Attracting International Migrant Labor: Investment Optimization to Alleviate Supply Chain Labor Shortages

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Dedication

This talk is dedicated to essential workers, who have sustained us in the COVID-19 pandemic.

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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

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Outline of Presentation

- **Background and Motivation**
- **Addition to the Literature**
- **The Model**
- **The Algorithm**
- **Numerical Examples**
- **Summary and Conclusions**

Background and Motivation

Background and Motivation

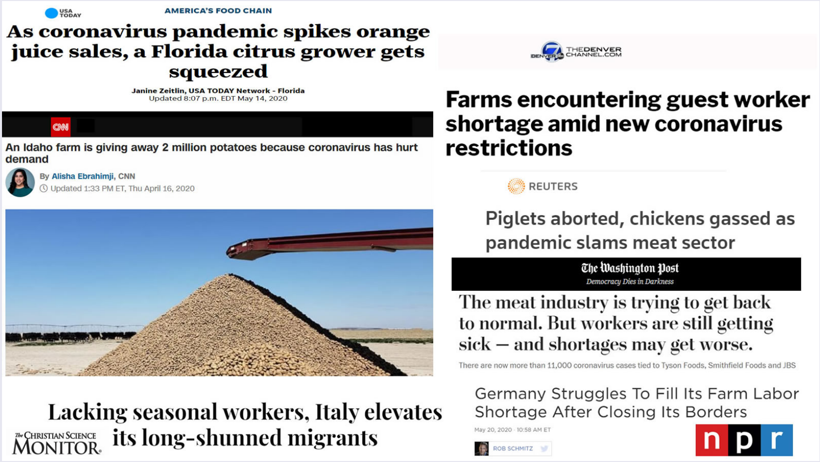
The COVID-19 pandemic has demonstrated the importance of supply chains and their effective and efficient operation. The reasons for disruptions have been multifaceted with shocks both on the demand side as well as on the supply side and challenges associated with transport.

A major characteristic 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.

Various countries imposed restrictions further impeding the flow of workers.

Background and Motivation

Employers have had difficulties recruiting workers not only with advanced technical skills but also those with low and middle level skills.



There are 164 million migrant laborers globally and, in many countries, they are a major proportion of the workforce. Many migrant workers face inequality in terms of a wage gap among other discriminatory practices.

Countries are increasingly looking towards immigration policy to mitigate the labor shortage crises with the new variant Omicron adding to the complexities.

Migrant laborers are among the most negatively affected workers by the economic recession due to the COVID-19 pandemic.

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.

Addition to the Literature

Addition to the Literature

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

• that of incorporating labor into supply chain network modeling, analysis, and computations (see Nagurney (2021a, b, c, d), (2022)) and

• problems of human migration, which have been exacerbated under COVID-19 (cf. Nagurney, Daniele, and Nagurney (2020), Cappello, Daniele, and Nagurney (2021), Nagurney, Daniele, and Cappello (2021a,b)).

Addition to the Literature

- **A supply chain network optimization model is constructed that captures the profit-maximizing behavior of a firm with respect to its supply chain network activities of production at multiple sites, the transport of the product to multiple storage sites, the storage at these facilities, and, finally, the ultimate distribution of the product to multiple points of demand.**

- **Associated with each of the supply chain network activities is a bound on domestic labor availability with possible investment in labor migration from other countries to attract workers.**

- **The migrants are responsive to the wages that they are told they will be paid for the respective supply chain network activities, as well as to the investments made.**

Addition to the Literature

In terms of the investigation of different wage scenarios, the model allows for the quantification of the impacts of:

1. paying international migrants the same wages for corresponding activities as the domestic workers are paid, under the scenario that the international migrant laborers are informed honestly of the wages that they will be paid;

2. paying international migrants less than the domestic workers are paid, but they are informed of this honestly before they migrate for work or

3. paying the international migrants less than the domestic workers but being dishonest as to what wages they will receive in order to attract them.

Addition to the Literature

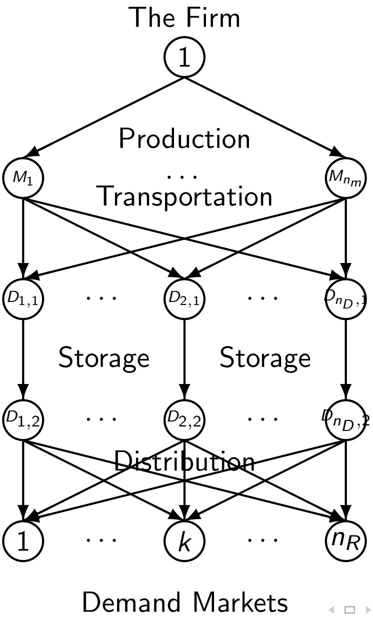
4. The model can handle different wages for national/domestic labor and for international migrant labor. The model can also evaluate impacts of truthful versus untruthful wage information provided to potential international migrants, as implemented in the attraction functions.

5. The theoretical framework is that of variational inequalities and this work is one of the very few that includes nonlinear constraints in the model and these can arise due to the form that the international migrant attraction functions take.

6. The solution of a series of numerical examples, inspired by a high value agricultural product - that of truffles, having a variety of the above features, via the proposed algorithm with nice features for implementation, yields interesting insights.

The Model

The Model - The Supply Chain Network Topology



The Model Notation - Parameters

w_a^1	hourly wage for a unit of labor on link a paid to domestic workers, $\forall a \in L$.
w_a^2	hourly wage for a unit of labor on link a paid to international migrant workers, $\forall a \in L$.
$\tilde{w}_a^j$	hourly wage for a unit of labor on link a that international migrant workers are told they will be paid, $\forall a \in L$, for all countries $j = 1, \ldots, J$.
α_a	the link productivity on link a, $\forall a \in L$, which maps labor hours into product flow.
δ_{ap}	indicator taking on the value 1 if link a is contained in path p and 0, otherwise.
$\bar{l}_a^1$	the maximum available domestic labor hours locally for work associated with link a, $a \in L$.
B	the amount of financing in the budget for investments in attracting migrant labor from different countries.

The Model Notation - Variables

d_k	demand for the product at demand market k; $k = 1, \ldots, n_R$. Group demands into vector $d \in R_+^{n_R}$.
x_p	product flow on path p, $\forall p \in P$. Group path flows into vector $x \in R_+^{n_P}$
f_a	product flow on link a, $\forall a \in L$. Group link flows into vector $f \in R_+^{n_L}$.
l_a^1	hours of domestic labor available for link a supply chain activity, $\forall a$.
l_a^2	hours of international migrant labor available for link a, $\forall a \in L$.
v_a^j	investment in attracting migrant labor from country j; $j = 1, \ldots, J$ for link a, $\forall a \in L$. Investments in attracting labor are grouped into vector $v \in R_+^{Jn_L}$.
η	nonnegative Lagrange multiplier associated with budget constraint.
λ_a	nonnegative Lagrange multiplier associated with bound on domestic labor hours on link a. Group Lagrange multipliers into vector $\lambda \in R_+^{n_L}$.
δ_a^1	nonnegative Lagrange multiplier associated with constraint guaranteeing that l_a^1 is nonnegative on link a. Group these Lagrange multipliers into vector $\delta^1 \in R_+^{n_L}$.
δ_a^2	nonnegative Lagrange multiplier associated with constraint guaranteeing that l_a^2 is nonnegative on link a. Group these Lagrange multipliers into vector $\delta^2 \in R_+^{n_L}$.

Conservation of Flow Equations

The sum of the product path flows to each demand market must be equal to the demand at the demand market:

$$\sum_{p \in P_k} x_p = d_k, \quad k = 1, \ldots, n_R, \tag{1}$$

with all the path flows being nonnegative:

$$x_p \geq 0, \quad \forall p \in P. \tag{2}$$

The amount of product flow on each link must be equal to the sum of product flows on paths that contain that link:

$$f_a = \sum_{p \in P} x_p \delta_{ap}, \quad \forall a \in L. \tag{3}$$

The Model

Labor Constraints

Liinear production functions are assumed, as in prior work, but extended to differentiate between domestic and international migrant labor:

$$f_a = \alpha_a(l_a^1 + l_a^2), \quad \forall a \in L. \tag{4}$$

Domestic worker labor hours available cannot exceed the bound on domestic labor hours of availability:

$$l_a^1 \leq \bar{l}_a^1, \quad \forall a \in L. \tag{5a}$$

The domestic labor hours available are nonnegative:

$$l_a^1 \geq 0, \quad \forall a \in L. \tag{5b}$$

Amount of international migrant labor hours available for a link a:

$$l_a^2 = \sum_{j=1}^{J} g_a^j(\tilde{w}_a^j, v_a^j), \quad \forall a \in L, \tag{6a}$$

$$l_a^2 \geq 0, \quad \forall a \in L. \tag{6b}$$

Constraints on Investments

The investments by the firm in attracting international migrant labor must be nonnegative:

$$v_a^j \geq 0, \quad j = 1, \ldots, J; \forall a \in L. \tag{7}$$

Finally, the firm's budget constraint in terms of attracting migrants is:

$$\sum_{j=1}^{J} \sum_{a \in L} v_a^j \leq B. \tag{8}$$

The Optimization Problem

The optimization problem faced by the firm in optimizing its supply chain network can now be stated. The firm seeks to maximize its objective function, denoted by U, which represents its profits, subject to the constraints (1) – (8):

$$\text{Maximize } U = \sum_{k=1}^{n_R} \rho_k(d) d_k - \sum_{a \in L} \hat{c}_a(f) - \sum_{j=1}^{J} \sum_{a \in L} v_a^j - \sum_{a \in L} (w_a^1 l_a^1 + w_a^2 l_a^2). \tag{9}$$

The demand price functions are assumed to be monotone decreasing and each $\rho_k(d) d_k$ is concave for each k, and that the total operational link cost functions are convex with both the demand price functions and the operational cost functions being continuously differentiable. The investment functions $g_a^j(\tilde{w}_a^j, v_a^j)$ are assumed all concave, which is reasonable, and continuously differentiable.

In lieu of (1), we can define demand price functions $\tilde{\rho}_k(x) \equiv \rho_k(d)$, for $k = 1, \ldots, n_R$, and, in lieu of (3), we can define link operational total cost functions $\tilde{c}_a(x) \equiv \hat{c}_a(f)$, for $a \in L$. Using (4) and (6):

$$l_a^1 = \frac{\sum_{p \in P} x_p \delta_{ap}}{\alpha_a} - \sum_{j=1}^{J} g_a^j(\tilde{w}_a^j, v_a^j), \quad \forall a \in L. \tag{10}$$

The firm's optimization problem (9) can be expressed as:

$$\text{Maximize} \quad \tilde{U}(x, v) = \sum_{k=1}^{n_R} \tilde{\rho}_k(x) \sum_{p \in P_k} x_p - \sum_{a \in L} \tilde{c}_a(x) - \sum_{j=1}^{J} \sum_{a \in L} v_a^j$$

$$- \sum_{a \in L} w_a^1 \left(\frac{\sum_{p \in P} x_p \delta_{ap}}{\alpha_a}\right) + \sum_{a \in L} (w_a^1 - w_a^2) \sum_{j=1}^{J} g_a^j(\tilde{w}_a^j, v_a^j), \tag{11}$$

subject to:

$$\frac{\sum_{p\in P} x_p \delta_{ap}}{\alpha_a} - \sum_{j=1}^{J} g_a^j(\tilde{w}_a, v_a^j) \leq \bar{l}_a^1, \quad \forall a \in L, \tag{12a}$$

$$\frac{\sum_{p\in P} x_p \delta_{ap}}{\alpha_a} - \sum_{j=1}^{J} g_a^j(\tilde{w}_a, v_a^j) \geq 0, \quad \forall a \in L, \tag{12b}$$

$$\sum_{j=1}^{J} g_a^j(\tilde{w}_a, v_a^j) \geq 0, \quad \forall a \in L, \tag{13}$$

$$\sum_{j=1}^{J} \sum_{a\in L} v_a^j \leq B, \tag{14}$$

$$x_p \geq 0, \quad \forall p \in P, \tag{15}$$

$$v_a^j \geq 0, \quad j = 1, \ldots, j; \forall a \in L. \tag{16}$$

The Variational Inequality Formulations

$K^1 \equiv \{(x,v) \in R_+^{n_P + Jn_L}$ satisfying $(12a,b) - (14)\}$. It follows from the classical theory of variational inequalities that the optimal solution $(x^*,v^*) \in K^1$ satisfies the variational inequality problem:

$$-\sum_{p \in P} \frac{\partial \tilde{U}(x^*,v^*)}{\partial x_p} \times (x_p - x_p^*) - \sum_{j=1}^{J} \sum_{a \in L} \frac{\partial \tilde{U}(x^*,v^*)}{\partial v_a^j} \times (v_a^j - v_a^{j*}) \geq 0,$$

$$\forall (x,v) \in K^1, \qquad (17)$$

or: Determine $(x^*,v^*) \in K^1$, such that

$$\sum_{k=1}^{n_R} \sum_{p \in P_k} \left[\frac{\partial \tilde{C}_p(x^*)}{\partial x_p} + \sum_{a \in L} \frac{w_a^1}{\alpha_a} \delta_{ap} - \tilde{\rho}_k(x^*) - \sum_{l=1}^{n_R} \frac{\partial \tilde{\rho}_l(x^*)}{\partial x_p} \sum_{q \in P_l} x_q^* \right] \times \left[x_p - x_p^* \right]$$

$$+ \sum_{j=1}^{J} \sum_{a \in L} \left[-(w_a^1 - w_a^2) \frac{\partial g_a^j(\tilde{w}_a^j, v_a^{j*})}{\partial v_a^j} + 1 \right] \times \left[v_a^j - v_a^{j*} \right] \geq 0, \ \forall (x,v) \in K^1,$$

$$(18)$$

$$\frac{\partial \tilde{C}_p(x)}{\partial x_p} \equiv \sum_{a \in L} \sum_{b \in L} \frac{\partial \hat{c}_b(f)}{\partial f_a} \delta_{ap}, \ \forall p, \ \frac{\partial \tilde{\rho}_l(x)}{\partial x_p} \equiv \frac{\partial \rho_l(d)}{\partial d_k}, \forall p \in P_k, \forall k. \quad (19)$$

A solution $(x^*, v^*) \in K^1$ to both variational inequalities (17) and (18) exists since the feasible set K^1 is compact and the underlying functions, under our imposed assumptions, are continuous.

The equivalent variational inequality to the one in (18) is: Determine $(x^*, \lambda^*, v^*, \eta^*, \delta^{1*}, \delta^{2*}) \in K^2$, where $K^2 \equiv \{(x, \lambda, v, \eta, \delta^1, \delta^2) | (x, \lambda, v, \eta, \delta^1, \delta^2) \in R_+^{n_P + n_L + Jn_L + 1 + 2n_L}\}$, such that

$$\sum_{k=1}^{n_R} \sum_{p \in P_k} \left[\frac{\partial \tilde{C}_p(x^*)}{\partial x_p} + \sum_{a \in L} \frac{w_a^1}{\alpha_a} \delta_{ap} - \tilde{\rho}_k(x^*) - \sum_{l=1}^{n_R} \frac{\partial \tilde{\rho}_l(x^*)}{\partial x_p} \sum_{q \in P_l} x_q^* + \sum_{a \in L} \frac{\lambda_a^*}{\alpha_a} \delta_{ap} - \frac{\delta_a^{1*}}{\alpha_a} \delta_{ap} \right] \times \left[x_p - x_p^* \right]$$

$$+ \sum_{a \in L} \left[\bar{l}_a^1 - \frac{\sum_{p \in P} x_p^* \delta_{ap}}{\alpha_a} + \sum_{j=1}^{J} g_a^j(\tilde{w}_a^j, v_a^{j*}) \right] \times [\lambda_a - \lambda_a^*]$$

$$+ \sum_{j=1}^{J} \sum_{a \in L} \left[1 + \eta^* - (w_a^1 - w_a^2 + \lambda_a^* - \delta_a^{1*} + \delta_a^{2*}) \frac{\partial g_a^j(\tilde{w}_a^j, v_a^{j*})}{\partial v_a^j} \right] \times \left[v_a^j - v_a^{j*} \right]$$

$$+ \left[B - \sum_{j=1}^{J} \sum_{a \in L} v_a^{j*} \right] \times [\eta - \eta^*]$$

$$+ \sum_{a \in L} \left[\frac{\sum_{p \in P} x_p^* \delta_{ap}}{\alpha_a} - \sum_{j=1}^{J} g_a^j(\tilde{w}_a^j, v_a^{j*}) \right] \times \left[\delta_a^1 - \delta_a^{1*} \right]$$

$$+ \sum_{a \in L} \left[\sum_{j=1}^{J} g_a^j(\tilde{w}_a^j, v_a^{j*}) \right] \times \left[\delta_a^2 - \delta_a^{2*} \right] \geq 0, \quad \forall (x, \lambda, v, \eta, \delta^1, \delta^2) \in K^2. \qquad (20)$$

The Variational Inequality Formulations

Standard Variational Inequality Form

Variational inequality (20) can be put into standard form (cf. Nagurney (1999)): Determine $X^* \in \mathcal{K}$ such that

$$\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K}, \tag{21}$$

where F is a given continuous function from $\mathcal{K}$ to $R^{\mathcal{N}}$, $\mathcal{K}$ is a given closed convex set, and $\langle \cdot, \cdot \rangle$ is the inner product in $\mathcal{N}$-dimensional Euclidean space.

The Algorithm

The Modified Projection Method

Step 0: Initialization

Initialize with $X^0 \in \mathcal{K}$. Set $\tau := 1$, where τ is the iteration counter, and let β be a scalar such that $0 < \beta \leq \frac{1}{\omega}$, where ω is the Lipschitz constant.

Step 1: Computation

Compute $\bar{X}^\tau$ satisfying the variational inequality subproblem:

$$\langle \bar{X}^\tau + \beta F(X^{\tau-1}) - X^{\tau-1}, X - \bar{X}^\tau \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{22}$$

Step 2: Adaptation

Compute X^τ satisfying the variational inequality subproblem:

$$\langle X^\tau + \beta F(\bar{X}^\tau) - X^{\tau-1}, X - X^\tau \rangle \geq 0, \quad \forall X \in \mathcal{K}. \tag{23}$$

Step 3: Convergence Verification

If $|X^\tau - X^{\tau-1}| \leq \epsilon$, with $\epsilon > 0$, a pre-specified tolerance, then terminate the algorithm; else, set $\tau := \tau + 1$ and go to Step 1.

Numerical Examples

Numerical Examples

The numerical examples are inspired by recent issues surrounding agricultural supply chains in the UK. The UK has been pummeled with shortfalls in labor due to COVID-19 as well as Brexit. The numerical examples are focused on a very interesting agricultural product, now being grown in the UK - truffles.

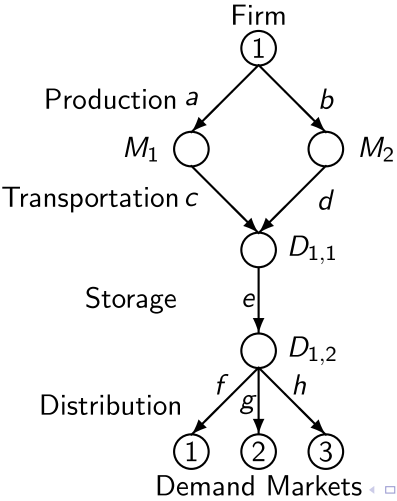
Numerical Examples

Truffles are a high value agricultural product, and are considered a delicacy, with challenges associated with production and harvesting.

In the Fall of 2021, due to a shortage, white truffle prices were about $4,500 a pound, whereas, in 2019, white truffle prices were in the range $1,100 to $1,200 a pound.

They are considered among the most expensive foods on the planet. The cost and price data, as well as the wages and the profits, in the numerical examples are in British pounds. The unit for the truffle product flows is a pound of weight. According to Elison (2021), vegetable pickers in the UK, due to shortages of labor are being paid 30 pounds an hour to pick the produce.

Example 1: Baseline Example: Migrant Workers Earn the Same Wage as Domestic Laborers and Migrants Are Told Their Truthful Wages in the Attraction Functions



The total operational link cost functions are:

$$\hat{c}_a(f) = 2.5f_a^2, \quad \hat{c}_b(f) = 2.5f_b^2, \quad \hat{c}_c(f) = .5f_c^2, \quad \hat{c}_d(f) = .5f_d^2,$$
$$\hat{c}_e(f) = f_e^2 + 2f_e, \quad \hat{c}_f(f) = .5f_f^2, \quad \hat{c}_g(f) = .5f_g^2, \quad \hat{c}_h(f) = .5f_h^2.$$

The demand price functions are:

$$\rho_1(d) = -5d_1 + 800, \quad \rho_2(d) = -5d_2 + 850, \quad \rho_3(d) = -5d_3 + 900.$$

The α link parameters are:

$$\alpha_a = .55, \quad \alpha_b = .50, \quad \alpha_c = .35, \quad \alpha_d = .35, \quad \alpha_e = .60, \quad \alpha_f = .38,$$

We assume that the supply chain firm considers a single country to obtain international migrants from, but the specific country can differ from supply chain network activity to activity. The international migrant attraction functions are of the form: $g_a(\tilde{w}_a, v_a) = \tilde{w}_a v_a - \gamma_a v_a^2$, for all links $a \in L$. These functions are concave. The γ parameters in these functions are:

$$\gamma_a = .2, \quad \gamma_b = .2, \quad \gamma_c = .4, \quad \gamma_d = .4, \quad \gamma_e = .3 \quad \gamma_f = .4, \quad \gamma_g = .4,$$

Series 1 Numerical Examples

The wages in Example 1 are:

$$w_a^1 = w_a^2 = \tilde{w}_a = 30, \quad w_b^1 = w_b^2 = \tilde{w}_b = 20,$$

$$w_c^1 = w_c^2 = \tilde{w}_c = 18, \quad w_d^1 = w_d^2 = \tilde{w}_d = 18,$$

$$w_e^1 = w_e^2 = \tilde{w}_e = 17, \quad w_f^1 = w_f^2 = \tilde{w}_f = 19,$$

$$w_g^1 = w_g^2 = \tilde{w}_g = 19, \quad w_h^1 = w_h^2 = \tilde{w}_h = 19.$$

The bounds on domestic labor are: $\bar{l}_a^1 = 100$, for all links in the supply chain from a through h and the budget $B = 1,000$.

Example 2: Domestic Workers Earn a Higher Wage at Production Sites than Migrants and Are Told Their Truthful Wages
Example 2 has the same data as that in Example 1, except that now the domestic workers earn a higher wage at the two production sites with $w_a^1 = 40$ and $w_b^1 = 30$.

Example 3: Domestic Workers Earn a Higher Wage at Production Sites than Migrants but Migrants Are Told Untruthfully That They Will Be Paid the Same Wage as the Domestic Workers In Example 3, we investigate the impact of the firm being untruthful. Specifically, the firm now tells the international migrant laborers that it will pay them the same (higher) wage at each production site that it is paying its domestic laborers, but it actually will pay them less. The data, hence, are exactly as in Example 2, but now we have that $\tilde{w}_a = 40$ and $\tilde{w}_b = 30$.

The firm earns a profit of: 41,453.10 in Example 1; a profit of 41,444.64 in Example 2, and a profit of 41,447.33 in Example 3. Observe that the profit now increases suggesting that, without oversight, "cheating can pay.".

Series 1 Numerical Examples

Notation	Optimal Value		
	Example 1	Example 2	Example 3
f_a^*	38.86	38.85	38.85
f_b^*	41.28	41.27	41.27
f_c^*	38.86	38.85	38.85
f_d^*	41.28	41.27	41.27
f_e^*	80.13	80.12	80.13
f_f^*	20.00	20.00	20.00
f_g^*	24.30	24.29	24.29
f_h^*	35.84	35.83	35.83
l_a^{1*}	70.65	0.00	0.00
l_b^{1*}	82.56	0.00	0.00
l_c^{1*}	100.00	100.00	100.00
l_d^{1*}	100.00	100.00	100.00
l_e^{1*}	100.00	100.00	100.00
l_f^{1*}	52.64	52.63	52.63
l_g^{1*}	67.49	67.48	67.48
l_h^{1*}	89.59	89.58	89.58
l_a^{2*}	0.00	70.64	70.64
l_b^{2*}	0.00	82.54	82.55
l_c^{2*}	11.01	11.01	11.01
l_d^{2*}	17.94	17.91	17.92
l_e^{2*}	33.56	33.54	33.54
l_f^{2*}	0.00	0.00	0.00
l_g^{2*}	0.00	0.00	0.00
l_h^{2*}	0.00	0.00	0.00

Table: Optimal Link Flows and Domestic and International Migrant Labor Values for Examples 1, 2, 3

Series 1 Numerical Examples

Notation	Optimal Value		
	Example 1	Example 2	Example 3
v_a^*	0.00	2.39	1.78
v_b^*	0.00	4.31	2.80
v_c^*	0.62	0.62	0.62
v_d^*	1.02	1.02	1.02
v_e^*	2.05	2.05	2.05
v_f^*	0.00	0.00	0.00
v_g^*	0.00	0.00	0.00
v_h^*	0.00	0.00	0.00
λ_a^*	0.00	0.00	0.00
λ_b^*	0.00	0.00	0.00
λ_c^*	0.06	0.06	0.06
λ_d^*	0.06	0.06	0.06
λ_e^*	0.06	0.06	0.06
λ_f^*	0.00	0.00	0.00
λ_g^*	0.00	0.00	0.00
λ_h^*	0.00	0.00	0.00

Table: Optimal Link International Migrant Attraction Investments and Domestic Labor Bound Lagrange Multipliers for Examples 1, 2, and 3

In Series 2 numerical examples, we use Example 1 as a baseline and we explore the impacts of increasing the prices that consumers are willing to pay.

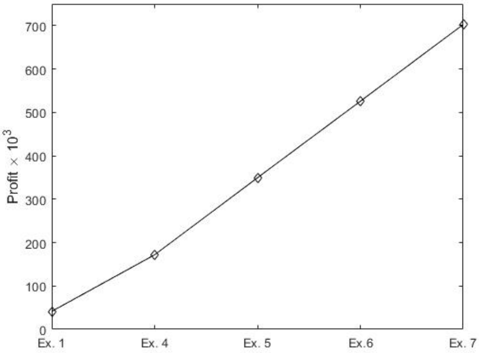


Figure: Effect on Profit of the Firm when the Demand Price Function Intercepts are Doubled, Tripled, and so on, with Example 1 Being the Baseline

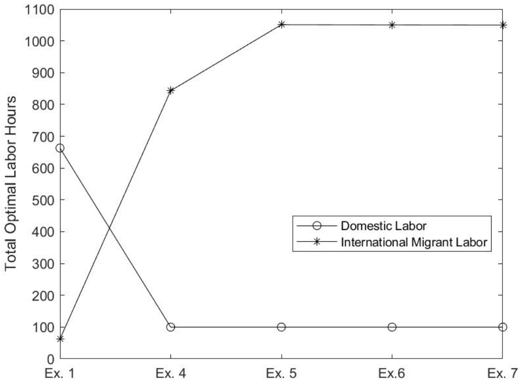


Figure: Effect on Optimal Total Labor Hours of Domestic Labor and of International Migrant Labor in the Supply Chain Network when the Demand Price Function Intercepts are Doubled, Tripled, and so on, with Example 1 Being the Baseline

In the third, final series of numerical examples, we first, again, explore the impacts of being untruthful in terms of wages in recruiting international migrant laborers and then we investigate the impact of a tighter budget on investments. The results can be found in the paper.

We see a huge increase in the hiring of international migrant laborers, which are all attracted to the work; however, under false pretenses in the form of higher wages than either the domestic laborers or the migrant laborers are being paid! The firm increases its profit.

Series 3 Numerical Examples

The examples, cheating or not, demonstrate also the importance of having a sufficient budget in order to be able to attract the needed international migrant labor.

Furthermore, through the use of Lagrange multipliers, we can see the value of increasing the availability of domestic labor in this endeavor, as well as the budget for investing in attracting international migrant labor.

The above examples are stylized, but do provide insights and, importantly, demonstrate both the breadth of the model and the effectiveness of the computational procedure.

Summary and Conclusions

• The COVID-19 pandemic is transforming our societies and economies and is also demonstrating the criticality of labor resources to supply chains. Many countries have been grappling with shortages of workers from the agricultural and manufacturing sectors to various services including healthcare. **Attracting international migrant labor may help to assuage shortages in domestic labor.**

• **In this paper, the aim was to establish the foundation for the integration of labor in supply chains coupled with international human migration, with the latter focused on labor**. We provide an advance to the existing literature through the synthesis of a supply chain network optimization model with labor that includes both domestic as well as migrant labor with the latter requiring investments subject to a budget constraint. The model has the flexibility to handle wages that are the same or different for domestic and migrant laborers and also the use of the truthful wage in the migration attraction functions that will be paid the migrant laborers for their work or not.

Summary and Conclusions

•**The theoretical framework that is utilized for the formulation, analysis, and solution of three series of numerical examples is the theory of variational inequalities.**

• The alternative variational inequality that we construct is in path flow and investment variables plus several sets of Lagrange multipliers, including those associated with the upper bounds on domestic labor on the various supply chain network links and the budget constraint. **The alternative variational inequality allows for the implementation of an elegant computational method with closed form expressions for the underlying variables at each iteration**.

Summary and Conclusions

• Three series of numerical examples are provided, with complete input and out data with the examples being motivated by a fairly rare, high priced, high value agricultural product - truffles, which are now even being grown in the United Kingdom.

• **The numerical examples reveal the benefits of having Lagrange multiplier information, and show that generating additional interest in an agricultural product in terms of prices that consumers are willing to pay, can yield sizeable increases in profit. The examples also show the impacts if a firm is untruthful in reporting wages that international migrants will actually be paid in attracting them, which suggests that policy makers need to be aware of such "cheating" since it can lead to higher profits.**

Summary and Conclusions

• The model in this paper can be extended to include**competition among different firms for international migrant labor and also to allow for different productivity factors associated with different levels of skilled migrants**.

• In addition,**it would be interesting and valuable to include a tier of brokers, along with their behavior**, who work to procure migrant laborers for firm' supply chain networks.

Thank You!

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