Refugee Migration Networks with Regulations

Anna Nagurney

Eugene M. Isenberg Chair in Integrative Studies
Director – Virtual Center for Supernetworks
Isenberg School of Management
University of Massachusetts Amherst

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Acknowledgments

Thanks to Dr. Geri Louise Dimas, Dr. Daniel Reichman, and Dr. Andrew C. Trapp for organizing this important conference!

The lifting of Title 42 on May 11, 2023 is likely to spur a significant increase in the number of migrants trying to cross into the United States and, hence, this conference is presciently timed.

Outline of Presentation

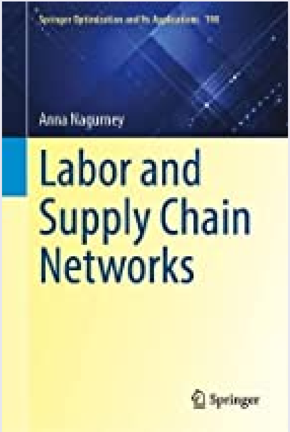
- **Motivation and Some Background**
- **Human Migration and Refugees**
- **The Refugee Migration Models and Variational Inequality Formulations**
- **Some Additional Research**
- **Summary and Conclusions**

Motivation and Some Background

I Work on the Modeling of Network Systems

Some of My Books

New Book



It's All About People

A major research theme of ours in the COVID-19 pandemic has been the inclusion of labor in supply chains, using optimization and game theory, as well as expanding the scope of human migration networks. Such research is also very relevant to Russia's war against Ukraine with the immense refugee crisis.

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January 29, 2021 in Supply Chain Networks

In the End, It's All About People

COVID-19 vaccine production reveals dependency on supply chains, labor workforce in the U.S.

By Anna Nagurney

SHARE: PRINT ARTICLE: https://doi.org/10.1287/orms.2021.01.17

The COVID-19 pandemic has dramatically revealed how dependent we are on supply chains and the availability of labor. Without the human element, meatpacking plants cannot function; fresh produce cannot be picked; grocery stores cannot be shelved; PPEs cannot be produced and distributed; and products cannot be delivered to our homes through e-commerce. Also, COVID-19 vaccine production may lack the human resources to ensure product quality and efficacy, as well as its distribution and ultimate administration into our arms. Without healthcare workers to

Human Migration and Refugees

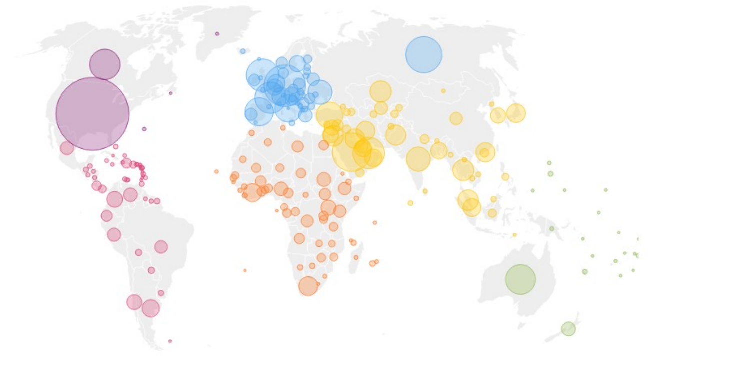
Human Migration and Refugees

• **Reasons for human migration are numerous**, from individuals **seeking better economic opportunities and enhanced prosperity for themselves and their families**, to **those fleeing conflict, violence, and persecution**. With climate change and the increasing number and severity of disasters, including hurricanes, floods, tornados, earthquakes, etc., some migrants are seeking locations of greater expected safety and security.

• **The current global estimate is that there were around 281 million international migrants in the world in 2020, about 3.6% of the global population. This is over three times the estimated number in 1970!**

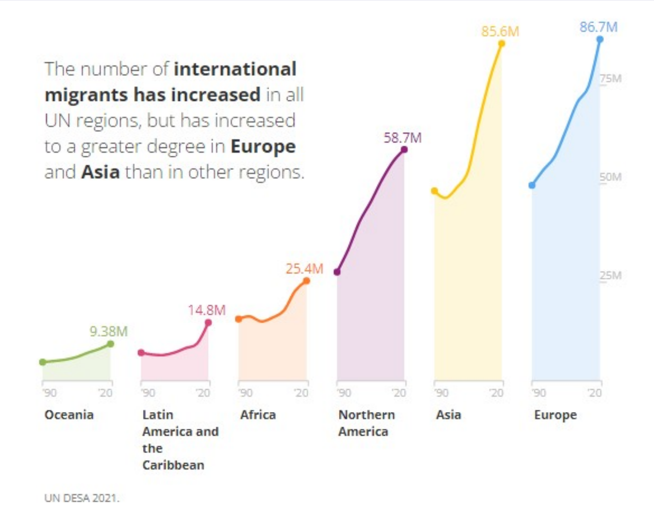
• **The number of international migrants is growing faster than the global population.**

The total number of international migrants within each country:



United Nations (2021)

International Migrants



United Nations (2021)

Definition of a Refugee

The United Nations Convention Relating to the Status of Refugees in 1951 defined a refugee as an individual living outside his or her country of nationality, who is unable or unwilling to return because of a well-substantiated fear of persecution due to race, religion, nationality, membership in a political social group, etc.

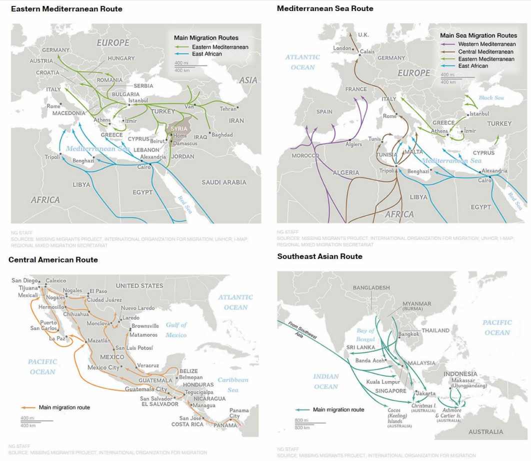
In our research, we also consider humans adversely affected by climate change, as refugees, and note that, as emphasized by Hebert, Perez, and Harati (2018), among the most studied causes of human migration are climate issues and conflicts, as well as economic reasons.

Refugees and the Pandemic

Refugees have historically always been part of human migration, seeking locations of greater safety and security for themselves and their families.

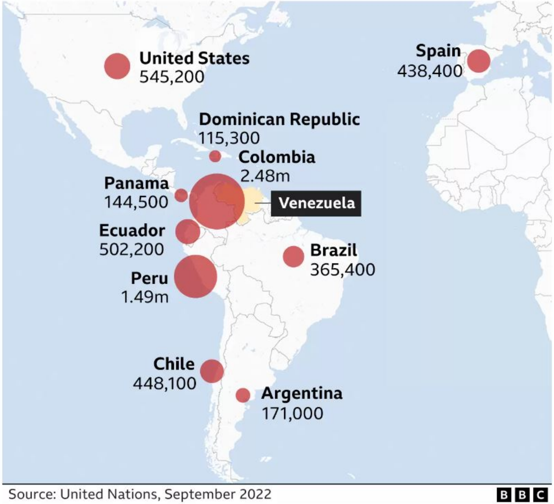
With the COVID-19 pandemic, declared by the World Health Organization on March 11, 2020, Dolmans et al. (2020) reported that COVID-19 likely exacerbated refugee flows and increased the difficulty in seeking asylum due to measures imposed by governments in response to the pandemic.

Some Migration Routes



Source: National Geographic via IOM UN Migration Blog - 2015 data

More than seven million Venezuelans have left their homeland since 2015 amid an ongoing economic and political crisis, according to recent United Nations data.

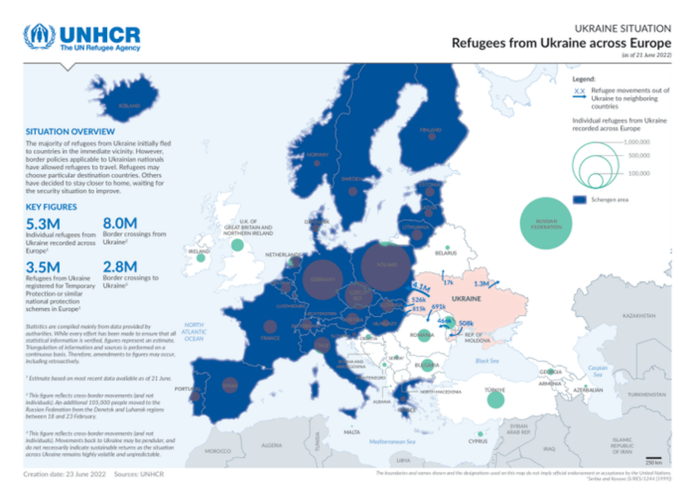


The Largest Refugee Crisis Since World War II

- **Russia's invasion of Ukraine on February 24, 2022, has resulted in the largest refugee crisis since World War II.**
- **In October 2022, the United Nations listed 7.6 million refugees across Europe from Ukraine.**
- **In all, nearly one-third of Ukrainians have been displaced. About 13 million are stranded in Ukraine due to fighting, impassable routes, or the lack of resources to move.**

- **About half of the refugees are children.**

Refugees from Ukraine



Source: UNHCR, June 27, 2022

Human Migrants and Refugees

Vivid depictions of people fleeing their origin locations permeate the news, whether attempting to escape the great strife and suffering in Syria; the violence in parts of Central America, the economic collapse of Venezuela, and even flooding in parts of Asia as well as droughts in parts of Africa.

At times, refugees will travel in extremely dangerous conditions to escape the dire circumstances at their origin nodes.

In 2015, the UN Refugee Agency reported a maritime refugee crisis with, in the first half of that year, 137,000 refugees crossing the Mediterranean Sea to Europe, via very risky transport modes, and with many more unsuccessfully attempting such a passage. 800 died in the largest refugee shipwreck on record that April.

Refugees from Afghanistan

Prior to Russia's war on Ukraine, the largest number of refugees were from Syria, Venezuela, and Afghanistan.

Afghan evacuees boarding American aircraft during Operation Allies Refuge in August 2021.

Government Policies

Governments of various nations, hence, are increasingly being faced with multiple challenges associated with human migration flows. In response to challenges, they are adopting different regulations.

According to the United Nations (2013), **migration policies in both origin and destination countries play an important role in determining the migratory flows**. In managing international migration flows, governments usually focus on different types of migrants, of which the most salient are highly skilled workers, dependents of migrant workers, irregular migrants, and refugees and asylum seekers (cf. Karagiannis (2016)).

Between 11 March 2020, when the WHO declared COVID-19 a pandemic, and 22 February 2021, nearly 105,000 movement restrictions were implemented around the world, according to the International Organization for Migration.

Government Policies

We can expect refugee migratory flows to continue to increase, posing a critical need for the provision of rigorous tools for policy-makers and decision-makers for the quantification of refugee migratory flows and the impacts of various regulations.

The construction of a relevant model with policy implications was one of our goals.

The Refugee Migration Models and Variational Inequality Formulations

This part of my presentation is based on the paper:

A. Nagurney, P. Daniele, and L.S. Nagurney, "Refugee Migration Networks and Regulations: A Multiclass, Multipath Variational Inequality Framework," *Journal of Global Optimization* **78 (2020), pp 627-649.**

Journal of Global Optimization
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Check for updates

Refugee migration networks and regulations: a multiclass, multipath variational inequality framework

Anna Nagurney[1] · Patrizia Daniele[2] · Ladimer S. Nagurney[3]

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Abstract
In this paper, we take up the timely topic of the modeling, analysis, and solution of refugee migration networks. We construct a general, multiclass, multipath model, determine the governing equilibrium conditions, and provide alternative variational inequality formulations in path flows and in link flows. We also demonstrate how governmental imposed regulations associated with refugees can be captured via constraints. We provide qualitative properties and then establish, via a supernetwork transformation, that the model(s) are isomorphic to traffic network equilibrium models with fixed demands. Illustrative examples are given, along with numerical examples, inspired by a refugee crisis from Mexico to the United States, which are solved using the Euler method embedded with exact equilibration. The work sets the foundation for the development of additional models and algorithms and also provides insights as to who wins and who loses under certain refugee regulations.

Keywords Refugees · Human migration · Networks · Variational inequalities · Regulations

1 Introduction

Refugees have historically always been part of human migration, seeking locations of greater safety and security for themselves and their families. Now, with the increasing impacts of climate change, and associated increases in the severity, as well as the frequency, of many disasters, including hurricanes and floods, coupled with numerous conflicts, strife, and violence in many parts of the globe, the number of refugees and asylum seekers is escalating. According to the United Nations [52], the number of international migrants was approximately 258 million (3.4% of the global population) in the year 2017, with the total number of international migrants increasing by almost 50% since 2000 (United Nations [52]). Also,

✉ Anna Nagurney
nagurney@isenberg.umass.edu

1 Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts, Amherst, MA 01003, USA

• Nagurney (1989) introduced a multiclass migration equilibrium model, which did not include migration/movement costs, and **was isomorphic to a traffic network equilibrium with special structure**. The model was then extended to include flow-dependent migration costs and an expanded set of equilibrium conditions in Nagurney (1990).

• Nagurney, Pan, and Zhao (1992a) proposed **a multiclass human migration model**, which further generalized to include class transformations in Nagurney, Pan, and Zhao (1992b).

• Pan and Nagurney (1994) considered **chain migration (unlike the earlier work) and introduced a multi-stage (but single class) Markov chain model**. The authors established a connection between a sequence of variational inequalities and a non-homogeneous Markov chain. They also proved that, under certain assumptions, the stability of the one-step transition matrix guarantees the stability of the *n*-step transition matrix.

Literature Review with a Focus on Networks and Migration

• Pan and Nagurney (2006) utilized **evolution variational inequalities for the first time to model the dynamic adjustment of a socio-economic process in the context of human migration**. Convergence of algorithms in this framework, which is infinite-dimensional, was addressed (see Daniele (2006)).

• Interestingly, many of the network equilibrium models of human migration have **found application to the migration of animals in ecology with a focus on fish and maritime ecosystems** (see Mullon and Nagurney (2012), Mullon (2014), Mariani et al. (2016)).

• Kalashnikov et al. (2008) constructed a human migration model with a **conjectural variations equilibrium (CVE)**.

• Capello and Daniele (2019) developed **a Nash equilibrium model of human migration** with features of CV and provided examples on the flow of migrants from Africa through the Mediterranean sea to Italy in 2018.

The paper by Nagurney and Daniele (2020) was the first to include regulations within a human migration network framework.

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International human migration networks under regulations

Anna Nagurney[a,*], Patrizia Daniele[b]

[a] Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts, Amherst, Massachusetts 01003, United States
[b] Department of Mathematics and Computer Science University of Catania, Italy

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ABSTRACT

International human migration has transformed economies and societies. The new millennium, with climate change and its impacts, and increasing conflicts and displacements, has experienced a great increase in international migrants, with associated challenges faced by governments. In this paper, we advance the modeling, analysis, and solution of international human migration problems by developing a network model with regulations. The formalism uses the theory of variational inequalities, coupled with Lagrange analysis, in order to gain insights as to the impacts of the regulations on utilities of multiple classes of migrants, and on the equilibrium flows. Our results add to the literature on operations research for societal impact, inspired by the real world.

1. Introduction

Humans have engaged in migration since time immemorial. Reasons for human migration are numerous, from individuals seeking better economic opportunities and enhanced prosperity for themselves and their families, to those fleeing conflict, violence, and persecution. With climate change and the increasing number and severity of natural disasters, including hurricanes, floods, tornados, earthquakes, etc., some migrants are seeking locations of greater expected safety and security. In 2017, the number of international migrants was an estimated 258 million persons (3.4% of the global population), with the total number of international migrants increasing by almost 50% since 2000 (United Nations, 2017). As also reported therein, the number of international migrants is growing faster than the global population. Moreover, in the same almost two decade period, the number of refugees and asylum seekers increased from 16 to 26 million, comprising about 10% of the international migrants.

Vivid depictions of people fleeing their origin locations permeate the news, whether attempting to escape the great strife and suffering in Syria (United Nations Refugee Agency, 2019); the violence in parts of Central America (Bartenstein & McDonald, 2019), the economic collapse of Venezuela (Kennedy, 2019), and even flooding in parts of Asia (Dash & Paul, 2017), as well as droughts in parts of Africa (cf. Linke, Witmer, O'Loughlin, Mc Cabe, & Tir, 2018). Interestingly, since the onset of the new millennium, the countries experiencing the largest increase in their diaspora populations are the Syrian Arab Republic (872%), India (108%), and the Philippines (85%) (cf. United Nations, 2017). At times, refugees will travel in extremely dangerous conditions to escape the dire circumstances at their origin nodes. For example, the United Nations Refugee Agency (2015) reported a maritime refugee crisis with, in the first half of that year, 137,000 refugees crossing the Mediterranean Sea to Europe, via very risky transport modes, and with many more unsuccessfully attempting such a passage. 800 died in the largest refugee shipwreck on record that April. Clearly, the issue of human migration is one of multiple dimensions, including economic, political, sociological, and even environmental aspects.

Governments of various nations, hence, are increasingly being faced with multiple challenges associated with human migration flows. In response to challenges, they are adopting different regulations. According to Bertossi (2008), since the 1990s, unprecedented efforts have been made to control the movement of people across state borders. As argued eloquently by Helbling and Leblang (2019), migration regulations are core to national sovereignty since they directly impact the composition of the community that makes up the country. According to the informative report by the United Nations (2013), migration policies in both origin and destination countries play an important role in determining the migratory flows. Moreover, as noted therein, in managing international migration flows, governments usually focus on different types of migrants, of which the most salient are highly skilled workers, dependents of migrant workers, irregular migrants, and refugees and asylum seekers (cf. Karagiannis, 2016).

* Corresponding author.
E-mail address: nagurney@isenberg.umass.edu (A. Nagurney).

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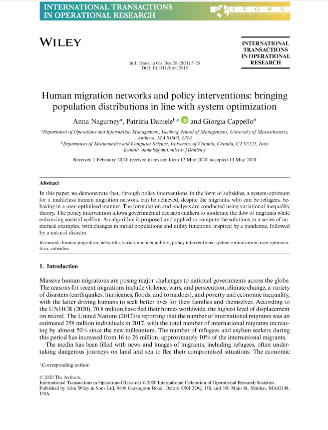

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Human migration networks and policy interventions: bringing population distributions in line with system optimization

Anna Nagurney[a], Patrizia Daniele[b,*] and Giorgia Cappello[b]

[a] Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts, Amherst, MA 01003, USA
[b] Department of Mathematics and Computer Science, University of Catania, Catania, CT 95125, Italy
E-mail: daniele@dmi.unict.it [Daniele]

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Abstract

In this paper, we demonstrate that, through policy interventions, in the form of subsidies, a system-optimum for a multiclass human migration network can be achieved, despite the migrants, who can be refugees, behaving in a user-optimized manner. The formulation and analysis are conducted using variational inequality theory. The policy intervention allows governmental decision-makers to moderate the flow of migrants while enhancing societal welfare. An algorithm is proposed and applied to compute the solutions to a series of numerical examples, with changes in initial populations and utility functions, inspired by a pandemic, followed by a natural disaster.

Keywords: human migration; networks; variational inequalities; policy interventions; system optimization; user optimization; subsidies

1. Introduction

Massive human migrations are posing major challenges to national governments across the globe. The reasons for recent migrations include violence, wars, and persecution, climate change, a variety of disasters (earthquakes, hurricanes, floods, and tornadoes), and poverty and economic inequality, with the latter driving humans to seek better lives for their families and themselves. According to the UNHCR (2020), 70.8 million have fled their homes worldwide, the highest level of displacement on record. The United Nations (2017) is reporting that the number of international migrants was an estimated 258 million individuals in 2017, with the total number of international migrants increasing by almost 50% since the new millennium. The number of refugees and asylum seekers during this period has increased from 16 to 26 million, approximately 10% of the international migrants.

The media has been filled with news and images of migrants, including refugees, often undertaking dangerous journeys on land and sea to flee their compromised situations. The economic

*Corresponding author.

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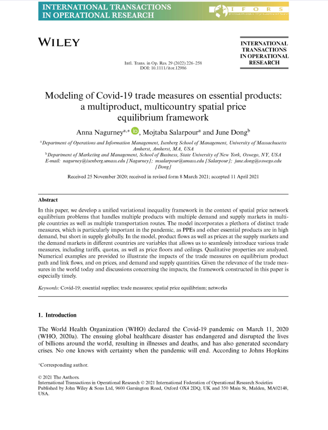

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Modeling of Covid-19 trade measures on essential products: a multiproduct, multicountry spatial price equilibrium framework

Anna Nagurney[a,*], Mojtaba Salarpour[a] and June Dong[b]

[a] Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts Amherst, Amherst, MA, USA
[b] Department of Marketing and Management, School of Business, State University of New York, Oswego, NY, USA
E-mail: nagurney@isenberg.umass.edu [Nagurney]; msalarpour@umass.edu [Salarpour]; june.dong@oswego.edu [Dong]

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Abstract

In this paper, we develop a unified variational inequality framework in the context of spatial price network equilibrium problems that handles multiple products with multiple demand and supply markets in multiple countries as well as multiple transportation routes. The model incorporates a plethora of distinct trade measures, which is particularly important in the pandemic, as PPEs and other essential products are in high demand, but short in supply globally. In the model, product flows as well as prices at the supply markets and the demand markets in different countries are variables that allows us to seamlessly introduce various trade measures, including tariffs, quotas, as well as price floors and ceilings. Qualitative properties are analyzed. Numerical examples are provided to illustrate the impacts of the trade measures on equilibrium product path and link flows, and on prices, and demand and supply quantities. Given the relevance of the trade measures in the world today and discussions concerning the impacts, the framework constructed in this paper is especially timely.

Keywords: Covid-19; essential supplies; trade measures; spatial price equilibrium; networks

1. Introduction

The World Health Organization (WHO) declared the Covid-19 pandemic on March 11, 2020 (WHO, 2020a). The ensuing global healthcare disaster has endangered and disrupted the lives of billions around the world, resulting in illnesses and deaths, and has also generated secondary crises. No one knows with certainty when the pandemic will end. According to Johns Hopkins

*Corresponding author.

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Contributions in Our Paper

1. An international human migration network model is constructed, which allows for route choices by the migrants, which are refugees.

2. The routes consist of one or more links, with cost functions that capture congestion, a factor that has been seen in practice.

3. The model is then extended to include regulations that can be imposed by distinct multiple countries. In previous work (cf. Nagurney and Daniele (2020)), it was assumed that a single country imposes the regulations on migrants.

4. A supernetwork transformation into a traffic network equilibrium problem with fixed demands is constructed. This identification enables the transfer of algorithmic schemes for the TNE problem, which has had a long history, to the novel application domain of refugee/migration networks.

5. Theoretical results are presented plus an algorithm.

6. Numerical examples reveal insights for policy-makers and decision-makers.

The Multiclass, Multipath Refugee Migration Models

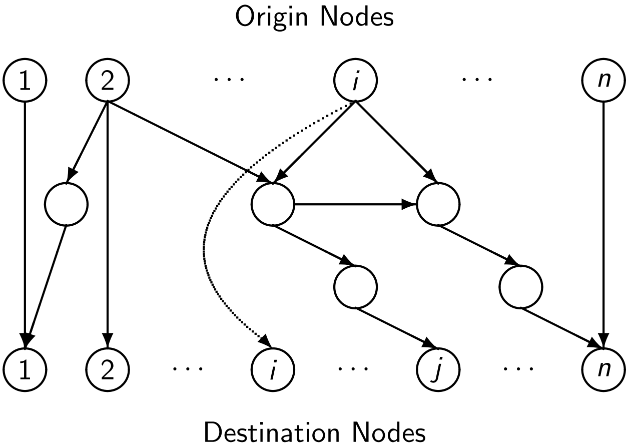


Figure: Sample Refugee Network Topology

Some Notation

Table: Common Notation for the Refugee Migration Models

Notation	Definition
x_r^k	flow of refugees of class k on route/path r. The $\{x_r^k\}$ elements are grouped into vector $x^k \in R_+^{n_P}$, where n_P denotes the number of paths in the migration network. We further group the x^k vectors; $k = 1, \ldots, J$, into vector $x \in R_+^{Jn_P}$.
f_a^k	flow of refugees of class k on link a. We group the link flows for class k for all links $a \in L$ into vector $f^k \in R^{n_L}$ where n_L is the number of links. We then group the link flows for all classes into vector $f \in R^{Jn_P}$.
p_i^k	nonnegative population of refugee class k at origin node i. We group the populations of class k; $k = 1, \ldots, J$, into vector $p^k \in R_+^n$. We further group all such vectors into vector $p \in R_+^{Jn}$.
$\bar{p}_i^k$	initial fixed population of class k at origin node i; $i = 1, \ldots, n$; $k = 1, \ldots, J$.
$u_i^k(p)$	utility perceived by refugee class k at node i; $i = 1, \ldots, n$; $k = 1, \ldots, J$. We group the utility functions for each k into vector $u^k \in R^n$ and then group all such vectors for all k into vector $u \in R^{Jn}$.
$c_a^k(f)$	migration cost associated with traversing link a by refugees of class k. Here we interpret the migration cost as a travel cost. We group link costs for each k into vector $c^k \in R^{n_L}$ and then group all such vectors into vector $c \in R^{Jn_L}$.
$C_r^k(x)$	cost of migration, that is, the travel cost, encumbered by class k in migrating on route r associated with an O/D pair w_{ij}; $i, j = 1, \ldots, n$; $k = 1, \ldots, J$.

Conservation of Flow

Since the route flows must be nonnegative, we have that

$$x_r^k \geq 0, \quad \forall r \in P, \forall k. \tag{1}$$

Furthermore, the refugee flows out of an origin node i must satisfy:

$$\bar{p}_i^k = \sum_{j=1}^{n} \sum_{r \in P_{w_{ij}}} x_r^k, \quad \forall i, \forall k. \tag{2}$$

The volume of population of each class k at each destination node j, after migration takes place, must satisfy the following equation:

$$p_j^k = \sum_{i=1}^{n} \sum_{r \in P_{w_{ij}}} x_r^k, \quad \forall j, \forall k. \tag{3}$$

The link flows are related to the route flows according to:

$$f_a^k = \sum_{r \in P} x_r^k \delta_{ar}, \quad \forall a, \forall k, \tag{4}$$

where $\delta_{ar} = 1$, if link a is contained in route r and 0, otherwise.

Additional Constructs

In view of the conservation of flow equations (4), we may define link cost functions in route/path flows, such that $\hat{c}_a^k = \hat{c}_a^k(x) \equiv c_a^k(f)$, for all links a and for all classes of refugees k.

The cost on a route r is equal to the sum of costs on the links that make up the route, that is,

$$C_r^k(x) = \sum_{a \in L} \hat{c}_a^k(x)\delta_{ar}, \quad \forall k, \forall r. \tag{5}$$

We define the feasible set $K^1 \equiv \{(p, x) | x \geq 0, \text{ and (2) and (3) hold}\}$.

Equilibrium Conditions for the Multiclass, Multipath Refugee Migration Model without Regulations

Definition 1: Multiclass, Multipath Refugee Migration Equilibrium without Regulations

A vector of populations and refugee migration flows $(p^*, x^*) \in K^1$ *is in equilibrium if it satisfies the following conditions: For each class* k*;* $k = 1, \ldots, J$*, and each pair of origin/destination nodes* i, j*;* $i, j = 1, \ldots, n$*, and all routes* $r \in P_{w_{ij}}$ *we have that*

$$u_i^k(p^*) + C_r^k(x^*) \begin{cases} = u_j^k(p^*) - \lambda_i^{k*}, & \text{if} \quad x_r^{k*} > 0, \\ \geq u_j^k(p^*) - \lambda_i^{k*}, & \text{if} \quad x_r^{k*} = 0, \end{cases} \tag{6}$$

and

$$\lambda_i^{k*} \begin{cases} \geq 0, & \text{if} \quad \sum_{j=1}^{n} \sum_{r \in P_{w_{ij}}, j \neq i} x_r^{k*} = \bar{p}_i^k, \\ = 0, & \text{if} \quad \sum_{j=1}^{n} \sum_{r \in P_{w_{ij}}, j \neq i} x_r^{k*} < \bar{p}_i^k. \end{cases} \tag{7}$$

Variational Inequality Formulations

Theorem 1: Variational Inequality Formulation of the Refugee Migration Model without Regulations in Path Flows

A population and refugee flow pattern $(p^*, x^*) \in K^1$ is a refugee migration equilibrium without regulations according to Definition 1, if and only if it satisfies the variational inequality problem in path flows

$$-\langle u(p^*), p - p^* \rangle + \langle C(x^*), x - x^* \rangle \geq 0, \quad \forall (p, x) \in K^1, \tag{8}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in the appropriately dimensioned Euclidean space.

Existence of a solution follows from the standard theory of variational inequalities (see Kinderlehrer and Stampacchia (1980) Theorem 3.1) under the assumption of continuity of the utility functions u and the migration cost functions c, since the feasible convex set K^1 is compact.

Variational Inequality Formulations

Alternative variational inequality formulations can induce distinct algorithmic schemes. Hence, for completeness, we now provide a link flow variational inequality formulation equivalent to the path flow one in (8). We first define the feasible set $K^2 \equiv \{(p,f) | \exists x \text{ such that } (1)-(4) \text{ hold}\}$.

Corollary 1: Variational Inequality Formulation of the Refugee Migration Model without Regulations in Link Flows

A population and refugee link flow pattern $(p^*, f^*) \in K^2$ is a refugee migration equilibrium without regulations according to Definition 1, if and only if it satisfies the variational inequality problem in link flows

$$-\langle u(p^*), p - p^* \rangle + \langle c(f^*), f - f^* \rangle \geq 0, \quad \forall (p,f) \in K^2. \tag{9}$$

Variational Inequality Formulation of the Refugee Migration Model with Regulations

We denote a specific country by h, where $h = 1, \dots, H$ and define the set O^h consisting of origin nodes of refugees from countries/locations that the country h imposes a regulation on, and let D^h denote the set of destination nodes, which lie in country h. C^h denotes the set of refugee classes that country h imposes the regulations on and U^h is the nonnegative upper bound imposed by country h on refugee migratory flows.

The constraints can then be stated as follows:

$$\sum_{i \in O^h} \sum_{j \in D^h} \sum_{k \in C^h} \sum_{r \in P_{w_{ij}}} x_r^k \leq U^h, \quad h = 1, \dots, H. \tag{10}$$

The set of constraints (10) is sufficiently general to capture specific, distinct migration regulations in practice. such as: an upper bound (which may be zero) of all classes from a certain country or countries; or an upper bound on a single class or several classes from a specific country or countries.

Variational Inequality Formulation of the Refugee Migration Model with Regulations

For the refugee migration model with regulations, the equilibrium conditions (6) and (7) are still relevant but with a new feasible set K^3 defined as below to include the constraints (10):

$$K^3 \equiv K^1 \cap \{x | (10) \text{ is satisfied}\}. \tag{11}$$

Theorem 2: Variational Inequality Formulation of the Refugee Migration Model with Regulations in Path Flows

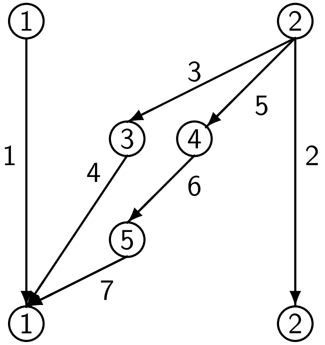
A population and refugee migration flow pattern $(p^*, x^*) \in K^3$ is a refugee migration equilibrium with regulations in path flows, if and only if it satisfies the variational inequality problem

$$-\langle u(p^*), p - p^* \rangle + \langle C(x^*), x - x^* \rangle \geq 0, \quad \forall (p, x) \in K^3. \tag{12}$$

Illustrative Examples

According to the network in the Figure below, refugees residing in country 1 are not interested in migrating to country 2. On the other hand, refugees residing in country 2 are interested in the possibility of migrating to country 1. There are two available paths joining country 2 with country 1.

Origin Nodes



Destination Nodes

Illustrative Example - No Regulation

The routes are comprised of links and are enumerated as follows:

$$r_1 = (1), \quad r_2 = (2), \quad r_3 = (3, 4), \quad r_4 = (5, 6, 7).$$

We consider a single class of migrant. Hence, we suppress the superscript 1 in the notation. The data are: $\bar{p}_1 = 100$ and $\bar{p}_2 = 200$ with the utility functions: $u_1(p) = -p_1 + 1000$ and $u_2(p) = -p_2 + 500$.

The link migration cost functions are:

$$c_1 = c_2 = 0,$$

$$c_3(f) = f_3 + 200, \quad c_4(f) = f_4 + 100,$$

$$c_5(f) = f_5 + 30, \quad c_6(f) = .5f_6 + 40, \quad c_7(f) = f_7 + 30.$$

We first consider the case without regulations. It is easy to compute the equilibrium solution, using simple algebra. Indeed, we find that:

$$x^*_{r_1} = 100, \quad x^*_{r_2} = 75, \quad x^*_{r_3} = 25, \quad x^*_{r_4} = 100;$$

hence,

$$p^*_1 = 225, \quad p^*_2 = 75,$$

with associated utilities being:

$$\hat{u}_1(x^*) = u_1(p^*) = 775, \quad \hat{u}_2(x^*) = u_2(p^*) = 425,$$

and the incurred migration costs on the routes at equilibrium: $C_{r_1} = 0$, $C_{r_2} = 0$, $C_{r_3} = C_{r_4} = 350$. Moreover, $\lambda^*_1 = \lambda^*_2 = 0$.

It is clear that the equilibrium conditions (6) and (7) hold.

Illustrative Example - No Regulation

Observe that, initially, before the refugee migration takes place, $u_1(\bar{p}_1) = 900$ and $u_2(\bar{p}_2) = 300$.

Once equilibrium is achieved, those who have migrated from country 2 to country 1 more than double their utility (from 300 to 775), whereas those who remain in country 2 experience a gain in utility of over 33% (from 300 to 425).

Those in country 1, because of the increase in the number of refugees and that they are not migrating, suffer a reduction in utility of approximately 14% (from 900 to 775).

Illustrative Example with Regulation

We now suppose that a regulation is imposed on destination node 1 by country 1 of the following form:

$$x_{r_3} + x_{r_4} \leq U^1 = 25.$$

The new equilibrium solution is:

$$x^*_{r_1} = 100, \quad x^*_{r_2} = 175, \quad x^*_{r_3} = 0, \quad x^*_{r_4} = 25;$$

hence,

$$p^*_1 = 125, \quad p^*_2 = 175,$$

with associated utilities being:

$$\hat{u}_1(x^*) = u_1(p^*) = 875, \quad \hat{u}_2(x^*) = u_2(p^*) = 325,$$

and the migration costs on the routes: $C_{r_1} = 0$, $C_{r_2} = 0$, $C_{r_3} = 300$, $C_{r_4} = 162.50$. Moreover, $\lambda^*_1 = \lambda^*_2 = 0$. The optimal Lagrange multiplier associated with the regulation constraint is: $\mu^*_1 = 387.50$. One can see that route r_3 is too expensive and will not be used under the refugee migratory flow pattern.

Illustrative Example with Regulation

Now, refugees in country 1, at equilibrium, enjoy a higher utility of 875 than before the regulation was imposed (775), an increase of about 13%.

On the other hand, refugees in country 2 now experience a lower utility (325), than before the regulation was imposed (425), a drop of about 30%. They are no longer all free to migrate because of the imposed regulatory upper bound of 25 limiting the migration from country 2 to country 1.

Computation of Solutions to Larger Examples

Our numerical examples are inspired by the refugee flows from Mexico to the United States, an issue that has been receiving a lot of attention in the press.

The baseline network for the numerical examples is depicted in the next Figure.

We consider a single class of refugee.

Computation of Solutions to Larger Examples

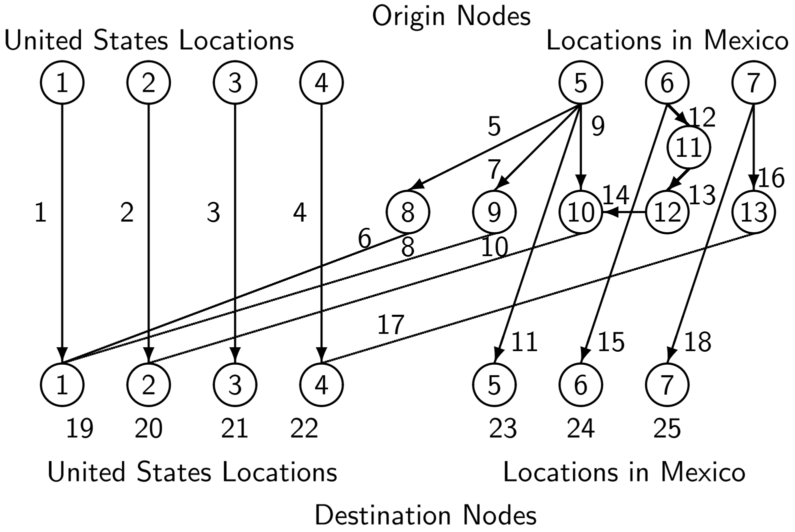


Figure: The Baseline Refugee Network Topology for the Larger Examples

Computation of Solutions to Larger Examples

We consider four examples: Example 1 through Example 4.

Example 1: No Regulations

The initial populations at the origin nodes are:

$$\bar{p}_1 = 1,400,000, \quad \bar{p}_2 = 20,000, \quad \bar{p}_3 = 70,000, \quad \bar{p}_4 = 260,000,$$

$$\bar{p}_5 = 50,000, \quad \bar{p}_6 = 225,000, \quad \bar{p}_7 = 30,000.$$

The utility functions associated with these locations are:

$$u_1(p) = -p_1 + 3,000,000, \; u_2(p) = -2p_2 + 200,000,$$

$$u_3(p) = -p_3 + 1,500,000, \; u_4(p) = 3p_4 + 900,000,$$

$$u_5(p) = -p_5 + 100,000, \; u_6(p) = -p_6 + 300,000,$$

$$u_7(p) = -p_7 + 100,000.$$

From the above utility functions, one can see that the locations in the United States are more attractive than those in Mexico, due to the significantly larger fixed utility term in the corresponding utility functions.

Computation of Solutions to Larger Examples

The link costs associated with remaining at one's location at nodes 1 through 7, respectively, are, all equal to 0.00:

$$c_1(f) = c_2(f) = c_3(f) = c_4(f) = c_{11}(f) = c_{15}(f) = c_{18}(f) = 0.00.$$

The costs associated with the refugee migrations are, in turn, as follows:

$$c_5(f) = .00006 f_5^4 + 6 f_5 + 4 f_6 + 200, \; c_6(f) = 7 f_6 + 3 f_8 + 300,$$

$$c_7(f) = .00008 f_7^4 + 8 f_7 + 2 f_8 + 400,$$

$$c_8(f) = .00004 f_8^4 + 5 f_8 + 2 f_{10} + 450, \; c_9(f) = .00001 f_9^4 + 6 f_9 + 2 f_{10} + 300,$$

$$c_{10}(f) = 4 f_{10} + f_{12} + 400,$$

$$c_{12}(f) = 8 f_{12} + 2 f_{13} + 100, \; c_{13}(f) = .00001 f_{13}^4 + 7 f_{13} + 3 f_9 + 50,$$

$$c_{14}(f) = 8 f_{14} + 3 f_9 + 100,$$

$$c_{16}(f) = 3 f_{16} + f_{12} + 100, \; c_{17}(f) = .00003 f_{17} + 3 f_{17} + 50.$$

The routes are enumerated as follows:

$$r_1 = (1), \quad r_2 = (2), \quad r_3 = (3), \quad r_4 = (4),$$

$$r_5 = (5,6), \quad r_6 = (7,8), \quad r_7 = (9,10), \quad r_8 = (11),$$

$$r_9 = (12,13,14,10), \quad r_{10} = (15),$$

$$r_{11} = (16,17), \quad r_{12} = (18).$$

For the solution of the problem, we first construct the supernetwork equivalence with the supernetwork topology as in the Figure and the O/D pairs, the links and paths, the link costs on the new links, the demands, and the path costs, defined accordingly.

Supernetwork Transformation of Examples

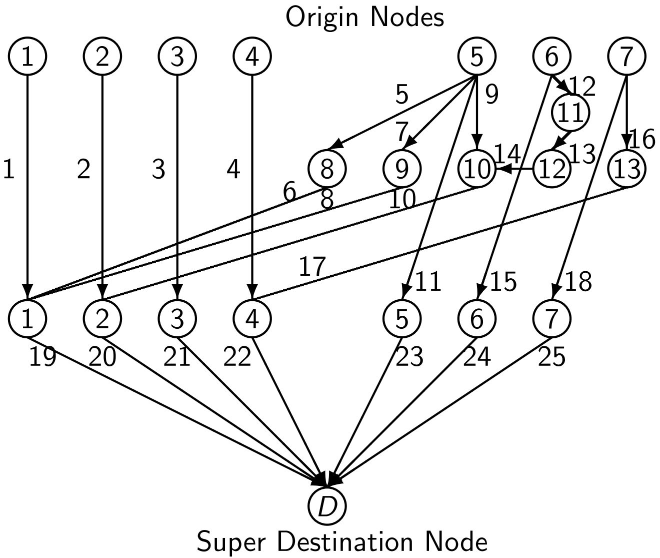


Figure: The Supernetwork Topology of the Examples

We implemented the Euler method, embedded with the exact equilibration algorithm as described in Nagurney and Zhang (1997); see also the book by Nagurney and Zhang (1996). We initialized the algorithm as follows. The initial populations were equally distributed among all the paths. The sequence $\{a_\tau\}$ in the Euler method satisfied the conditions required for convergence and was set to: $.1\{1, \frac{1}{2}, \frac{1}{2}, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}, \ldots\}$.

The algorithm was deemed to have converged if the absolute value of the difference between each successively computed path flow differed by no more than 10^{-7}. The computer system utilized was a Linux system at the University of Massachusetts Amherst.

Solution to Example 1

The computed equilibrium path flow pattern for Example 1 is:

$$x^*_{r_1} = 1,400,000.00, \; x^*_{r_2} = 20,000.00, \; x^*_{r_3} = 700,000.00,$$

$$x^*_{r_4} = 260,000.00, \; x^*_{r_5} = 400.25, \; x^*_{r_6} = 336.64, \; x^*_{r_7} = 317.17,$$

$$x^*_{r_8} = 48,945.95, \; x^*_{r_9} = 290.25, \; x^*_{r_{10}} = 224,709.75, \; x^*_{r_{11}} = 199.54,$$

$$x^*_{r_{12}} = 29,800.46.$$

The computed equilibrium populations at the four locations in the United States and at the three locations in Mexico are:

$$p^*_1 = 1,400,736.88, \quad p^*_2 = 20,607.42, \quad p^*_3 = 700,000.00,$$

$$p^*_4 = 260,199.55, \; p^*_5 = 48,945.95, \; p^*_6 = 224,709.75, \; p^*_7 = 29,800.46.$$

Solution to Example 1

The associated incurred utilities at the equilibrium at the locations are:

$$u_1(p^*) = 1,599,263.13, \; u_2(p^*) = 158,785.17, \; u_3(p^*) = 800,000.00,$$

$$u_4(p^*) = 119,401.38, \; u_5(p^*) = 51,054.05, \; u_6(p^*) = 75,290.25,$$

$$u_7(p^*) = 70,199.55.$$

We also, for completeness, report the path costs at the computed equilibrium flows since it is easy to then verify that the equilibrium conditions, as stated in Definition 1, hold. Specifically, the incurred path costs at the equilibrium are:

$$C_{r_1}(x^*) = C_{r_2}(x^*) = C_{r_3}(x^*) = C_{r_4}(x^*) = 0.00,$$

$$C_{r_5}(x^*) = 1,548,207.50, \; C_{r_6}(x^*) = 1,548,196.38, \; C_{r_7}(x^*) = 107,729.39,$$

$$C_{r_8}(x^*) = 0.00, \quad C_{r_9}(x^*) = 83,500.69, \quad C_{r_{10}}(x^*) = 0.00,$$

$$C_{r_{11}}(x^*) = 49,200.66, \quad C_{r_{12}}(x^*) = 0.00.$$

Solutions to Examples 1 Through 4

Examples 2 through 4 are analogues of Example 1, but with regulations.

• In Example 2, we considered the following scenario: The US government has told the Mexican government that it is restricting the flow on route $r_5 = (5, 6)$ to zero; essentially resulting in the elimination of this path, since its processing facilities are experiencing delays due to congestion. The rest of the data remain as in Example 1.

• In Example 3, we studied the following scenario: Route $r_6 = (7, 8)$ is now unavailable to refugees, but the other routes and data remain as in Example 1.

• And, in Example 4, we investigate the scenario that the United States is concerned about the influx of refugees and both routes r_5 and r_6 from Mexico are, in effect, banned/eliminated.

Solutions to Examples 1 Through 4

In order to enable cross comparisons with the examples with regulations and with the baseline Example 1, in the following Tables, we report, respectively, the associated computed equilibrium populations, whereas the incurred utilities at the locations are reported in the final Table.

Solutions to Examples 1 Through 4

Node	Equilibrium Populations			
	Example 1	Example 2	Example 3	Example 4
1	1,400,736.88	1,400,336.63	1,400,400.38	1,400,000.00
2	20,607.42	20,607.72	20,607.67	20,607.67
3	700,000.00	700,000.00	700,000.00	700,000.00
4	260,199.55	260,199.55	260,199.55	260,199.55
5	48,945.95	49,345.84	49,282.21	49,682.27
6	224,709.75	224,709.75	224,709.75	224,709.75
7	29,800.46	224,709.75	224,709.75	29,800.46

Solutions to Examples 1 Through 4

Node	Utility at Equilibrium			
	Example 1	**Example 2**	**Example 3**	**Example 4**
1	1,599,263.13	1,599.663.38	1,599,599.63	1,600,000.00
2	158,785.17	158,784.56	158,784.66	158,784.00
3	800,000.00	800,000.00	800,000.00	800,000.00
4	119,401.38	119,401.38	119,401.38	119,401.38
5	51,054.05	50,654.16	50,717.79	50,317.73
6	75,290.25	75,290.25	75,290.25	75,290.25
7	70,199.55	70,199.55	70,199.55	70,199.55

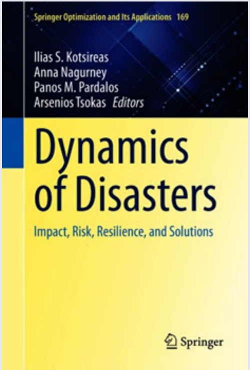
Insights

One can see, from the preceding Table, that (as occurred also in the illustrative examples), under the regulations (as in Examples 2 through 4), the utility of those subject to regulations, as for those in node 5, is reduced.

On the other hand, those in location 1, which now has a lower flow of refugees, experience a higher utility.

Also, with both refugee routes blocked to the US, the population that remains at node 5 is the highest in Example 4, as compared to the value in Examples 2 and 3.

Some Additional Research



In our edited volume, we have a paper with Daniele and Cappello, "Capacitated Human Migration Networks and Subsidization."

This work demonstrates that one can make system-optimized solutions for human migration sustainable through the imposition of subsidies at locations - in this way, migrants' user-optimizing behavior with also be system-optimizing.

Migrant Labor to Alleviate Labor Shortages

A. Nagurney, “Attracting International Migrant Labor: Investment Optimization to Alleviate Supply Chain Labor,” *Operations Research Perspectives* **9 (2022), 100233.**

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Attracting international migrant labor: Investment optimization to alleviate supply chain labor shortages

Anna Nagurney

Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts, Amherst, MA 01003, United States of America

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ABSTRACT

The COVID-19 pandemic has disrupted supply chains globally with a major shortfall being that of labor shortages from production through distribution activities. In this paper, we construct a new supply chain network optimization model that includes both domestic labor and international migrant labor from multiple countries, with the latter made possible through investments in attracting labor subject to a budget constraint. We allow for different wage settings for domestic versus migrant labor and also have the flexibility of providing true information as to the wages of migrants or not. We derive variational inequality formulations of the model, along with qualitative properties, and present an algorithm that yields closed form expressions for the underlying problem variables at each iteration. The model is one of the very few variational inequality operations research models with nonlinear constraints. Three series of algorithmically solved numerical examples, motivated by a high value agricultural product — that of truffles, demonstrate the insights in terms of profits, prices, product path flows, and investments, with variations in the data including that of truthful and untruthful wages being used to attract migrant labor.

1. Introduction

The COVID-19 pandemic has demonstrated the importance of supply chains and their effective and efficient operation, with disruptions adversely affecting product prices and deliveries, as well as the prosperity of companies and the health and well-being of consumers [1]. The reasons for the disruptions have been multifaceted with shocks both on the demand side as well as on the supply side and challenges associated with transport [2–6]. One of the major characteristics of the pandemic has been that of labor shortages. Workers throughout the pandemic have been falling ill; some, sadly, have lost their lives, whereas others chose to switch jobs or to leave the labor force [7]. Furthermore, various countries imposed restrictions further impeding the flow of workers [8]. Even with vaccinations continuing, the challenges of ameliorating labor shortages throughout many supply chains remain [9]. Employers have had difficulties recruiting workers not only with advanced technical skills. but also those with low and middle level skills. Countries are increasingly looking towards immigration policy to mitigate the labor shortage crises (see [10,11] with the new variant Omicron adding to the complexities [12]. Attracting workers from other countries, who are known as international migrant laborers, may assist in alleviating labor shortages.

According to [13], noting the most recent estimate by the International Labour Organization, there are 164 million migrant laborers globally and, in many countries, they are a major proportion of the workforce, with contributions to economies both where they work and in terms of remittances to their countries of origins. Nevertheless, many migrant workers face inequality in terms of a wage gap (being paid less that the workers from the particular nation) among other discriminatory practices [14]. For example, migrant laborers in High Income Countries (HICs) earn, on the average, approximately 12.6% less than nationals, with the wages earned by migrants widening over the past 6 years or so in many HICs (see [13]). Furthermore, migrant laborers are among the most negatively affected workers by the economic recession due to the COVID-19 pandemic, in terms of job losses and a decrease in earnings for those who have been able to stay employed. This is happening despite the fact that the United Nations' Sustainable Development Goals (SDGs), in the framework of the UN agenda for 2030, have as their targets 8.5 and 8.8: having equal pay for work of equal value and protected labor rights for all workers, including migrant workers [13,15].

This paper aims to integrate and advance two streams of literature, which have received significant attention in the pandemic: that of

E-mail address: nagurney@isenberg.umass.edu.

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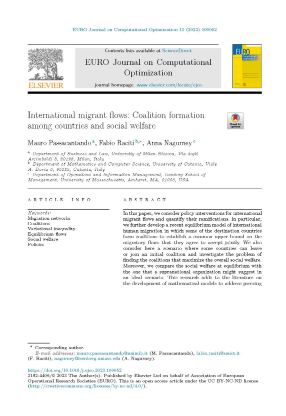
Coaltion Formation Among Countries

M. Passacantando, F. Raciti, and A. Nagurney, "International Migrant Flows: Coalition Formation Among Countries and Social Welfare," *EURO Journal on Computational Optimization* **11 (2023), 100062.**


EURO Journal on Computational Optimization 11 (2023) 100062

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International migrant flows: Coalition formation among countries and social welfare

Mauro Passacantando[a], Fabio Raciti[b,*], Anna Nagurney[c]

[a] *Department of Business and Law, University of Milan-Bicocca, Via degli Arcimboldi 8, 20126, Milan, Italy*
[b] *Department of Mathematics and Computer Science, University of Catania, Viale A. Doria 6, 95125, Catania, Italy*
[c] *Department of Operations and Information Management, Isenberg School of Management, University of Massachusetts, Amherst, MA, 01003, USA*

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ABSTRACT

In this paper, we consider policy interventions for international migrant flows and quantify their ramifications. In particular, we further develop a recent equilibrium model of international human migration in which some of the destination countries form coalitions to establish a common upper bound on the migratory flows that they agree to accept jointly. We also consider here a scenario where some countries can leave or join an initial coalition and investigate the problem of finding the coalitions that maximize the overall social welfare. Moreover, we compare the social welfare at equilibrium with the one that a supranational organization might suggest in an ideal scenario. This research adds to the literature on the development of mathematical models to address pressing

* Corresponding author.
E-mail addresses: mauro.passacantando@unimib.it (M. Passacantando), fabio.raciti@unict.it (F. Raciti), nagurney@isenberg.umass.edu (A. Nagurney).

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Summary and Conclusions

Summary and Conclusions

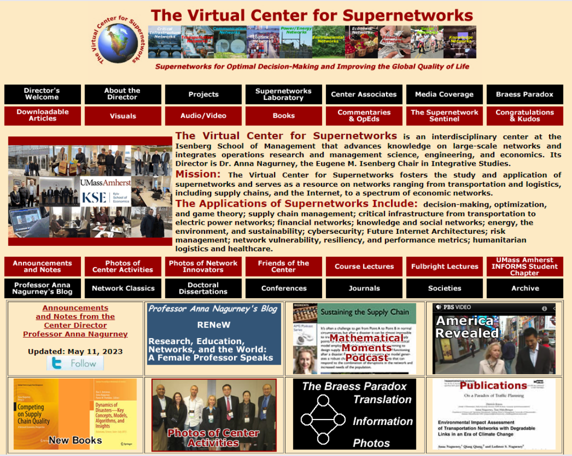
- **In this presentation, I have highlighted some of our Operations Research contributions to address societal issues of human migration networks in the context of refugees as well related issues.**

- **The work is inspired by the need to include "people" in various network systems including supply chain networks.**

- **The world has benefited greatly from the developments in our profession of models, methodologies, associated insights, and relevance to both practice and policy making.**

- **Together we can continue to accomplish what needs to be done in these challenging times.**

Thank You Very Much!



More information on our work can be found on the Supernetwork Center site: https://supernet.isenberg.umass.edu/