بسم الله الرحمن الرحيم

# Game Theory and Covid-19

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# Roadmap

Motivation → Supply Chains → Cooperate → Other Disasters

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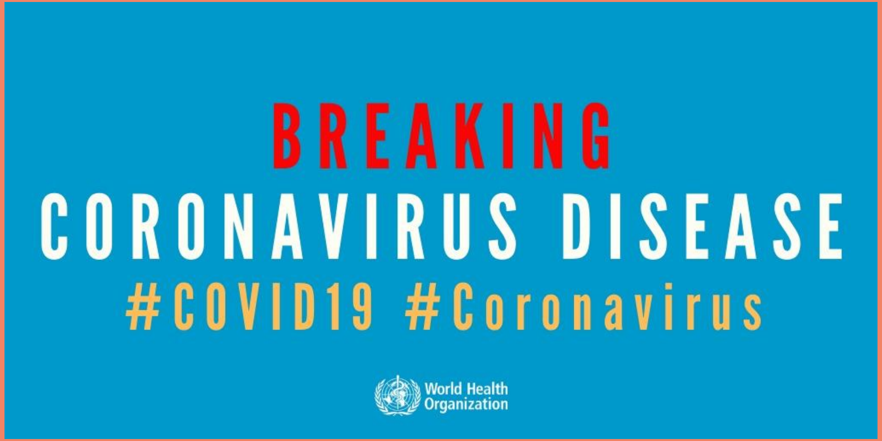
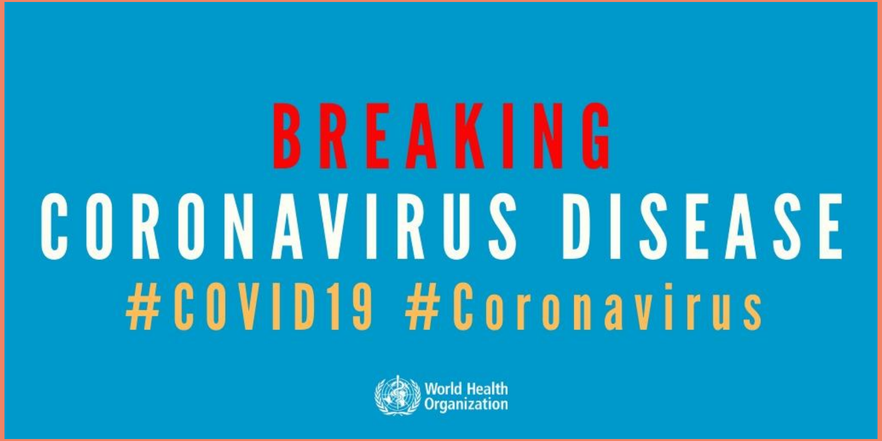



# What is a pandemic?




# COVID-19 impacts

- Education
- Transportation
- Supply chains

# Methodology

- Variational Inequalities
- Generalized Nash Equilibrium

# Variational Inequalities

Variational inequality theory is a powerful unifying methodology for the study of equilibrium problems.

# VI problems

- Traffic network equilibrium
- Migration equilibrium
- Financial equilibrium
- Supply chain network
- The internet

# VI Definition

*The finite - dimensional variational inequality problem,* $\mathrm{VI}(F, K)$, *is to determine a vector* $x^* \in K \subset R^n$, *such that*

$$F(x^*)^T \cdot (x - x^*) \geq 0, \quad \forall x \in K,$$

*or, equivalently,*

$$\langle F(x^*), x - x^* \rangle \geq 0, \quad \forall x \in K$$

*where* $F$ *is a given continuous function from* $K$ *to* $R^n$, $K$ *is a given closed convex set, and* $\langle \cdot, \cdot \rangle$ *denotes the inner product in n-dimensional Euclidean space, as does "·".*

# Monotonicity

*$F(X)$ is monotone on $\mathcal{K}$ if*

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle \geq 0, \quad \forall X^1, X^2 \in \mathcal{K}.$$

*$F(X)$ is strictly monotone on $\mathcal{K}$ if*

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle > 0, \quad \forall X^1, X^2 \in \mathcal{K}, X^1 \neq X^2.$$

# Uniqueness and Existence of a Solution

*Suppose that $F(X)$ is strictly monotone on $\mathcal{K}$. Then the solution to the $\mathrm{VI}(F, \mathcal{K})$ problem is unique, if one exists.*

*If $\mathcal{K}$ is a compact convex set and $F(X)$ is continuous on $\mathcal{K}$, then the variational inequality problem admits at least one solution $X^*$.*

# VI and Game Theory

Consider a game with $m$ players, each player $i$ having, without loss of generality, a strategy vector $X_i = \{X_{i1}, ..., X_{in}\}$ selected from a closed, convex set $K_i \subset R^n$. Each player $i$ seeks to maximize her utility function, $U_i$: $\mathcal{K} \to R$, where $\mathcal{K}=K_1 \times K_2 \times \cdots \times K_m \subset R^{mn}$. The utility of player $i$, $U_i$, depends not only on her own strategy vector, $X_i$, but also on the strategy vectors of the other players, $(X_1, \ldots, X_{i-1}, X_{i+1}, \ldots, X_m)$. An equilibrium is achieved if no one can increase her utility by unilaterally altering the value of her strategy vector.

*Under the assumption that each utility function $U_i$ is continuously differentiable and concave, $X^*$ is a Nash equilibrium if and only if $X^* \in \mathcal{K}$ is a solution of the variational inequality*

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

*where* $F(X) \equiv (-\nabla_{X_1} U_1(X), \ldots, -\nabla_{X_m} U_m(X))^T$, *and* $\nabla_{X_i} U_i(X) = (\frac{\partial U_i(X)}{\partial X_{i1}}, \ldots, \frac{\partial U_i(X)}{\partial X_{in}})$.

*A strategy vector $X^*$ is said to be a variational equilibrium of the above Generalized Nash Equilibrium game if $X^* \in \mathcal{K}$, where $\mathcal{K} \equiv K \cap \mathcal{S}$, is a solution of the variational inequality:*

$$-\sum_{i=1}^{m} \langle \nabla_{X_i} \hat{U}_i(X^*), X_i - X_i^* \rangle \geq 0, \quad \forall X \in \mathcal{K}.$$

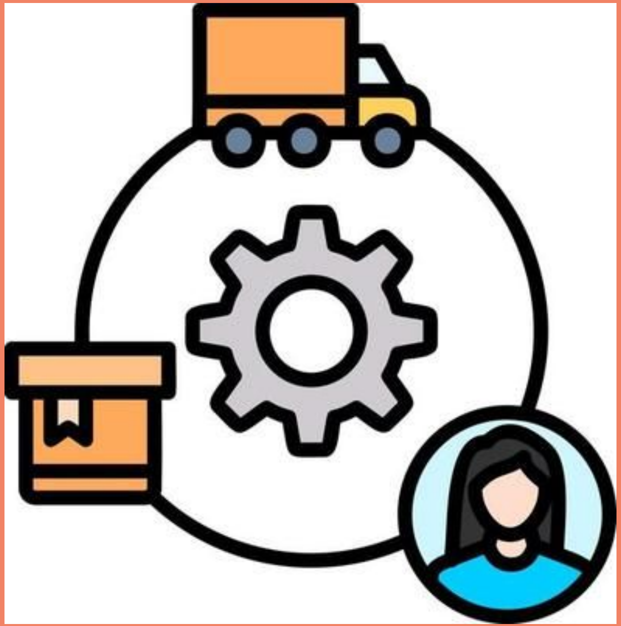
# Roadmap

Motivation

Supply Chains

Cooperate

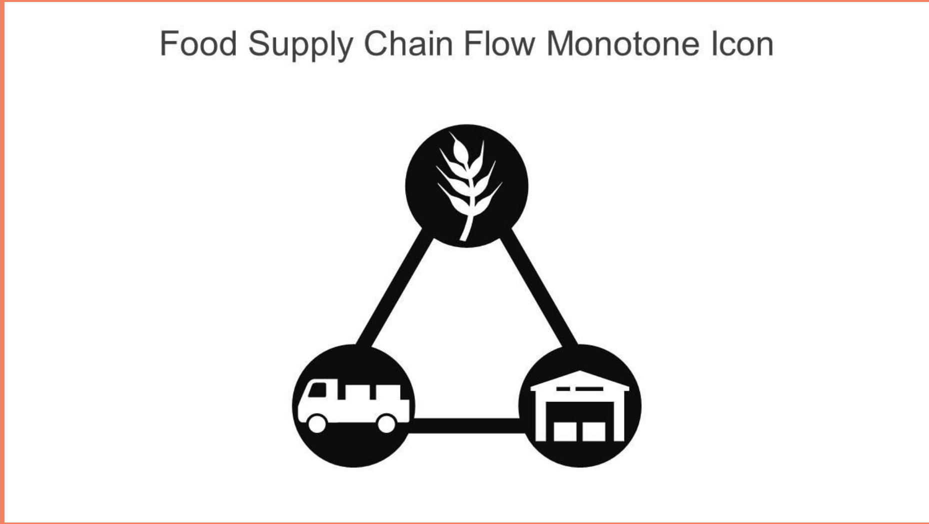
Other Disasters



# Supply Chains

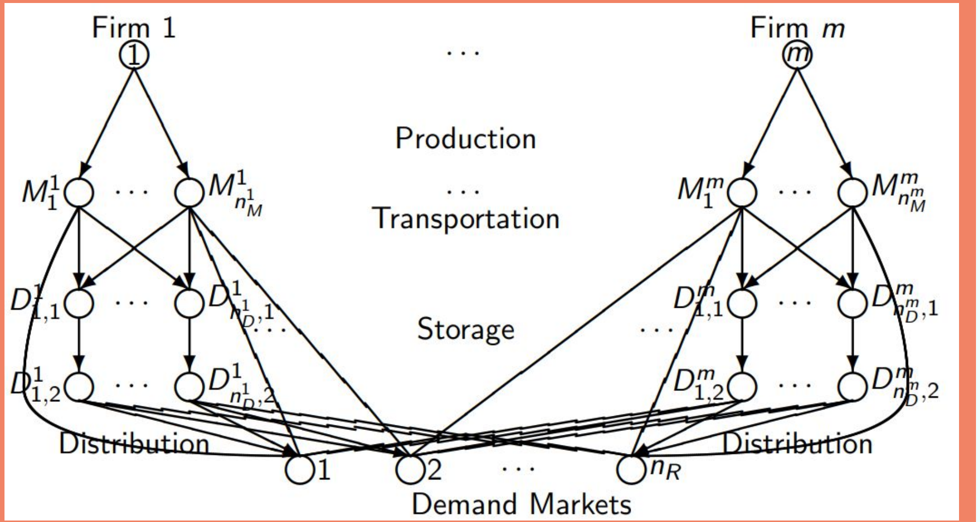
- Definition
- Networks
- Chain Disruptions
- Competitions

# Food Chains

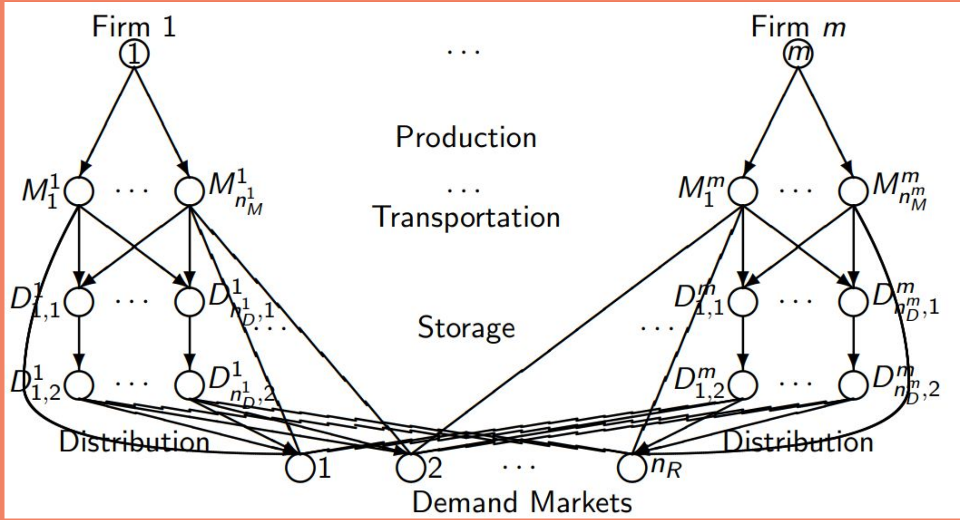



- Covid Impact
- Disruptions
- Animals Culled
- Shortage of Meat
- Price Increase
- Stop Fresh Production
- Labor Problem
- Food Insecurity

# Food Network

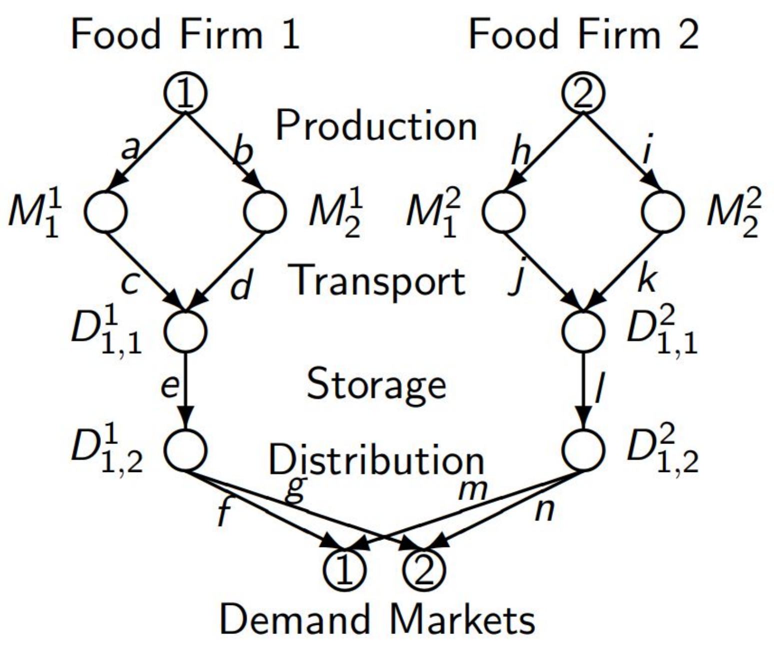



- Model Food Chain Network
- Production
- Transportation
- Storage
- Markets
- Providers



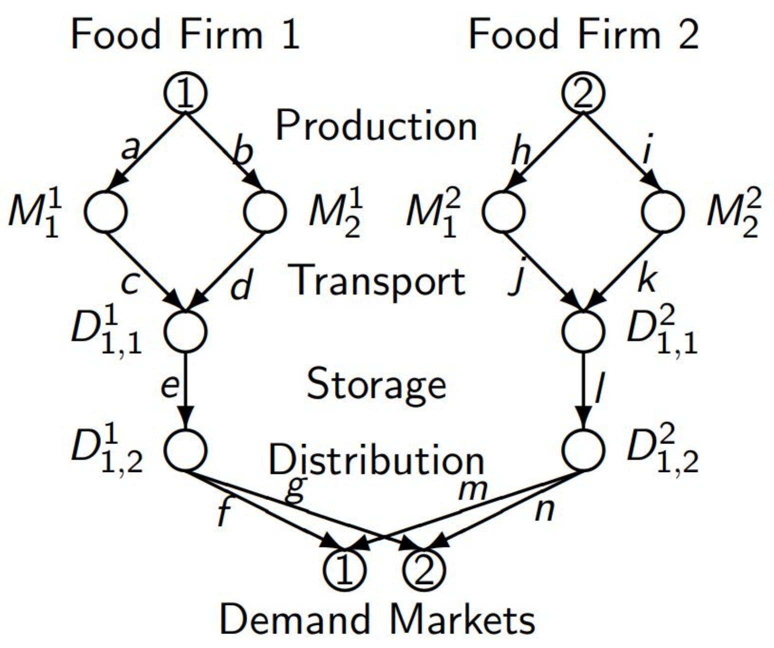

# Product System

- Non-negative Flows
- Links
- Constraints
- Optimization Problem
- Maximize Profit
- Firms Compete
- Max Flow Problem




# Farm Example

- Blueberry Farms
- Demand/Price
- Labor Disruptions
- Operational Costs
- Price Equilibrium
- Link Reduction

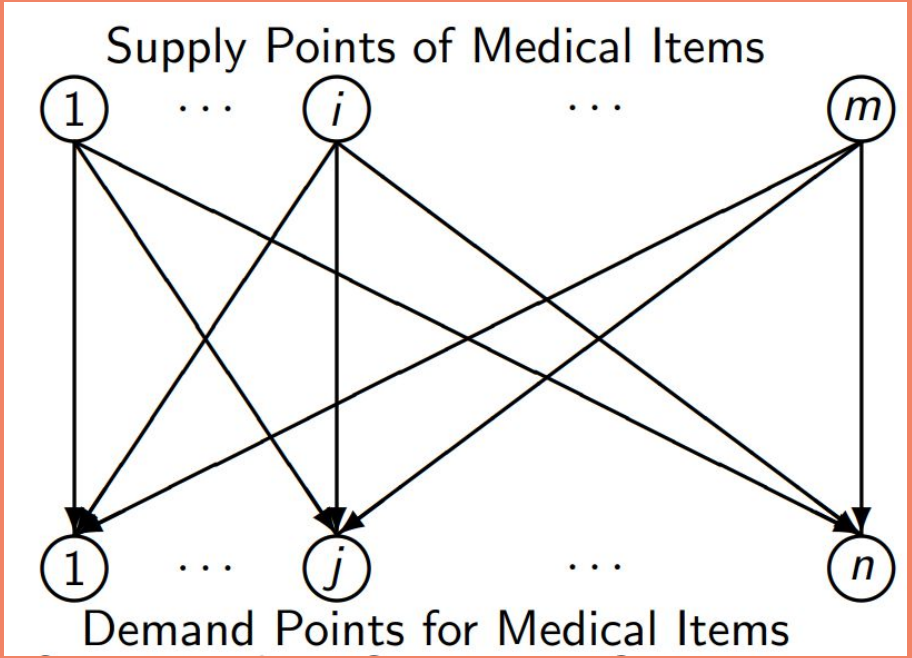



# Farm Results

- Secure Worker Health
- Profits Suffer
- Worker Impacts Bottom
- Wage-Labor Equilibrate
- No Wage Ceilings

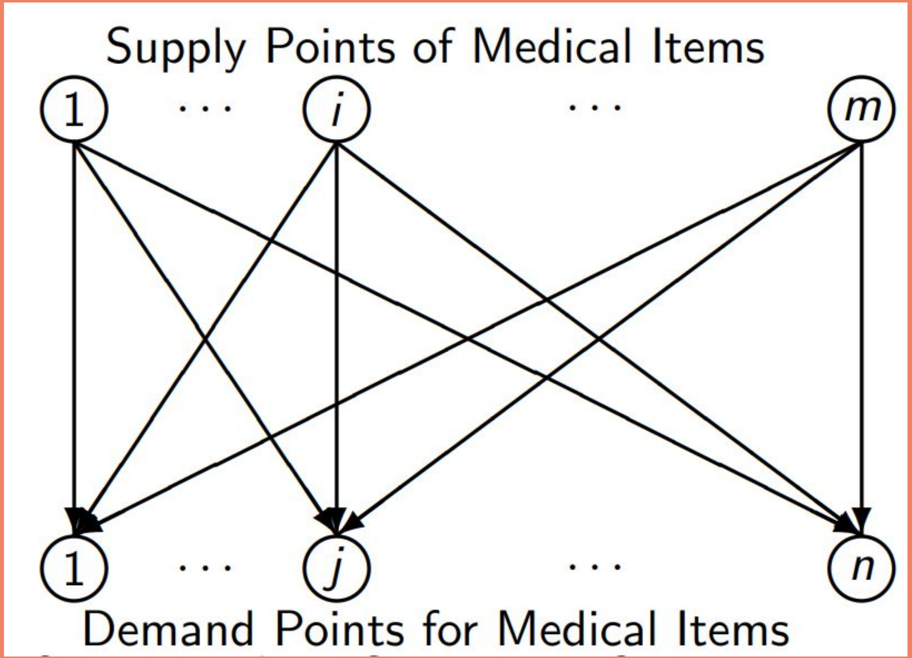
# Medical Chains

- Healthcare Disaster
- Needs Arise
- N95 Mask
- Competition
- Price Increase




# Medical Network

- Limited Capacities
- Uncertain Demands
- Global Costs
- General Nash Equilibrium
- Strategy of Suppliers



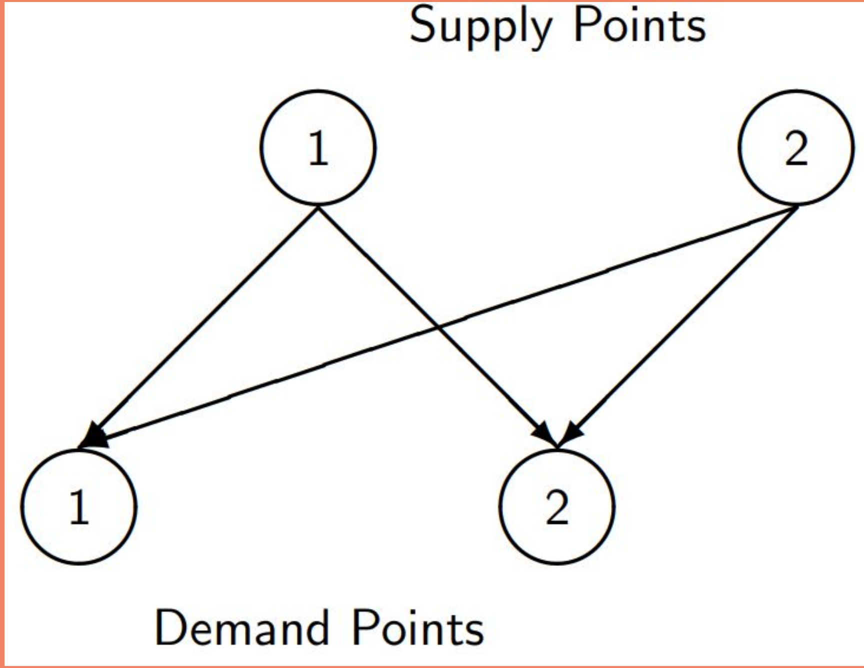

# Medical System

- Shortage/Surplus
- Minimize Costs
- Constraints
- General Transport Cost
- Equilibrium
- No Demand Change
- Stochastic Demands

# Mask Example

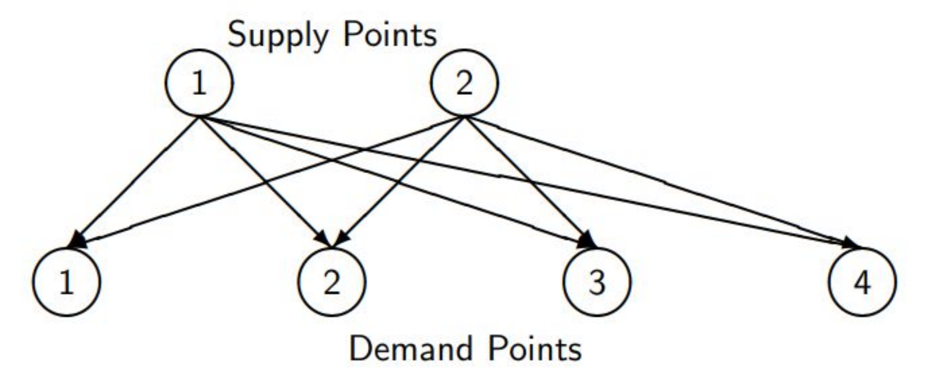
- N95 Masks
- Increase Demand
- Competition

# Mask Chain




- Intense Demand
- Fully Sold Out
- Increasing Supply
- Secure Demands

# Mask Results




- More Supplier Needed
- Local Production
- Long Term Economics

# Chain Conclusion

Chains

Examples

Results

# Roadmap

Motivation

Supply Chains

Cooperate

Other Disasters

# Cooperation in Disaster Relief

# Cooperation in Disaster Relief

**In the previous parts of this tutorial, the focus of the modeling parts was on noncooperative game theory and supply chain network models inspired by the COVID-19 pandemic.**

**We now turn to cooperation among organizations in a disaster setting. The COVID-19 pandemic is a healthcare disaster and is exacerbating the challenges associated with disaster management of other disasters, including those fueled by climate change.**

# Cooperation in Disaster Relief

**Opportunities for cooperation among organizations engaged in disaster response may exist in their supply chains from procurement to storage and even in the case of transportation and distribution.**

Plus, cooperation among organizations may reduce materiel convergence and release resources, including personnel, for more important life-saving tasks.

There is also great promise in the COVID-19 pandemic of enhanced partnerships and these even may be between private companies, including pharmaceutical ones.

**Lessons learned from disaster management are, hence, potentially of great benefit to pandemic preparedness, response, and even recovery.**

# The Multiproduct Supply Chain Network Models

**The Case without Horizontal Cooperation Multiproduct Supply Chain Network Model**

We first formulate the multiproduct decision-making optimization problems faced by $m$ organizations without horizontal cooperation. This model is Case 0. Each organization is represented as a network of its supply chain activities, as depicted in the next Figure.

Each organization $i$; $i = 1, \ldots, m$, has available $n^i_M$ procurement facilities, $n^i_S$ storage facilities, and serves $n^i_D$ disaster areas.

Let $G_i = [N_i, L_i]$ denote the graph consisting of nodes $[N_i]$ and directed links $[L_i]$ representing the supply chain activities associated with each organization $i$; $i = 1, \ldots, m$.

Let $L^0$ denote the links: $L_1 \cup L_2 \cup \cdots L_m$ as in the Figure. Each organization is involved in the procurement, transportation, storage, and distribution of $J$ products, with a typical product denoted by $j$.

# Case Without Cooperation

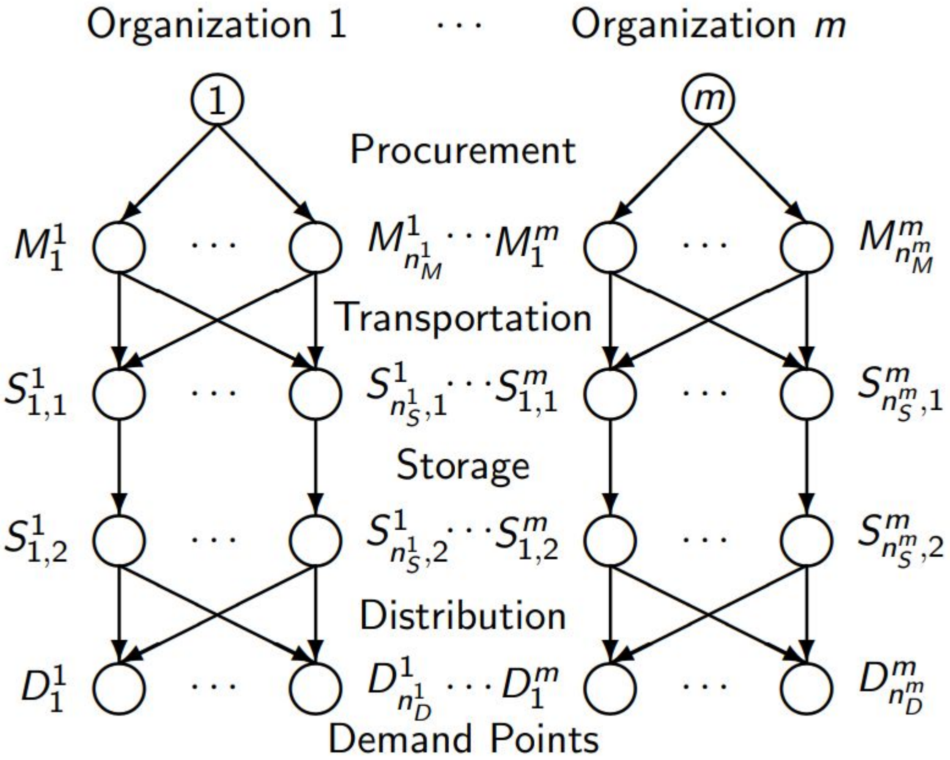



Figure: Supply Chains of Organizations 1 through $m$ Prior to Cooperation

# Case Without Cooperation

**The notation and discussion below build upon those for the previous model.**

Demands for the products are assumed to be random and are associated with each product, and each demand point.

Let $d_{ik}^j$ denote the random variable representing the actual demand for product $j$ and let $v_{ik}^j$ denote the projected random demand for product $j$; $j = 1, \ldots, J$, at demand point $D_k^i$ for $i = 1, \ldots, m$; $k = 1, \ldots, n_D^i$.

In addition, the probability density function of the actual demand for product $j$ is $\mathcal{F}_{ik}^j(t)$ at disaster area $D_k^i$; $i = 1, \ldots, m$; $k = 1, \ldots, n_D^i$.

## The Multiproduct Supply Chain Network Models

Hence, we can define the cumulative probability distribution function of $d_{ik}^j$ as $\mathcal{P}_{ik}^j(v_{ik}^j) = \mathcal{P}_{ik}^j(d_{ik}^j \leq v_{ik}^j) = \int_0^{v_{ik}^j} \mathcal{F}_{ik}^j(t)d(t)$.

Following Masoumi, Yu, and Nagurney (2017) and Dong, Zhang, and Nagurney (2004), we also define the supply shortage and surplus for product $j$; $j = 1, \ldots, J$, at disaster area $D_k^i$; $i = 1, \ldots, m$; $k = 1, \ldots, n_D^i$, as

$$\Delta_{ik}^{j-} \equiv \Delta_{ik}^{j-}(v_{ik}^j) \equiv \max\{0, d_{ik}^j - v_{ik}^j\} \quad (5.1a)$$

$$\Delta_{ik}^{j+} \equiv \Delta_{ik}^{j+}(v_{ik}^j) \equiv \max\{0, v_{ik}^j - d_{ik}^j\}. \quad (5.1b)$$

# The Multiproduct Supply Chain Network Models

The expected value of the shortage $\Delta_{ik}^{j-}$, denoted by $E(\Delta_{ik}^{j-})$, and of the surplus $\Delta_{ik}^{j+}$, denoted by $E(\Delta_{ik}^{j+})$, for $j = 1, \dots, J$; $D_k^i$; $i = 1, \dots, m$; $k = 1, \dots, n_D^i$, are

$$E(\Delta_{ik}^{j-}) = \int_{v_{ik}^j}^{\infty} (t - v_{ik}^j)\mathcal{F}_{ik}^j(t)d(t), \quad E(\Delta_{ik}^{j+}) = \int_0^{v_{ik}^j} (v_{ik}^j - t)\mathcal{F}_{ik}^j(t)d(t). \tag{5.2}$$

The penalty associated with the shortage and the surplus of the demand for product $j$; $j = 1, \dots, J$, at the disaster area $D_k^i$ is denoted by $\lambda_{ik}^{j-}$ and $\lambda_{ik}^{j+}$, respectively, where $i = 1, \dots, m$; $k = 1, \dots, n_D^i$.

# Case Without Cooperation

A path consists of a sequence of links originating at a node $i$; $i = 1, \dots, m$, corresponding to supply chain activities of: procurement, transportation, storage, and distribution of the products to the disaster area nodes.

Let $x^j_p$ denote the nonnegative flow of product $j$ on path $p$. Let $P^0_{D^i_k}$ denote the set of all paths joining an origin node $i$ with (destination) disaster area node $D^i_k$.

The conservation of flow equations are: for each organization $i; i = 1, \dots, m$, each product $j; j = 1, \dots, J$, and each disaster area $D^i_k; k = 1, \dots, n^i_D$:

$$\sum_{p \in P^0_{D^i_k}} x^j_p = v^j_{ik}, \quad i = 1, ..., m; \quad j = 1, \dots, J; \quad k = 1, \dots, n^i_D. \qquad (5.3)$$

## Case Without Cooperation

Links are denoted by $a$, $b$, etc. Let $f_a^j$ denote the flow of product $j$ on link $a$.

We also have the following conservation of flow equations:

$$f_a^j = \sum_{p \in P^0} x_p^j \delta_{ap}, \quad j = 1 \ldots, J; \quad \forall a \in L^0, \tag{5.4}$$

where $\delta_{ap} = 1$ if link $a$ is contained in path $p$ and $\delta_{ap} = 0$, otherwise.

$P^0$ denotes the set of *all* paths in the Figure, that is, $P^0 = \cup_{i=1,\ldots,I;k=1,\ldots,n_D^i} P^0_{D_k^i}$. The path flows must be nonnegative, that is,

$$x_p^j \geq 0, \quad j = 1, \ldots, J; \quad \forall p \in P^0. \tag{5.5}$$

The path flows are grouped into the vector $x$.

# Case Without Cooperation

There is a total cost associated with each product $j$; $j = 1, \ldots, J$, and each link of the network of each organization $i$; $i = 1, \ldots, m$.

The total cost on a link $a$ associated with product $j$ is denoted by $\hat{c}_a^j$. The total costs can be influenced by uncertainty factors.

The total cost on link $a$, $\hat{c}_a^j$, takes the form:

$$\hat{c}_a^j = \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j), \quad j = 1, \ldots, J; \quad \forall a \in L^i, \forall i, \qquad (5.6)$$

where $\omega_a^j$ is a random variable associated with various disaster events, which have an impact on the total cost of link $a$, $\forall a$, and product $j$; $j = 1, \ldots, J$. It is assumed that the distribution of the $\omega_a^j$s is known.

# Case Without Cooperation

## The Optimization Problem of Each Organization

Each organization $i$; $i = 1, \ldots, m$ seeks to determine the link flows and the projected random demands that solve the following optimization problem:

$$\text{Minimize} \quad \Bigg[ E\Big(\sum_{j=1}^{J} \sum_{a \in L_i} \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j)\Big) + \xi_i\Big(V\Big(\sum_{j=1}^{J} \sum_{a \in L_i} \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j)\Big)\Big)$$

$$+ \sum_{j=1}^{J} \sum_{k=1}^{n_D^i} \left(\lambda_{ik}^{j-} E(\Delta_{ik}^{j-}) + \lambda_{ik}^{j+} E(\Delta_{ik}^{j+})\right) \Bigg] \qquad (5.7)$$

subject to: (5.3) – (5.5) and the following capacity constraints:

$$\sum_{j=1}^{J} \gamma_j f_a^j \le u_a, \quad \forall a \in L_i, \qquad (5.8)$$

where $\gamma_j$ in (5.8) is the volume taken up by product $j$ and $u_a$ is the capacity of $a$.

## Case Without Cooperation

The total operational costs and the variances in (5.7) are assumed to be convex. We know that $\sum_{k=1}^{n_D^i}(\lambda_{ik}^{j-}E(\Delta_{ik}^{j-})+\lambda_{ik}^{j+}E(\Delta_{ik}^{j+}))$ is also convex (see, also, Nagurney, Masoumi, and Yu (2012)). We know then that the objective function (5.7) is convex for each $i$; $i=1,\ldots,m$. Also, the individual terms in (5.7) are continuously differentiable.

Under the above imposed assumptions, the optimization problem is a convex optimization problem and, clearly, the feasible set underlying the problem represented by the constraints (5.3) – (5.5) and (5.8) is non-empty, so it follows from the standard theory of nonlinear programming that an optimal solution exists.

# Case Without Cooperation

The objective function (5.7) is referred to as the total generalized cost $TGC_i^0$ for $i = 1, \ldots, m$. We associate the Lagrange multiplier $\eta_a$ with constraint (5.8) for each $a \in L^0$ with $\eta_a \geq 0, \forall a \in L^0$ and we denote the associated optimal Lagrange multiplier by $\eta_a^*, \forall a \in L^0$. We group the link flows into the vector $f$, the projected demands into the vector $v$, and the Lagrange multipliers into the vector $\eta$.

Let $\mathcal{K}^0$ denote the set where
$\mathcal{K}^0 \equiv \{(f, v, \eta) | \exists x \, \text{such that} \, (5.3) - (5.5) \, \text{and} \, \eta \geq 0 \, \text{hold}\}$.

Since we are considering Case 0, we denote the solution of variational inequality (VI) (5.9) below as $(f^{0*}, v^{0*}, \eta^{0*})$ and we refer to the corresponding vectors of variables with superscripts of 0. We now state a theorem, due to Nagurney and Qiang (2020).

# Case Without Cooperation

## Theorem 5.1: VI Formulation of Case 0: No Cooperation

*The vector $(f^{0*}, v^{0*}, \eta^{0*}) \in \mathcal{K}^0$ is an optimal solution to (5.7), for all organizations $i$; $i = 1, \ldots, m$, subject to their constraints (5.3)–(5.5) and (5.8), if and only if it satisfies the variational inequality problem:*

$$\sum_{i=1}^{m} \sum_{j=1}^{J} \sum_{a \in L_i} [\frac{\partial E(\sum_{l=1}^{J} \sum_{a \in L_i} \hat{c}_a^l(f_a^{1*}, \ldots, f_a^{J*}, \omega_a^l))}{\partial f_a^j}$$

$$+\xi_i \frac{\partial V(\sum_{l=1}^{J} \sum_{a \in L_i} \hat{c}_a^l(f_a^{1*}, \ldots, f_a^{J*}, \omega_a^l))}{\partial f_a^j} + \gamma_j \eta_a^*] \times [f_a^j - f_a^{j*}]$$

$$+\sum_{i=1}^{m} \sum_{j=1}^{J} \sum_{k=1}^{n_D^i} \left[\lambda_{ik}^{j+} \mathcal{P}_{ik}^j(v_{ik}^{j*}) - \lambda_{ik}^{j-}(1 - \mathcal{P}_{ik}^j(v_{ik}^{j*})\right] \times [v_{ik}^j - v_{ik}^{j*}]$$

$$+\sum_{a \in L^0} [u_a - \sum_{j=1}^{J} \gamma_j f_a^{j*}] \times [\eta_a - \eta_a^*] \geq 0, \quad \forall (f^0, v^0, \eta^0) \in \mathcal{K}^0. \tag{5.9}$$

# Case with Cooperation

We now formulate the case with horizontal cooperation of the multiproduct supply chain network model, referred to as Case 1.

The next Figure represents the supply chain network topology for Case 1.

There is a *supersource* node 0, which represents the "teaming/merging" in terms of cooperation of the organizations in terms of their supply chain networks with additional links connecting node 0 to nodes 1 through $m$.

# Case with Cooperation

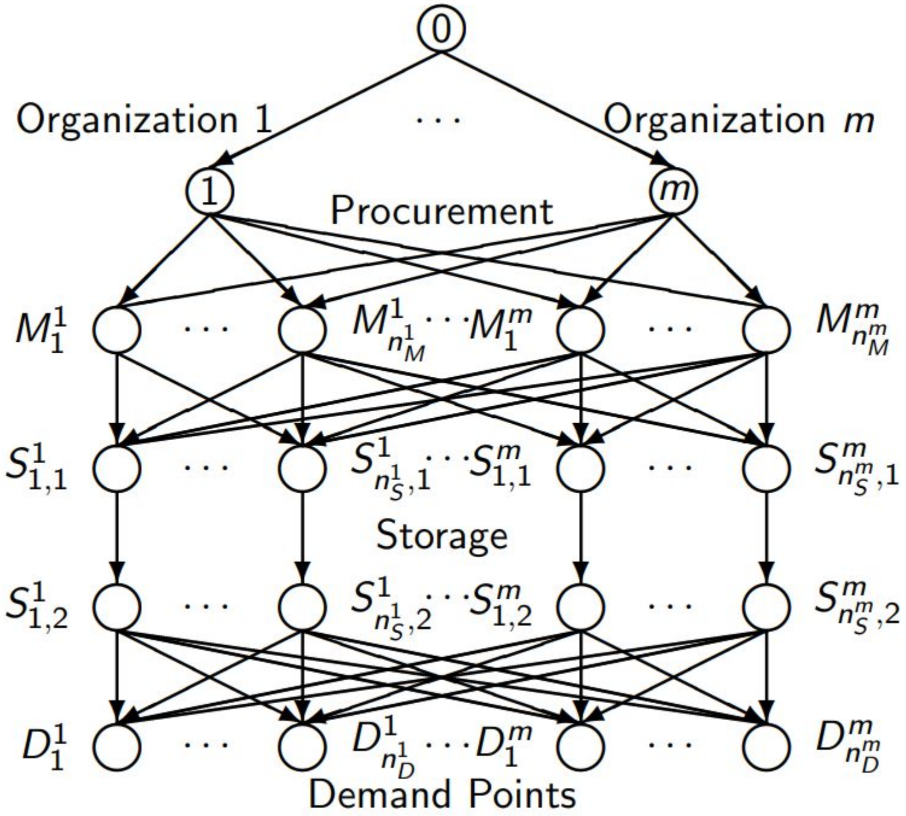



Figure: Supply Chain Network after Cooperation



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# Case with Cooperation

The optimization problem in Case 1 is also concerned with cost and risk minimization.

We refer to the network in the latest Figure, underlying this integration, as $G^1 = [N^1, L^1]$ where $N^1 \equiv N^0 \cup$ node 0 and $L^1 \equiv L^0 \cup$ the additional links as in the Figure and we associate total cost functions as in (5.6) with the new links, for each product $j$.

If the total cost functions on the cooperation links connecting node 0 to node 1 through node $m$ are set equal to zero, this means that the cooperation is *costless* in terms of the integrated supply chain network of the organizations.

# Case with Cooperation

A path $p$ now originates at node 0 and ends in one of the bottom disaster nodes. Let $x_p^j$, under the cooperation network configuration given in the Figure, denote the flow of product $j$ on path $p$ joining (origin) node 0 with a disaster area node.

Then, the following conservation of flow equations must hold for each $i, j, k$:

$$\sum_{p \in P^1_{D^i_k}} x_p^j = v_{ik}^j, \tag{5.10}$$

where $P^1_{D^i_k}$ denotes the set of paths connecting node 0 with disaster area node $D^i_k$ in the Figure. Because of cooperation, the disaster areas can obtain each product $j$ from any procurement facility, and any storage facility. The set of paths $P^1 \equiv \cup_{i=1,m;k=1,\ldots,n^i_D} P^1_{D^i_k}$.

# Case with Cooperation

As previously, let $f_a^j$ denote the flow of product $j$ on link $a$.

We must also have the following conservation of flow equations satisfied:

$$f_a^j = \sum_{p \in P^1} x_p^j \delta_{ap}, \quad j = 1, \ldots, J; \quad \forall a \in L^1. \tag{5.11}$$

In addition, the path flows must be nonnegative for each product $j$:

$$x_p^j \geq 0, \quad j = 1, \ldots, J; \quad \forall p \in P^1. \tag{5.12}$$

The supply chain network activities have nonnegative capacities, denoted as $u_a$, $\forall a \in L^1$, with $\gamma_j$ representing the volume factor for product $j$. The following constraints must, hence, hold:

$$\sum_{j=1}^{J} \gamma_j f_a^j \leq u_a, \quad \forall a \in L^1, \tag{5.13}$$

where $\xi$ is the associated risk aversion factor of the teamed organizations under cooperation.

# Case with Cooperation

## The Optimization Problem for Cooperation

$$\text{Minimize} \quad E\left(\sum_{j=1}^{J}\sum_{a\in L^1}\hat{c}_a^j(f_a^1,\ldots,f_a^J,\omega_a^j)\right)+\xi\left[V\left(\sum_{j=1}^{J}\sum_{a\in L^1}\hat{c}_a^j(f_a^1,\ldots,f_a^J,\omega_a^j)\right)\right]$$

$$+\sum_{i=1}^{m}\sum_{j=1}^{J}\sum_{k=1}^{n_D^i}\left(\lambda_{ik}^{j-}E(\Delta_{ik}^{j-})+\lambda_{ik}^{j+}E(\Delta_{ik}^{j+})\right) \qquad (5.14)$$

subject: (5.10) – (5.13).

The solution to the optimization problem (5.14) subject to the constraints can also be obtained as a solution to a VI problem, similar to (5.9), where now links $a \in L^1$. The vectors $f$, $v$, and $\eta$ keep their prior definitions, but are re-dimensioned accordingly and superscripted with 1. Instead of the feasible set $\mathcal{K}^0$ we now have
$\mathcal{K}^1 \equiv \{(f, v, \eta) | \exists x \text{ such that } (5.10) - (5.12) \text{ hold and } \eta \geq 0\}$.

## Case with Cooperation

We denote the solution to the VI problem (5.15) governing Case 1 by $(f^{1*}, v^{1^*}, \eta^{1*})$ and the vectors of corresponding variables as $(f^1, v^1, \eta^1)$.

### Theorem 5.2: VI Formulation of Case 1: Cooperation

*The vector $(f^{1*}, v^{1*}, \eta^{1*}) \in \mathcal{K}^1$ is an optimal solution to (5.14), subject to constraints (5.10)–(5.13), if and only if it satisfies the variational inequality problem:*

$$\sum_{j=1}^{J} \sum_{a \in L^1} \frac{\partial E(\sum_{l=1}^{J} \sum_{a \in L^1} \hat{c}_a^l(f_a^1, \ldots, f_a^J, \omega_a^l))}{\partial f_a^j} + \xi \frac{\partial V(\sum_{l=1}^{J} \sum_{a \in L^1} \hat{c}_a^l(f_a^{1*}, \ldots, f_a^{J*}, \omega_a^l))}{\partial f_a^j}$$

$$\times [f_a^j - f_a^{j*}] + \sum_{i=1}^{m} \sum_{j=1}^{J} \sum_{k=1}^{n_D^i} \left[\lambda_{ik}^{j+} \mathcal{P}_{ik}^j(v_{ik}^{j*}) - \lambda_{ik}^{j-}(1 - \mathcal{P}_{ik}^j(v_{ik}^{j*})\right] \times [v_{ik}^j - v_{ik}^{j*}]$$

$$+ \sum_{a \in L^1} [u_a - \sum_{j=1}^{J} \gamma_j f_a^{j*}] \times [\eta_a - \eta_a^*] \geq 0, \quad \forall (f^1, v^1, \eta^1) \in \mathcal{K}^1. \qquad (5.15)$$

# Total Generalized Cost Definitions

**Definition 5.1: Total Generalized Costs at the Optimal Solutions to the Supply Chain Network Problems without and with Cooperation**

*Let* $TGC^{0*}$ *denote the total generalized cost:*
$\sum_{i=1}^{m} TGC_i^0 = E(\sum_{j=1}^{J} \sum_{a \in L^0} \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j)) + \sum_{i=1}^{m} \xi_i \left[ V(\sum_{j=1}^{J} \sum_{a \in L_i} \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j)) \right] + \sum_{i=1}^{m} \sum_{j=1}^{J} \sum_{k=1}^{n_D^i} (\lambda_{ik}^{j-} E(\Delta_{ik}^{j-}) + \lambda_{ik}^{j+} E(\Delta_{ik}^{j+}))$, *evaluated at the optimal solution* $(f^{0*}, v^{0*}, \eta^{0*})$ *to (5.9).*

*Also, let* $TGC^{1*} = E(\sum_{j=1}^{J} \sum_{a \in L^1} \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j)) + \xi \left[ V(\sum_{j=1}^{J} \sum_{a \in L^1} \hat{c}_a^j(f_a^1, \ldots, f_a^J, \omega_a^j)) \right] + \sum_{i=1}^{m} \sum_{j=1}^{J} \sum_{k=1}^{n_D^i} (\lambda_{ik}^{j-} E(\Delta_{ik}^{j-}) + \lambda_{ik}^{j+} E(\Delta_{ik}^{j+}))$, *denote the total generalized cost evaluated at the solution* $(f^{1*}, v^{1*}, \eta^{1*})$ *to (5.15).*

## Synergy Quantification

We denote the synergy by $\mathcal{S}^{TGC}$. It is the percentage difference between the total generalized cost without *vs.* with the horizontal cooperation (evaluated at the respective optimal solutions):

$$\mathcal{S}^{TGC} \equiv [\frac{TGC^{0*} - TGC^{1*}}{TGC^{0*}}] \times 100\%. \qquad (5.16)$$

**Observe from (5.16) that the lower the total generalized cost $TGC^{1*}$, the higher the synergy associated with the supply chain network cooperation and, therefore, the greater the total cost savings resulting from the cooperation.**

# Synergy Quantification

**The total generalized costs include not only the monetary costs, but also the risks and uncertainties involved in the supply chain as well as the associated penalties of shortages and surpluses.**

**In specific disaster relief operations, including in the pandemic, one may evaluate the integration of supply chain networks with only a subset of the links connecting the original supply chain networks.**

# A Theoretical Result

We now recall an interesting theorem, due also to Nagurney and Qiang (2020), which reveals that, under certain assumptions related to the total operational costs associated with the supply chain integration and risk factors, the associated synergy can never be negative.

**Theorem 5.3**

*If the total generalized cost functions associated with the cooperation links from node* 0 *to nodes* 1 *through* $m$ *for each product are identically equal to zero, and if the risk aversion factors* $\xi_i$*;* $i = 1, \ldots, m$*, are all equal and set to* $\xi$*, then the associated synergy,* $\mathcal{S}^{TGC}$*, can never be negative.*

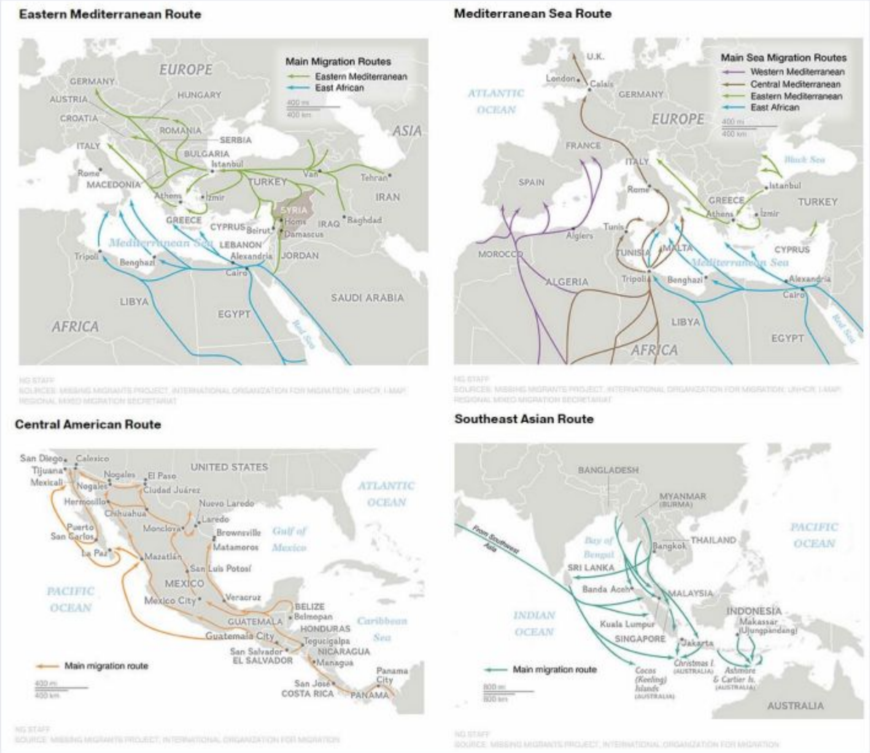
# Numerical Examples

The numerical examples are inspired, in part, by ongoing refugee/migrant crises as in Central America and Mexico, which are ongoing and have been exacerbated in the COVID-19 pandemic.

**Slow-onset, ongoing disasters are providing huge challenges for various organizations, including humanitarian ones, and governments, to provide the necessary food, water, medicines, etc., to the needy in a variety of shelters.**

The numerical examples are stylized but reflect real-world features. Furthermore, as in the case of the refugee/migrant crisis emanating from Central America, numerous organizations are involved in providing assistance and, hence, it is valuable to be able to assess possible synergies since the demand is so great. Using carefully calibrated historical data and information, the models can be used to assist the organizations on how to cooperate in terms of the delivery of relief products in a cost-effective manner.

# Migration Routes




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

# Roadmap

- Motivation
- Supply Chains
- Cooperate
- Other Disasters

# Motivation and Some Background

**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. And we have seen the news about refugees from Afghanistan.

# Motivation and Some Background

**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.

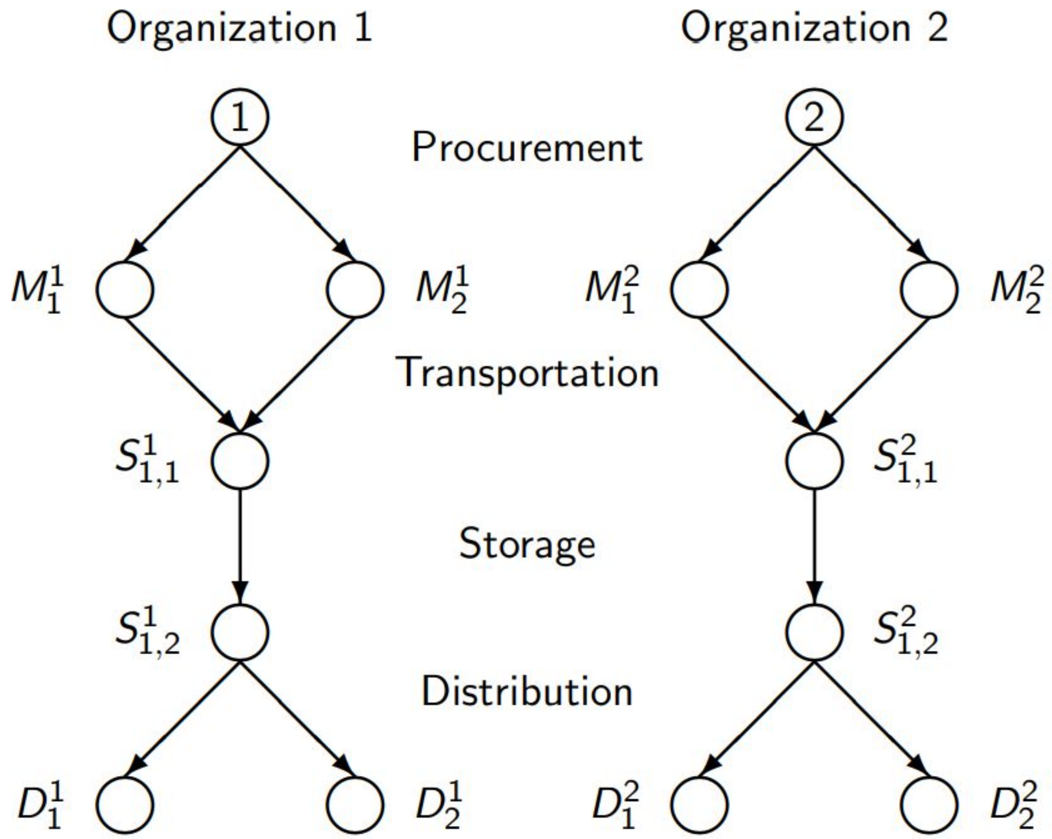



Figure: Pre-Cooperation Supply Chain Network Topology for the Numerical Examples

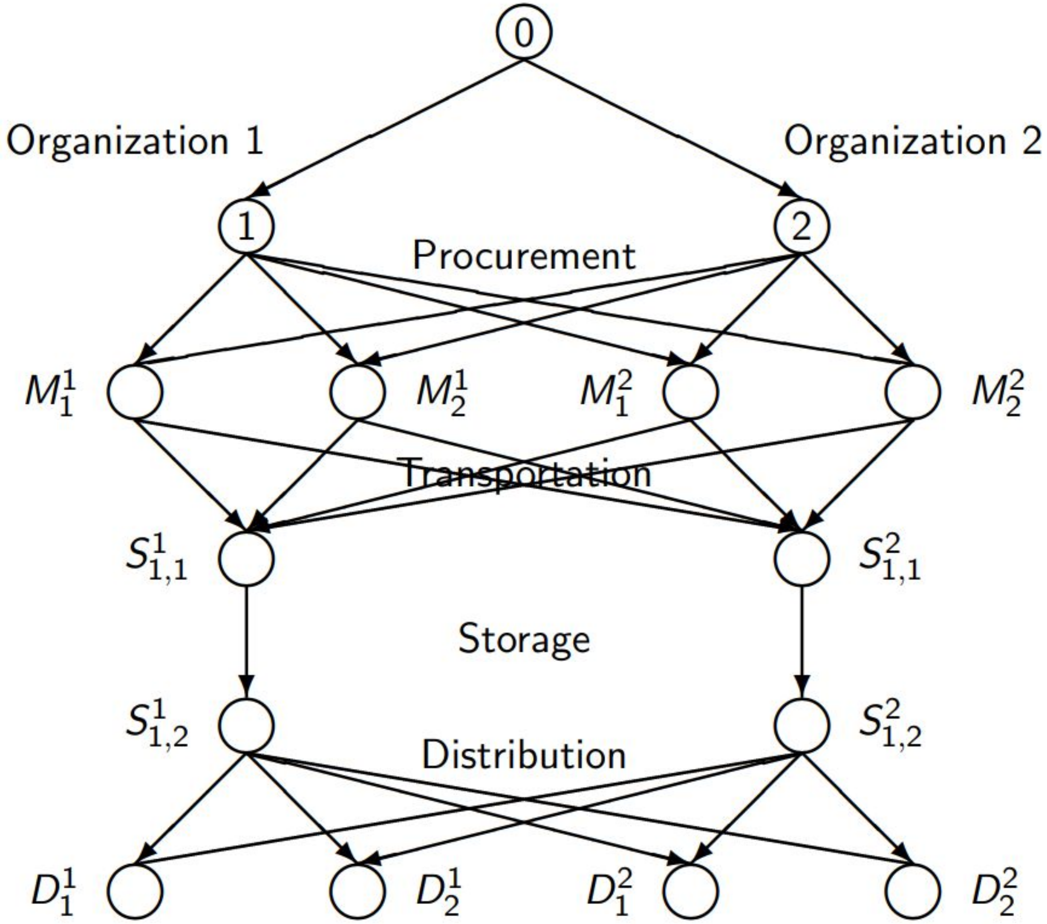
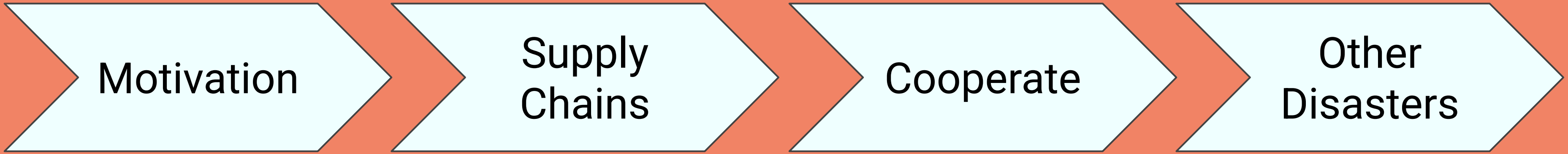



Figure: Cooperation Supply Chain Network Topology for the Examples

# Conclusions



# Numerical Examples

**In the paper version of this tutorial a series of numerical examples, with complete input and output data are reported.**

• We find that the relief item flows to the demand points are all greater than the lower value of the interval of the respective probability distribution and the volume is higher under cooperation than before. Hence, victims benefit from the cooperation of organizations.

• Also, we find that the generalized total synergy that can be achieved is substantial, as high as 99% in several of the examples.

**This work quantifies the benefits to both organizations and victims of cooperation among organizations involved in disaster relief.**

# Writing OpEds

THE CONVERSATION

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## How disaster relief efforts could be improved with game theory

UMASS AMHERST

The number of disasters has doubled globally since the 1980s, with the

Chicago Tribune

## Response to natural disasters like Harvey could be helped with game theory

By Anna Nagurney

(The Conversation is an independent and nonprofit source of news, analysis and commentary from academic experts.)

Anna Nagurney, University of Massachusetts Amherst

(THE CONVERSATION) The devastation by Hurricane Harvey continues, with the National Weather Service calling the event unprecedented, thus making the response even more complicated.

Nearly half a million people are expected to seek federal aid in the aftermath of the Category 4 hurricane, which already has dumped more than 30 inches on the Houston

SALON

VIDEO NEWS POLITICS ENTERTAINMENT LIFE

THURSDAY, AUG 31, 2017 10:38 AM EST

## Time for some game theory: How responses to natural disasters like Harvey could be improved

The damage and losses from natural disasters are estimated to cost us $100 billion a year since 2000

ANNA NAGURNEY, THE CONVERSATION

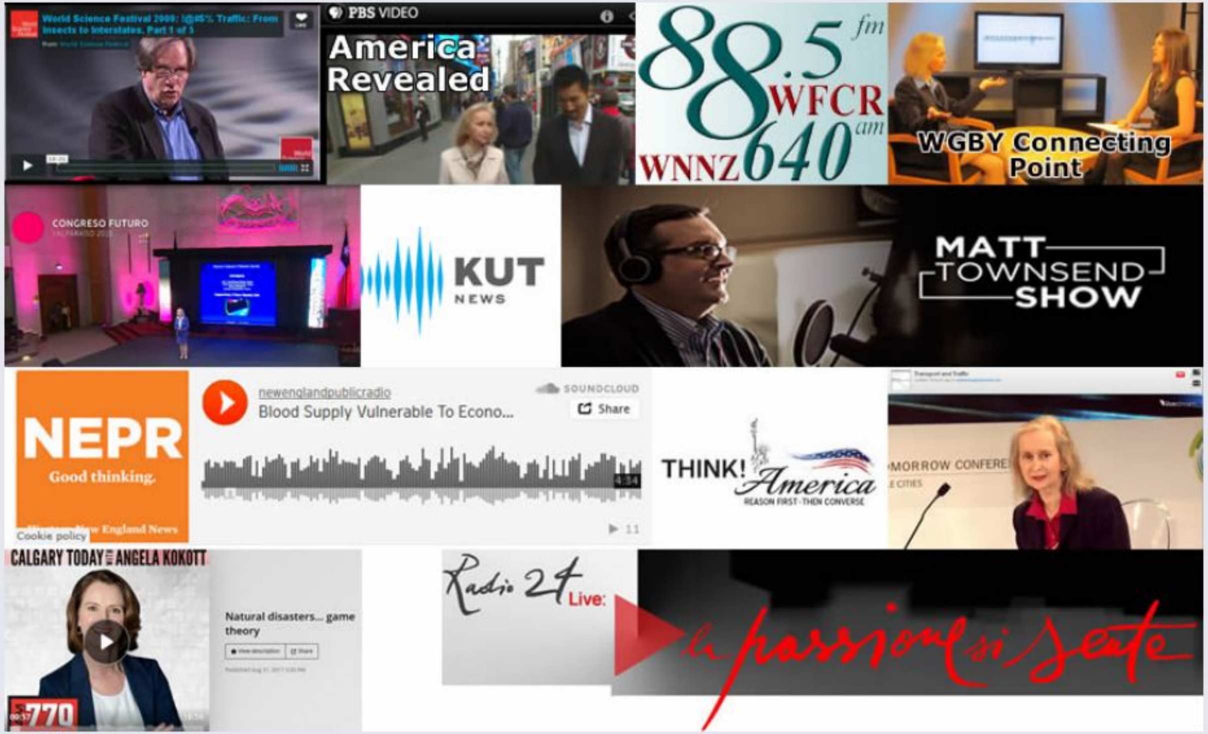
Homeland Security News Wire

BIOMETRICS BORDER/IMMIG. BUSINESS CYBERSECURITY
PUBLIC SAFETY PUBLIC HEALTH REGIONAL SCI-TECH

Yale Cyber Leadership Forum · March 30–April 1, 2017

Disaster response

# Coverage by the Media



# Writing OpEds in the Pandemic

On March 11, 2020 the WHO declared the pandemic. On March 12 my article on blood supply chains in *The Conversation* appeared and, on March 24 my article in INFORMS *Analytics Coronavirus Chronicles*.

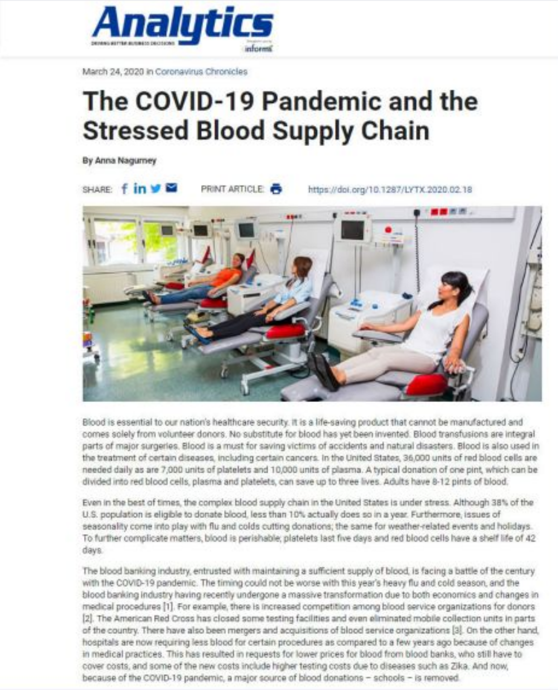
THE CONVERSATION

**How coronavirus is upsetting the blood supply chain**

The coronavirus, which causes the disease COVID-19, has created enormous anxiety, uncertainty, and disruption to our lives. Much has already been written about potential shortages of medicines and face masks, but little has been said about something only you and I can provide – lifesaving blood.

Our nation's blood supply is essential to our health care security. Blood transfusions are integral parts of major surgeries. Blood is used in the treatment of diseases, particularly sickle cell anemia and some cancers. Blood is needed for victims who have injuries caused by accidents or natural disasters. Every day, the U.S. needs 36,000 units of red blood cells, 7,000 units of platelets, and 10,000 units of plasma.

I am a professor and director of the Virtual Center for Supernetworks at the University of Massachusetts Amherst. Because of the escalating coronavirus health care crisis, I am deeply concerned the U.S. blood supply chain is under stress. The timing could hardly be worse; the COVID-19 outbreak coincides with our seasonal flus and colds.



Analytics

March 24, 2020 in Coronavirus Chronicles

**The COVID-19 Pandemic and the Stressed Blood Supply Chain**

By Anna Nagurney

SHARE: PRINT ARTICLE: https://doi.org/10.1287/LYTX.2020.02.18

Blood is essential to our nation's healthcare security. It is a life-saving product that cannot be manufactured and comes solely from volunteer donors. No substitute for blood has yet been invented. Blood transfusions are integral parts of major surgeries. Blood is a must for saving victims of accidents and natural disasters. Blood is also used in the treatment of certain diseases, including certain cancers. In the United States, 36,000 units of red blood cells are needed daily as are 7,000 units of platelets and 10,000 units of plasma. A typical donation of one pint, which can be divided into red blood cells, plasma and platelets, can save up to three lives. Adults have 8-12 pints of blood.

Even in the best of times, the complex blood supply chain in the United States is under stress. Although 38% of the U.S. population is eligible to donate blood, less than 10% actually does so in a year. Furthermore, issues of seasonality come into play with flu and colds cutting donations; the same for weather-related events and holidays. To further complicate matters, blood is perishable; platelets last five days and red blood cells have a shelf life of 42 days.

The blood banking industry, entrusted with maintaining a sufficient supply of blood, is facing a battle of the century with the COVID-19 pandemic. The timing could not be worse with this year's heavy flu and cold season, and the blood banking industry having recently undergone a massive transformation due to both economics and changes in medical procedures [1]. For example, there is increased competition among blood service organizations for donors [2]. The American Red Cross has closed some testing facilities and even eliminated mobile collection units in parts of the country. There have also been mergers and acquisitions of blood service organizations [3]. On the other hand, hospitals are now requiring less blood for certain procedures as compared to a few years ago because of changes in medical practices. This has resulted in requests for lower prices for blood from blood banks, who still have to cover costs, and some of the new costs include higher testing costs due to diseases such as Zika. And now, because of the COVID-19 pandemic, a major source of blood donations – schools – is removed.

# Writing OpEds in the Pandemic

On August 4, 2020, I published an article in *The Conversation*,

**"The Raging Competition for Medical Supplies is not a Game, but Game Theory Can Help."**


On September 18, 2020, I published another article in *The Conversation*,

**"Keeping Coronavirus Vaccines at Subzero Temperatures During Distribution Will Be Hard, but Likely Key to Ending Pandemic."**

# Writing OpEds in the Pandemic

On January 8, 2021, my article,

**"Vaccine Delays Reveal Unexpected Weak Link in Supply Chains: A Shortage of Workers,"** appeared in *The Conversation*.

On April 5, 2021, I published the article,

**"Today's Global Economy Runs on Standardized Containers, as the Ever Given Fiasco Illustrates,"** also in *The Conversation*.

# با تشکر

# Resources

1. Covid-19 And Game Theory
2. Covid-19 And Game Theory Video