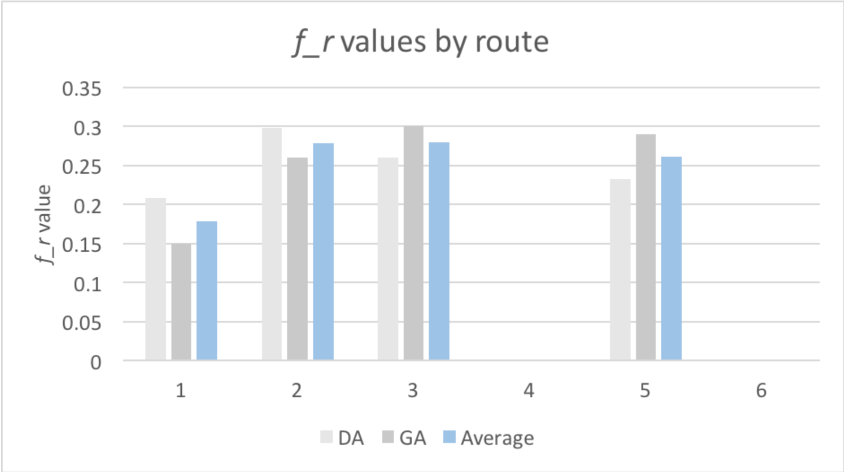

Figure 5: Consolidated f_r values.

Both optimization methods suggest sending no one through the West Balkans and Albania to Greece route, as they do not seem to be efficient uses of resources or time, on part of both asylum-seekers and refugee centers/shelters. The other four routes have roughly equal f_r values, indicating that these routes are about equally useful in accessing Europe.

Consolidated results are shown in Table 4. We believe, with good confidence, that the highlighted column represents optimal refugee movement.

r	Route	f_r (DA)	f_r (GA)	Average
1	West Mediterranean	0.208	0.15	0.179
2	Central Mediterranean	0.298	0.26	0.279
3	Eastern Mediterranean	0.260	0.30	0.280
4	West Balkans	0	0	0
5	Eastern Borders	0.233	0.29	0.262
6	Albania to Greece	0	0	0

Table 4: Consolidated f_r values.

4.2 Crisis Dynamics (Task 3)

We divide the problem of resource allocation into sub-categories depending on the level of available resources. Specifically, we consider the cases of:

- zero additional resources (as a base for comparison);
- basic resources allocated by local governments in first border countries;
- both basic resources and supplies provided by non-governmental organizations (NGOs). NGOs are valuable in that their influence is not limited to within country borders.

For each sub-category, we further consider collective refugee welfare with three metrics: health only, hunger only, and both together. This allows us to provide an even more intricate plan for resource allocation.

4.2.1 No Additional Resources

Figures 6-8 illustrate the location of asylum-seeker deaths due to either hunger, poor health, or both, given that no additional resources are provided. The majority of deaths from both health

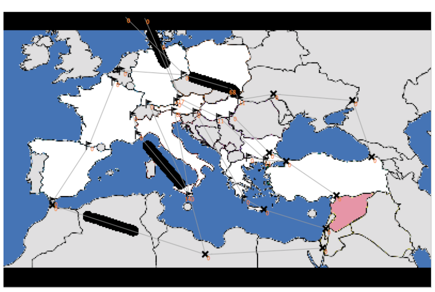

Figure 6: Areas of death due to low health, marked in black, given no additional resources.

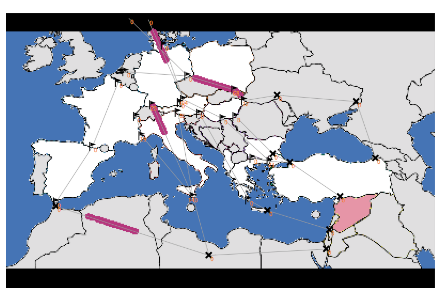

Figure 7: Areas of death due to starvation, marked in purple, given no additional resources.

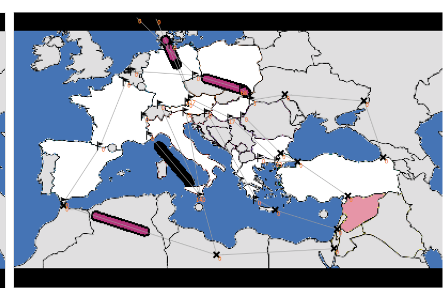

Figure 8: Death due to both poor health (black) and/or starvation (purple), given no additional resources.

and/or hunger are concentrated in the furthest reaches of the four most populated travel paths: Western Mediterranean, Central Mediterranean, East Mediterranean, and Eastern Borders. In comparing the Central Mediterranean route in Figures 6 and 7, we notice that asylum-seekers make it farther down the path (i.e. more people reach safety), we when consider health rather than starvation. In Figure 8, the Central Mediterranean route contains an area of death caused solely by health comparable to that in the map of solely health. The absence of this high level of death on this route in Figure 7 causes the refugee flow to be diverted slightly to the east. Our model indicates that health and hunger metrics, given the population-dependency of the dynamic model, affect both the distance traveled and the actual movement of refugee flow.

4.2.2 Limited Governmental Resources at Entry Points

Based on the results of section 4.2.1, we supply limited governmental resources in the areas of most need - these are the first entry points of each of the four death-concentrated areas shown in Figures 6-8. We scale resources proportional to the number of asylum-seekers passing through. Figures 6-8 illustrate resulting, modified refugee flow. Resource-rich points are labeled green, indicating our suggestion for countries' resources to be allocated in these areas.

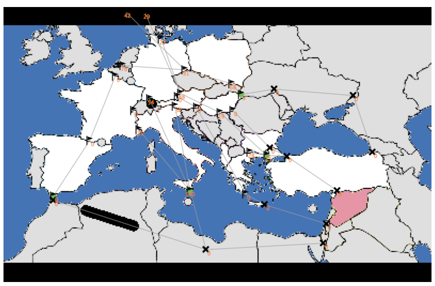

Figure 9: Areas of death due to low health, marked in black, given governmental resources at four entry points.

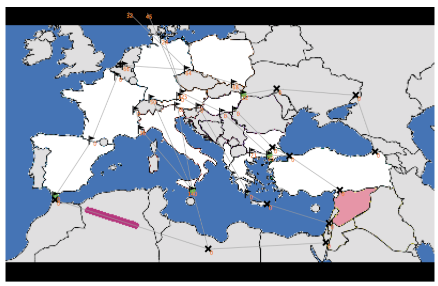

Figure 10: Areas of death due to starvation, marked in purple, given governmental resources at four entry points.

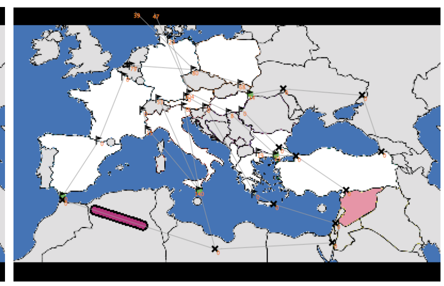

Figure 11: Death due to both poor health (black) and/or starvation (purple), given governmental resources.

This preliminary allocation of resources eliminates death along three of the four most populated routes. The heaviest area of need, along the Western Mediterranean route for Figures 9-11, must be targeted with additional resources not necessarily available to the heavily burdened border countries.

4.2.3 Non-Governmental Organization (NGO) Involvement

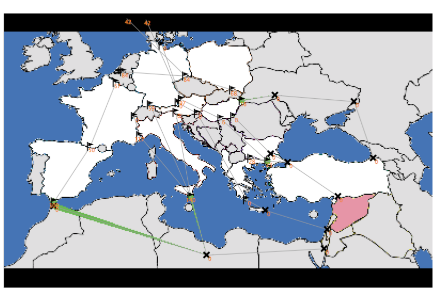

Figure 12: Areas of death due to low health, marked in black, given both governmental and NGO resources.

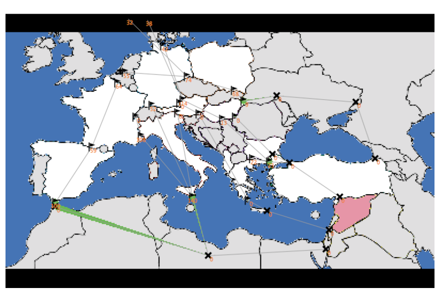

Figure 13: Areas of death due to starvation, marked in purple, given both governmental and NGO resources.

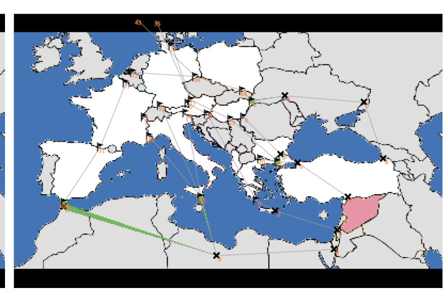

Figure 14: Death due to both poor health and/or starvation, given both governmental and NGO resources.

To target the last route, Western Mediterranean, we consider additional resources from NGOs. Because NGOs lack affiliation, they can be assigned to regions that span multiple country borders if necessary. We maximize their influence by positioning them directly along the route; again, resource-rich areas are marked with green. Figures 12-14 illustrate resulting refugee flow. This final plan for resource allocation eliminates all refugee death along the designated paths. This allows for the safe travel of asylum-seekers to their destinations.

4.3 Effects of Exogenous Events (Task 5)

The effects of a concentrated shock are limited to the country of origin; the effects of a diffused shock spread to countries with entry ports directly adjacent to the country of origin. After introducing exogenous events into our model, we obtain the following optimized refugee distributions along the six routes in Table 5.

r	Route	Original f_r	New f_r (France)		New f_r (Germany)	
			Concentrated	Dispersed	Concentrated	Dispersed
1	West Mediterranean	0.179	0.203	0.119	0.273	0.314
2	Central Mediterranean	0.279	0.207	0.209	0.494	0.439
3	Eastern Mediterranean	0.280	0.274	0.274	0.041	0.069
4	West Balkans	0	0	0	0	0
5	Eastern Borders	0.262	0.288	0.274	0.192	0.180
6	Albania to Greece	0	0.0274	0.122	0	0

Table 5: Optimized f_r values across the six routes given various types of exogenous events.

In France, where there is limited mobility (available routes guide refugees directly from one entry point to the next), concentrated shocks produce little change in refugee distribution. The most noticeable difference transfers a portion of those from Central Mediterranean, where the refugees have more options to avoid travel to France, to the east (to Eastern Mediterranean, Eastern Borders, and Albania-Greece). The dispersed shock causes a more pronounced shift from western routes to eastern routes as the entry points adjacent to France are also impacted. With this larger area of impact, refugees give increasingly greater preference to the eastern routes.

In Germany, where there is more mobility in terms of route choices from a single entry point and the number of entry points in general, we observe greater changes in refugee distribution. Similar to the model in France, however, the dispersed shock causes a more pronounced impact in the same direction as the concentrated shock. Both types of shocks in Germany cause refugees to move from eastern routes, where Germany is the last safe-country of many of the routes (limiting mobility), towards the western routes, where refugees have the option of applying for asylum in other safe countries.

4.4 Scope of Crisis and Model Scalability (Task 6)

The distribution of refugees across the six routes for the increased population are considered to test the scope of our solution.

4.4.1 Constant Time Frame

Keeping the time limit of a single year, refugees now emigrate from the Middle East at a rate 10 times faster. The resulting optimized distribution is shown in Table 6.

r	Route	Original f_r	New f_r
1	West Mediterranean	0.208	0.341
2	Central Mediterranean	0.324	0.120
3	Eastern Mediterranean	0.193	0.182
4	West Balkans	0	0.027
5	Eastern Borders	0.276	0.315
6	Albania to Greece	0	0.014

Table 6: New optimal f_r rates given the same time frame of a single year, compounded with the parameters from prior tasks.

4.4.2 Constant Rate of Emigration

Keeping the emigration rate of 41 refugees/5 days, the scale of the refugee crisis must now be lengthened to 10 years to allow the same number of asylum-seekers to reach safety. The resulting optimized distribution is shown in Figure 7.

r	Route	Original f_r	New f_r
1	West Mediterranean	0.208	0.183
2	Central Mediterranean	0.324	0.302
3	Eastern Mediterranean	0.193	0.223
4	West Balkans	0	0
5	Eastern Borders	0.276	0.270
6	Albania to Greece	0	0.023

Table 7: New optimal f_r rates given the same emigration rate, compounded with the parameters from prior tasks.

4.4.3 Analysis of Scope

Increasing the scale of the model with a limited time rate suggests that the increased congestion of the six routes forces refugees to redirect towards less popular routes. We also observe a significant decrease in the number of refugees along the Central Mediterranean route due to long backlogs where refugees must be processed at a single entry point for multiple northern legs of the route (for example, at the tip of Italy). On the other hand, routes that direct towards a single entry point allow for quicker processing and, as such, the distributions of refugees along those routes increase. There is no noticeable increase in the time it takes to process and grant asylum to the asylum-seekers after the year ends (the number of ticks past the one year mark is comparable to that of the normal refugee population model). The only limitation to this model is the rate at which resources can be allocated to the areas of need with the increased congestion. In our model, we considered a similarly scaled distribution of resources to address refugee welfare. Therefore, while the distribution of refugees along the six routes changes and resource allocation must be addressed accordingly, the time it takes to grant asylum to the refugees does not and our model holds consistent. This suggests that with the given resources, our solution system can sufficiently process and withstand an influx of refugees ten times the projected volume, given their optimal movement.

Increasing the scale of the model with a limited emigration rate suggests that asylum is granted at a fast enough rate in our solution for the system to process refugees for an extended period (beyond the original scope of a single year) without significant changes to the optimal flow of refugees. Thus, in this scenario, the only limiting factor is the volume of resources that can be obtained for the increased volume of asylum-seekers. Volume per period of time, however, remains relatively constant as the backlog of the increased population (ticks it takes to process the remaining refugees after the emigration period) remains constant. Therefore, assuming resources can be assembled at a reasonable rate, our solution system can also sufficiently process and withstand an influx of refugees across an extended period of ten years, given optimal refugee movement.

5 Model Evaluation

5.1 Sensitivity Analysis

It is important that our model show tolerance to a small variance in its inputs. If our model is robust, the outputs will not vary dramatically given small differences in inputs. To test our model's sensitivity, we thus intentionally introduce small amounts of error and compare the resulting output to our original solution.

One adjustment we make is ignoring survival rates s_r of each route, i.e. assuming that no asylum-seeker dies solely due to the terrain of the route. Because the s_r values are so close, we reasoned that they do not play a significant role in the decision-making of each asylum-seeker. After removing them from our preference calculations (Equation 2), we find that new refugee flows differ by at most 3.6%, indicating that survival rates indeed play a small role in refugee movement.

We also vary our model by spawning asylum-seekers at sources other than Syria. The resulting f_r values turn out to be identical, showing that our model is insensitive to the initial location of asylum-seekers. Regardless of where they come from, they will sort themselves out along the optimal routes.

5.2 Model Strengths

By computationally modeling the European Refugee Crisis, we more closely simulate the actual situation. Our choice of software (NetLogo) is ideal because of its agent-based modeling environment, which allows us to visualize the movement of people as a function of time and incorporate the issue of distance.

Our results are also strengthened by our use of two optimization methods: Dijkstra's Algorithm and a Genetic Algorithm. As described in section 4.1, our two separate solutions are very close. This validates and enables us to report a final set of f_r values, which is an average of the two.

Lastly, our model is solid because we compound the different parameters and metrics from task to task. We address all of the tasks by easily incorporating elements (such as resources and exogenous events) one after the other, building off of a single base. This makes our model useful and efficient in considering even more parameters and dynamics in the future.

5.3 Model Weaknesses

Our model fails to take into account routes which were not explicitly defined. For example, we only allow asylum-seekers to access France through the West Mediterranean and Central Mediterranean route, restricting the number of ways they can come into the country. However, these explicit definitions were necessary because our model looks at optimizing the flow rates through each route.

The parameters of our model also do not consider asylum-seekers on an individual basis, and so information such as family interactions, age, and special circumstances such as physical disabilities are not accounted for.

6 Conclusions and Future Work

We build a computational mathematical model of the European Refugee Crisis. By using the Genetic Algorithm and Dijkstra's Algorithm on our model, we determine the optimal flow rate of refugees to be nothing for the West Balkans and Albania to Greece routes and roughly equally split among the other four routes. Using this distribution, we find that the best allocation of governmental resources is at entry points in Spain, Italy, Greece, and Hungary, to maximize the distance weary refugees can travel. The best allocation of NGO resources is along Northern Africa, in Ukraine, and across the sea passage between Libya and Malta/Italy. To give our model additional depth, we would include more routes and countries as well as research additional factors that might affect the refugee crisis. Our model uses available data to find the most preferred way to deal with the refugee crisis. The model is both robust and computational, but there may be additional factors that lend new insight into the recommended policy for Europe to address the refugee crisis.

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