Blood Supply Chains: Challenges for the Industry and How Operations Research Can Help

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Outline of This Presentation

- Background and Motivation
- Perishable Product Supply Chains
- Methodology - The Variational Inequality Problem
- New Trend in Demand for Blood Products in US
- The Supply Chain Network Model of a Blood Bank Merger or Acquisition
- Case Study: A Merger Between Two Blood Banks
- Game Theory and Blood Supply Chains
- Summary and Conclusions

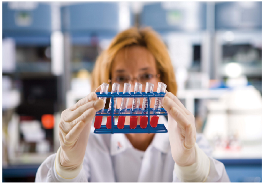
Background and Motivation

Blood Service Operations

Blood service operations are a key component of the healthcare system all over the world.

38,000 donations are needed every day in the US. Every 2 seconds someone needs blood in the US.

Large, medium and small hospitals request an average of **495, 300**, and **110** units of blood per week, respectively.



Blood Service Operations

A blood donation occurs when a person voluntarily has blood drawn and used for transfusions.

In the developed world, most blood donors are unpaid volunteers who give blood for an **established community supply** (allogeneic donation). In poorer countries, donors usually give blood when family or friends need a transfusion (directed donation).

Blood Service Operations

In the United States, the **American Red Cross supplies about 40% of the blood**, with **America's Blood Centers, with 600 blood donor centers, providing about 50%** (and about one quarter of the blood in Canada) (cf. American Red Cross (2016)).

American
Red Cross
Together, we can save a life

Blood Services Around the World

The remainder of the blood in the US is collected by hospitals and medical centers themselves or, **lately, by profit-maximizing blood suppliers**.

Other countries around the world differ in terms of their blood services, which can be hospital-based, national, or regional.

In the United States, and also in many countries globally, donors are not compensated financially for their blood donations.

Blood Services Around the World

In Germany, **blood services are provided by four types of organizations: German Red Cross Blood Transfusion Services, state and communal blood transfusion services, commercial blood centers and plasmapheresis centers of the plasmafractionation industry**. The German Red Cross has seven blood transfusion services including 28 donation centers and institutes. Some of these offer also an opportunity for plasmapheresis.

Blood services in ECO countries, including Iran, Turkey, and Afghanistan, **have both national governments and private organizations involved, but to varying degrees** (Seighali et al. (2015)).

Perishable Product Supply Chains

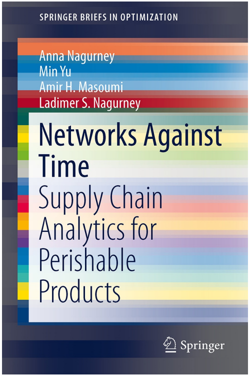
Blood is a Perishable Product

Not only must blood be voluntarily donated and it can't be manufactured, but blood is also a perishable product.

- Platelets: the longest shelf life is **7 days**;
- Red Blood Cells: a shelf life of **35-42 days** at refrigerated temperatures;
- Plasma: can be stored frozen for up to **one year**.

It is rather difficult to have a **stockpile of blood to prepare for a disaster.**

Multidisciplinary Approach to Perishable Products



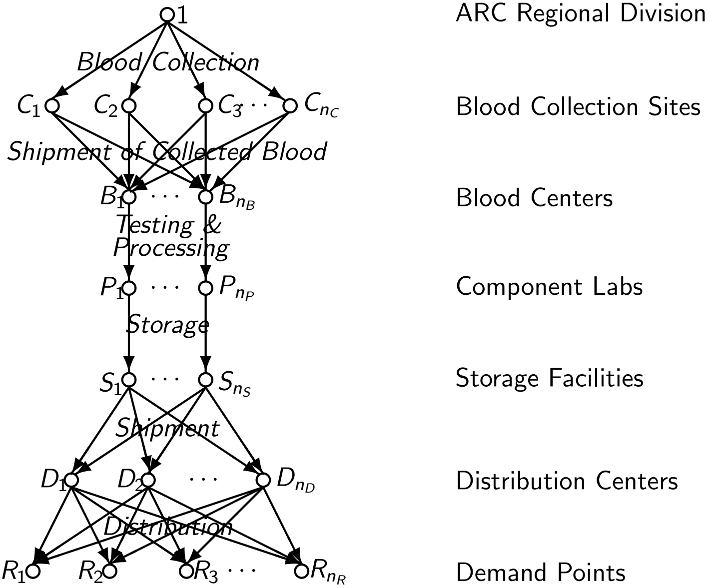
We utilize results from physics, chemistry, biology, and medicine in order to capture the perishability of various products in supply chains from food to healthcare products such as blood, medical nucleotides, and pharmaceuticals.

Blood Supply Chains for the Red Cross

A. Nagurney, A.H. Masoumi, and M. Yu, "Supply Chain Network Operations Management of a Blood Banking System with Cost and Risk Minimization," *Computational Management Science* **9(2)** (2012), pp 205-231.

A. Nagurney and A.H. Masoumi, "Supply Chain Network Design of a Sustainable Blood Banking System," in *Sustainable Supply Chains: Models, Methods and Public Policy Implications*, T. Boone, V. Jayaraman, and R. Ganeshan, Editors, Springer, London, England (2012), pp 49-72.

Supply Chain Network Topology for a Regionalized Blood Bank



Blood Supply Chains for the Red Cross

We developed a supply chain network optimization model for the management of the procurement, testing and processing, and distribution of a perishable product – that of human blood.

Novel features of the model include:

- It captures **perishability of this life-saving product** through the use of arc multipliers;
- It contains **discarding costs** associated with waste/disposal;
- It handles **uncertainty** associated with demand points;
- It assesses **costs associated with shortages/surpluses at the demand points**, and
- It quantifies the **supply-side risk** associated with procurement.

Medical Nuclear Supply Chains

We developed a medical nuclear supply chain network design model which captures the decay of the radioisotope molybdenum.

"Medical Nuclear Supply Chain Design: A Tractable Network Model and Computational Approach," A. Nagurney and L. S. Nagurney, *International Journal of Production Economics* **140(2)** (2012), pp 865-874.

Medical Nuclear Supply Chains

In our medical nuclear supply chain models we capture the radioactive decay through the use of arc multipliers.

Hence, the framework for both our blood supply chain work and medical nuclear work is that of *generalized* networks.

Because of the exponential decay of molybdenum, we have that the quantity of the radioisotope:

$$N(t) = N_0 e^{-\lambda t}$$

so that an arc multiplier on a link a that takes t_a hours of time corresponds to:

$$\alpha_a = e^{-\frac{ln2}{66.7} t_a}.$$

Medical Nuclear Supply Chains

Medical nuclear supply chains are essential supply chains in healthcare and provide the conduits for products used in nuclear medical imaging, which is routinely utilized by physicians for diagnostic analysis for both cancer and cardiac problems.

Such supply chains have unique features and characteristics due to the products' time-sensitivity, along with their hazardous nature.

Salient Features:

- complexity
- economic aspects
- underlying physics of radioactive decay
- importance of considering both waste management and risk management.

Medical Nuclear Supply Chains

^{99}Mo Supply Chain Challenges:

- The majority of the reactors are between **40 and 50 years old**. Several of the reactors currently used are due to be retired by the end of this decade (Seeverens (2010) and OECD Nuclear Energy Agency (2010a)).
- **Limitations in processing capabilities** make the world critically vulnerable to Molybdenum supply chain disruptions.
- The number of generator manufacturers is **under a dozen** (OECD Nuclear Energy Agency (2010b)).
- **Long-distance transportation** of the product raises safety and security risks, and also results in greater decay of the product.

Medical Nuclear Supply Chains

For over two decades, all of the Molybdenum necessary for US-based nuclear medical diagnostic procedures has come from **foreign** sources.

In 2015, NorthStar Medical Radioisotopes LLC has received approval to begin routine production of molybdenum-99 (Mo-99) at the University of Missouri Research Reactor (MURR) facility in Columbia, Missouri. LEU rather than HEU will be used there.

This transitioning of NorthStar's Mo-99 line at MURR from a development process to a routine production process is another significant step toward establishing a domestic source of Mo-99.

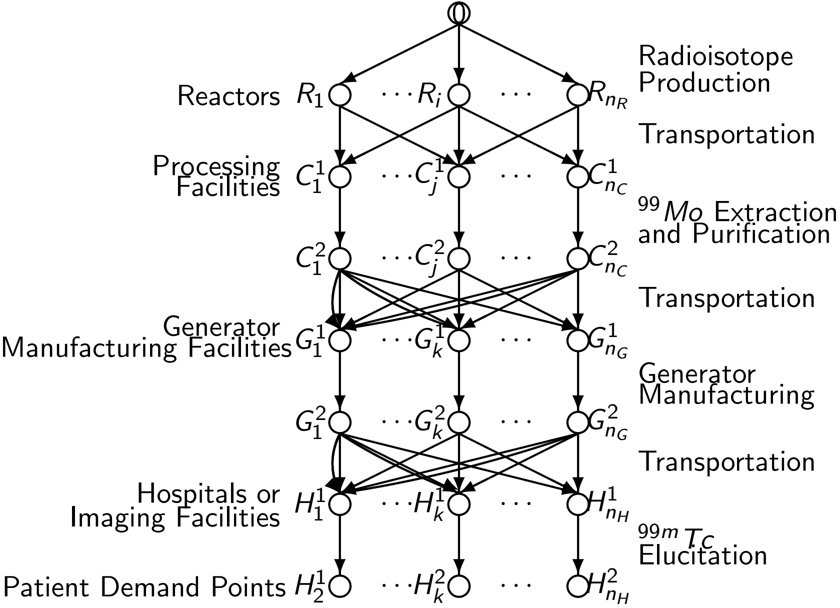


Figure: The Medical Nuclear Supply Chain Network Topology

Food Supply Chains

Food is something anyone can relate to.

Fascinating Facts About Food Perishability

Source: Food and Agriculture Organization (2011)

Fresh Produce Food Supply Chains

We developed a fresh produce supply chain network game theory oligopoly model that

1. captures the **deterioration of fresh food along the entire supply chain from a network perspective**;
2. handles the **exponential time decay through the introduction of arc multipliers**;
3. formulates **oligopolistic competition** with product differentiation;
4. includes the **disposal of the spoiled food products**, along with the associated costs;
5. allows for the **assessment of alternative technologies involved in each supply chain activity**.

Reference: "Competitive Food Supply Chain Networks with Application to Fresh Produce," Min Yu and Anna Nagurney, *European Journal of Operational Research* **224(2)** (2013), pp 273-282.

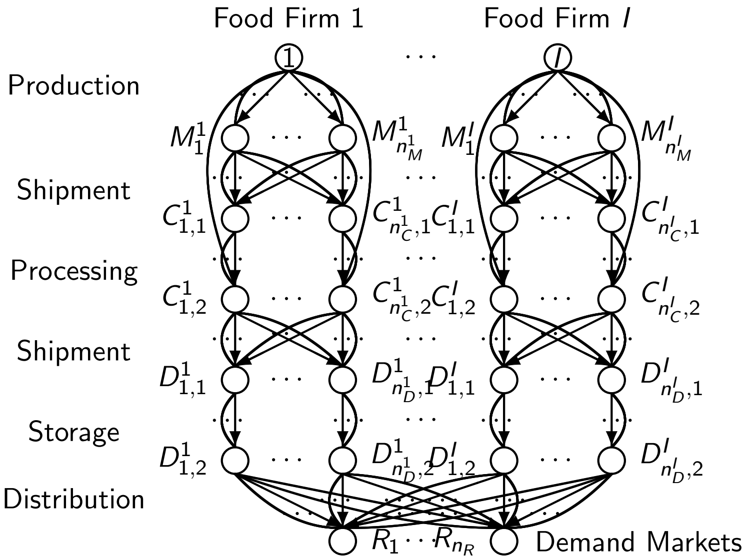


Figure: The Fresh Produce Supply Chain Network Topology

Fresh Produce Food Supply Chains

Food products also deteriorate over time and especially fresh produce. According to Nahmias (1982), each unit has a probability of $e^{\lambda t_a}$ of surviving t_a units of time where λ is the decay rate. Hence, arc multipliers can be constructed in a similar manner as those for the medical nuclear supply chain:

$$\alpha_a = e^{-\lambda t_a}$$

where λ is the decay rate for the food.

In rare cases, food deterioration follows the zero order reactions with linear decay (see Tijskens and Polderdijk (1996) and Rong, Akkerman, and Grunow (2011)). Then,

$$\alpha_a = 1 - \lambda t_a$$

for a post-production link.

Methodology - The VI Problem

Methodology - The Variational Inequality Problem

We utilize the theory of variational inequalities for the formulation, analysis, and solution of both centralized and decentralized supply chain network problems.

Definition: The Variational Inequality Problem

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

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

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

Methodology - The Variational Inequality Problem

The vector X consists of **the decision variables** – typically, the flows (products, prices, etc.).

$\mathcal{K}$ is the **feasible set representing how the decision variables are constrained** – for example, the flows may have to be nonnegative; budget constraints may have to be satisfied; similarly, quality and/or time constraints may have to be satisfied.

The function F that enters the variational inequality represents **functions that capture the behavior in the form of the functions such as costs, profits, risk, etc.**

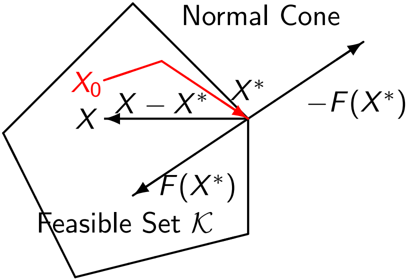
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- game theory problems, operating under Nash equilibrium,
- and is related to the fixed point problem.

Hence, it is a natural methodology for a spectrum of supply chain network problems from centralized to decentralized ones.

Geometric Interpretation of VI($F, \mathcal{K}$) and a Projected Dynamical System (Dupuis and Nagurney, Nagurney and Zhang)

In particular, $F(X^*)$ is "orthogonal" to the feasible set $\mathcal{K}$ at the point X^*.



Associated with a VI is a Projected Dynamical System, which provides the natural underlying dynamics.

To model the **dynamic behavior of complex networks**, including supply chains, we utilize *projected dynamical systems* (PDSs) advanced by Dupuis and Nagurney (1993) in *Annals of Operations Research* and by Nagurney and Zhang (1996) in our book *Projected Dynamical Systems and Variational Inequalities with Applications*.

Such nonclassical dynamical systems are now being used in

evolutionary games (Sandholm (2005, 2011)),

ecological predator-prey networks (Nagurney and Nagurney (2011a, b)),

even **neuroscience** (Girard et al. (2008), and

dynamic spectrum model for cognitive radio networks (Setoodeh, Haykin, and Moghadam (2012)).

New Trend in Demand for Blood Products in US

New Trend in Demand for Blood Products in US

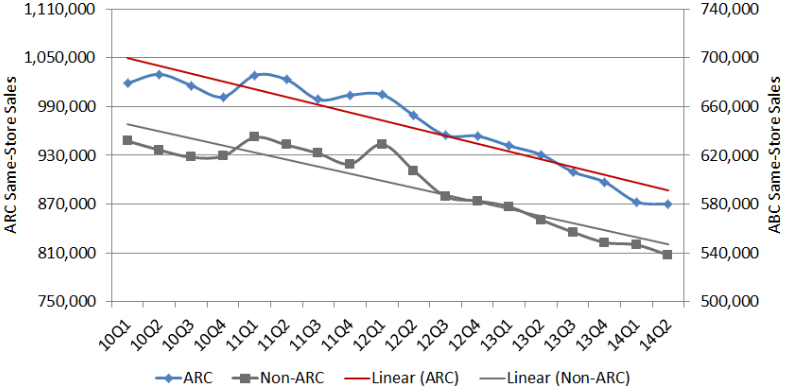
The dynamics for blood suppliers around the US has drastically changed over the past few years. **Demand for blood has declined since 2008**.

Prior to 2008 there were many cases of blood **shortages** in the U.S. but the scenario has changed. Now there is an **excess**.

In 2011, the number of units of whole blood and red blood cells collected and transfused, decreased by **9.1% and 8.2%** from 2008, respectively (Whitaker (2011)). This downward trend continued over the 2011 to 2013 period with both numbers suffering **4.4% and 9.4%** (Chung et al. (2016)).

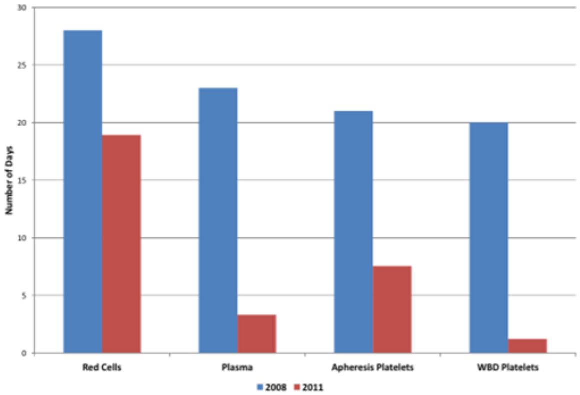
Demand for blood **continues to drop** despite population growth and a soaring number of people over 65.

Nationwide Distribution Trend of RBC



America's Blood Centers; January 2010-June 2014 DW Sales/Pricing Universe

Blood Shortages in 2008 vs 2011



Average number of days a hospital order was incomplete.

The 2011 National Blood Collection and Utilization Survey Report

Root Causes of the New Trend

Post-Recession **Economic Influences**

- Fewer elective surgeries.
- Reduced hospital census and historically low occupancy rates.

Medical/Technological Advancements

- Changes in **cancer therapy**, **coronary bypass surgery**, **hip replacement**, and **anemia**: *More transfusions do not yield better outcomes according to recent studies*.
- Implementation of Patient Blood Management (PBM) initiatives.

Impacts of the Recent Situation on Blood Operations

- **Reduced prices:** Hospitals, seeing strong supply and weak demand, are asking for a lower price per unit.
- **Reduced revenues:** From a high of $5 billion in 2008 to $1.5 billion (expected soon).
- **Lost jobs:** Expected to reach 12,000 within the next 3-5 years, roughly a quarter of the total in the industry.
- **Impaired research:** Less investment in quality improvement and slower progress in testing. System's ability to invest in new products or research is reduced.

Impacts of the Recent Situation on Blood Operations

The American Red Cross Blood Services:

- **Closed** 3 of its 5 testing centers.
- **Consolidated** divisions and regional leadership teams to oversee the operations.
- Operated **bigger blood collection sites** to increase efficiency.

Average Cost of a Blood Unit

The hospital cost of a unit of red blood cells in the US:

- **increased by 6.4%** from 2005 to 2007,
- almost **stayed the same** from 2008 to 2011.
- **decreased by almost 10%** from 2011 to 2014.

Mean hospital cost per unit of Red Blood Cells in 2014: **$225.**

Patients can be billed up to **$1,000** for this unit of blood.

Mergers & Acquisitions in Blood Services

The industry is going through **a wave of mergers and acquisitions**.
Americas Blood Centers, an association of independent blood banks, said its membership had fallen to **68** from **87** five years ago.
Most **collection agencies may survive** as independent entities. **Behind-the-scene activities** such as storage, testing, and distribution of blood banks will merge.

Instances of M&A in Blood Banking Industry

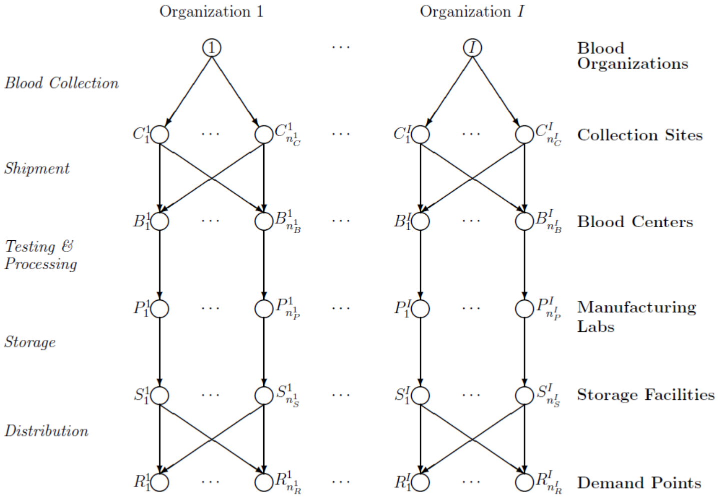
- In April 2010, Blood Center of **Iowa** and Siouxland Community Blood Bank merged operations.
- In August 2013, the American Red Cross acquired Delta Blood Bank, a nonprofit community blood bank serving **California**.
- In September 2013, **five nationally recognized blood centers across the US** announced the formation of a new alliance known as the HemeXcel Purchasing Alliance LLC.
- In July 2014, OneBlood, Inc. of Orlando, **Florida** and The Institute for Transfusion Medicine, Inc. (ITxM) announced that they have reached an agreement to pursue a merger.
- In December 2015, San Francisco's Blood Centers of the Pacific (BCP) and Sacramento's BloodSource announced their merger plan which would form the largest blood supplier in Northern and Central **California**.

The Supply Chain Network Model of a Blood Bank Merger or Acquisition

Our recent work seeks to determine whether it makes sense to have a merger or acquisition in this industry.

"Mergers and Acquisitions in Blood Banking Systems: A Supply Chain Network Approach," A.H. Masoumi, M. Yu, and A. Nagurney, *International Journal of Production Economics* **193** (2017), pp 406-421.

Network Topology for *I* Blood Organizations in the **Pre-Merger Problem**



Notation for the **Pre-Merger Blood Banking Problem**

Notation	Definition
$G_i = [N_i, L_i]$	Graph of nodes N_i and directed links L_i representing the activities associated with each Organization i; $i = 1, \ldots, I$.
$G^0 = [N^0, L^0]$	Graph of set of nodes and set of links in the topology for pre-merger problem.
$\mathcal{P}^0_{R^i_k}$	Set of paths joining top node of each Organization i to demand node k.
$\mathcal{P}^0$	Set of all paths in pre-merger problem. $n_{\mathcal{P}^0}$ denotes number of paths.

Notation for the **Pre-Merger Blood Banking Problem**

Parameter	Definition
d_{ik}	Stochastic parameter representing actual demand for RBCs at demand market R_k^i during a week.
$\bar{u}_a$	Existing capacity of link a; $a \in L^0$.
δ_{ap}	$\delta_{ap} = 1$, if link a is contained in path p; $\delta_{ap} = 0$, otherwise.
α_a	Arc multiplier associated with link a; $\alpha_a \in (0, 1]$.
α_{ap}	Arc-path multiplier is product of multipliers of links on path p that precede link a; $a \in L^0$ and $p \in \mathcal{P}^0$; $$\alpha_{ap} \equiv \begin{cases} \delta_{ap} \prod_{b \in \{a' < a\}_p} \alpha_b, & \text{if } \{a' < a\}_p \neq \emptyset, \\ \delta_{ap}, & \text{if } \{a' < a\}_p = \emptyset, \end{cases}$$ where $\{a' < a\}_p$ is set of links preceding link a in path p.

Notation for the Pre-Merger Blood Banking Problem

Parameter	Definition
μ_p	Multiplier corresponding to percentage of throughput on path p; $\mu_p \equiv \prod_{a \in p} \alpha_a$.
λ^-_{ik}	Penalty associated with shortage of unit of blood at R^i_k.
λ^+_{ik}	Penalty associated with the surplus of a unit of blood at R^i_k.

Notation for the Pre-Merger Blood Banking Problem

Decision Variable	Definition
v_{ik}	Projected demand for RBC at the demand point R_k^i during a week. Group the projected demands into $\sum_{i=1}^{I} n_R^i$-dimensional vector v.
x_p	Nonnegative flow of RBC on path p; $p \in \mathcal{P}^0$. Group path flows into $n_{\mathcal{P}^0}$-dimensional vector x.
f_a	Initial flow of RBC on link a; $a \in L^0$. Group link flows into n_{L^0}-dimensional vector f.
γ_a	Activity frequency of link a; $a \in L^0$ in time period. Group activity frequencies into n_{L^0}-dimensional vector γ.

Notation for the Pre-Merger Blood Banking Problem

Function	Definition
$\hat{c}_a = \hat{c}_a(f_a, \gamma_a)$	Total operational cost on link a; $a \in L^0$.
$\mathcal{F}_{ik}(t)$	Probability density function of actual demand at demand market R^i_k.
$P_{ik}(v_{ik})$	Cumulative distribution function of d_{ik}; $P_{ik}(v_{ik}) = P_{ik}(d_{ik} \leq v_{ik}) = \int_0^{v_{ik}} \mathcal{F}_{ik}(t)d(t)$.
$\hat{z}_a = \hat{z}_a(f_a)$	Total discarding cost function associated with product flow on link a.
$\Delta^-_{ik} = \Delta^-_{ik}(v_{ik})$	Shortage of blood at R^i_k; $\Delta^-_{ik} \equiv \max\{0, d_{ik} - v_{ik}\}$; $i = 1, \ldots, I$ and $k = 1, \ldots, n^i_R$. Expected shortage $E(\Delta^-_{ik}) = \int_{v_{ik}}^{\infty}(t - v_{ik})\mathcal{F}_{ik}(t)d(t)$.
$\Delta^+_{ik} = \Delta^+_{ik}(v_{ik})$	Surplus of blood at R^i_k; that is, $\Delta^+_{ik} \equiv \max\{0, v_{ik} - d_{ik}\}$. Expected surplus $E(\Delta^+_{ik}) = \int_0^{v_{ik}}(v_{ik} - t)\mathcal{F}_{ik}(t)d(t)$.

Pre-Merger Model: Formulation

Constraints

- Relationship between link flows and path flows:

$$f_a = \sum_{p \in \mathcal{P}^0} x_p \alpha_{ap}, \qquad \forall a \in L^0. \tag{1}$$

- Relationship between path flows and projected demand:

$$v_{ik} = \sum_{p \in \mathcal{P}^0_{R^i_k}} x_p \mu_p, \qquad i = 1, \ldots, I;\ k = 1, \ldots, n_R. \tag{2}$$

- Nonnegativity of path flows:

$$x_p \geq 0, \qquad \forall p \in \mathcal{P}^0. \tag{3}$$

- Capacity on links, and frequency of the activities:

$$f_a \leq \bar{u}_a \gamma_a, \qquad \forall a \in L^0. \tag{4}$$

Pre-Merger Model: Formulation

Objective Function

$$\text{Minimize} \sum_{i=1}^{I} \sum_{a \in L_i} \hat{c}_a(f_a, \gamma_a) + \sum_{i=1}^{I} \sum_{a \in L_i} \hat{z}_a(f_a) + \sum_{i=1}^{I} \sum_{k=1}^{n_R^i} \lambda_{ik}^- E(\Delta_{ik}^-) + \lambda_{ik}^+ E(\Delta_{ik}^+) \tag{5}$$

subject to: constraints (1)–(4).

Let $K \equiv \{(x, \gamma, \eta) | x \in R_+^{n_{\mathcal{P}^0}}, \gamma \in R_+^{n_{L^0}}, \eta \in R_+^{n_{L^0}}\}$ and for each p; $p \in \mathcal{P}^0_{R_k^i}$; $i = 1, \ldots, I$; $k = 1, \ldots, n_R^i$.

Equivalent Variational Inequality Formulation: Determine the vectors of **path flows**, **activity frequencies**, and **Lagrange multipliers** $(x^*, \gamma^*, \eta^*) \in K$:

$$\sum_{i=1}^{I} \sum_{k=1}^{n_R^i} \sum_{p \in \mathcal{P}^0_{R_k^i}} \left[\frac{\partial \hat{C}_p(x^*, \gamma^*)}{\partial x_p} + \frac{\partial \hat{Z}_p(x^*)}{\partial x_p} + \lambda_{ik}^+ \mu_p P_{ik} \left(\sum_{q \in \mathcal{P}^0_{R_k^i}} x_q^* \mu_q \right) \right.$$

$$\left. -\lambda_{ik}^- \mu_p \left(1 - P_{ik} \left(\sum_{q \in \mathcal{P}^0_{R_k^i}} x_q^* \mu_q \right) \right) + \sum_{a \in L_i} \eta_a^* \alpha_{ap} \right] \times [x_p - x_p^*]$$

$$+ \sum_{i=1}^{I} \sum_{a \in L_i} \left[\frac{\partial \hat{C}_p(x^*, \gamma^*)}{\partial \gamma_a} - \bar{u}_a \eta_a^* \right] \times [\gamma_a - \gamma_a^*]$$

$$+ \sum_{i=1}^{I} \sum_{a \in L_i} \left[\bar{u}_a \gamma_a^* - \sum_{q \in \mathcal{P}^0} x_q^* \alpha_{aq} \right] \times [\eta_a - \eta_a^*] \geq 0, \forall (x, \gamma, \eta) \in K. \quad (6)$$

With the following definitions:

For each path p:

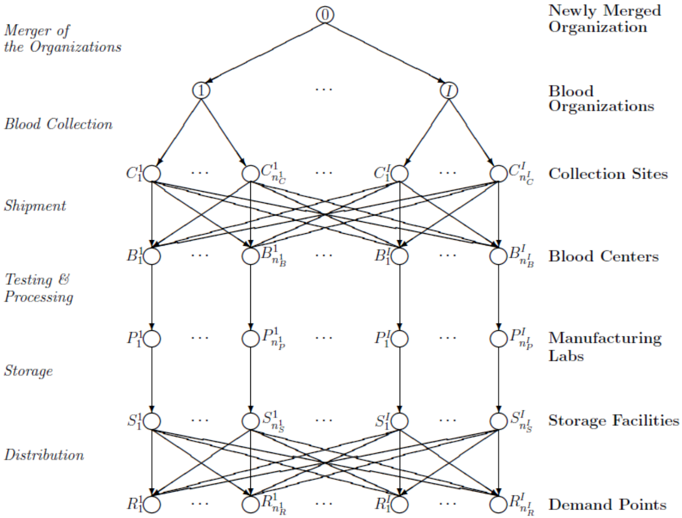
$$\frac{\partial \hat{C}_p(x,\gamma)}{\partial x_p} \equiv \sum_{a \in L^i} \frac{\partial \hat{c}_a(f_a,\gamma_a)}{\partial f_a} \alpha_{ap},$$

$$\frac{\partial \hat{Z}_p(x)}{\partial x_p} \equiv \sum_{a \in L^i} \frac{\partial \hat{z}_a(f_a)}{\partial f_a} \alpha_{ap}$$

and for each link a; $a \in L_i$; $i = 1, \ldots, I$,

$$\frac{\partial \hat{C}_p(x,\gamma)}{\partial \gamma_a} \equiv \frac{\partial \hat{c}_a(f_a,\gamma_a)}{\partial \gamma_a}.$$

Network Topology for the Merged Organizations (**Post-Merger Problem**)



Post-Merger Model: Formulation

Objective Function

For the merged blood organization, the total cost minimization problem can be expressed as:

$$\text{Minimize} \sum_{a \in L^1} \hat{c}_a(f_a, \gamma_a) + \sum_{a \in L^1} \hat{z}_a(f_a) + \sum_{i=1}^{I} \sum_{k=1}^{n_R^i} \lambda_{ik}^- E(\Delta_{ik}^-) + \lambda_{ik}^+ E(\Delta_{ik}^+) \tag{7}$$

Constraints (1)–(4) are updated accordingly for the post-merger problem.

Efficiency Measures Associated with a Merger

- **Total Cost Efficiency**:

$$\mathcal{E}^{\mathcal{TC}} \equiv \left[\frac{TC^0 - TC^1}{TC^0} \right] \times 100\%, \tag{8}$$

where TC^0 and TC^1 represent the optimal objective values of the pre-merger model and the post-merger model, respectively.

Efficiency Measures Associated with a Merger

- **Supply Shortage Synergy Measure**:

$$\mathcal{S}^{-} = \left[\frac{S^{0-} - S^{1-}}{S^{0-}}\right] \times 100\%, \tag{9}$$

- **Supply Surplus Synergy Measure**:

$$\mathcal{S}^{+} = \left[\frac{S^{0+} - S^{1+}}{S^{0+}}\right] \times 100\%, \tag{10}$$

where S^{0-} and S^{1-} represent the expected total supply shortage costs (penalties) associated with the pre-merger model and the post-merger model.

Case Study: A Merger Between Two Blood Banks

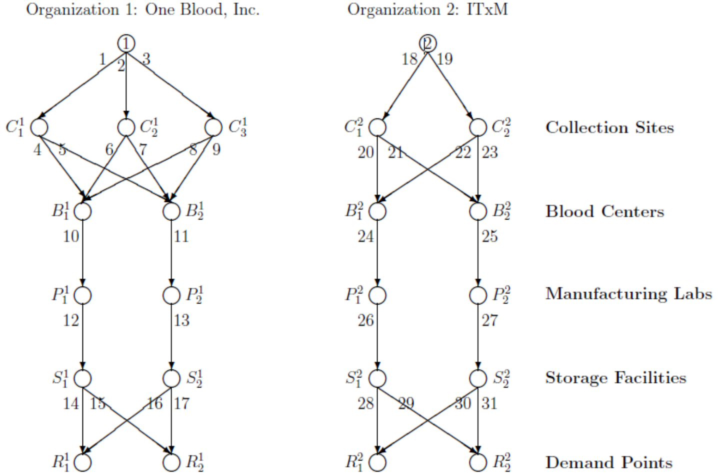
Case Study

A recent pending case of the merger between **OneBlood, Inc.,** and **The Institute for Transfusion Medicine, Inc. (ITxM)** was examined in this research.

The two blood banks announced their agreement to pursue a merger in July 2014 which would create the **largest independent not-for-profit blood center in the United States** distributing nearly 2 million units of blood annually, with combined revenues of $480 million and employing more than 3,500 people.

The merger process is said to have become **suspended in 2015**.

Case Study: Topology for the Pre-Merger Problem



Case Study: Assumptions

For Organization 1 (OneBlood,Inc.):

- Blood centers, manufacturing labs, and storage centers are co-located in two consolidated facilities, one in Fort Lauderdale, the other one in Tampa.

- Weekly demand for red blood cells in the two Floridian hospitals is assumed to follow a continuous uniform distribution on the intervals [200,400] and [150,250], respectively.

Case Study: Assumptions

For Organization 2 (ITxM):

- Blood centers, manufacturing labs, and storage centers are co-located in two consolidated facilities, one in Chicago, the other one in Pittsburgh.
- Weekly demand for red blood cells in the two hospitals (located in Chicago and Pittsburgh) is assumed to follow a continuous uniform distribution on the intervals [220,370] and [80,110], respectively.

Case Study: Assumptions

Shortage and surplus penalty units at the hospitals

$$\lambda_1^{1-} = 7,000,\ \lambda_2^{1-} = 6,000,\ \lambda_1^{2-} = 8,000, \quad \text{and } \lambda_2^{2-} = 3,700.$$

$$\lambda_1^{1+} = 50,\ \lambda_2^{1+} = 60,\ \lambda_1^{2+} = 40, \quad \text{and } \lambda_2^{2+} = 75.$$

Throughput Multipliers, Weekly Capacities, and Total Cost Functions for Blood Banks in the Pre-Merger Problem

Link a	α_a	$\bar{u}_a$	$\hat{c}_a(f_a, \gamma_a)$	$\hat{z}_a(f_a)$
1	.97	200	$.13(f_1)^2 + .2f_1 + (\gamma_1)^2$	$.8f_1$
2	.98	225	$.15(f_2)^2 + .3f_2 + 1.5(\gamma_2)^2$	$.7f_2$
3	.99	225	$.10(f_3)^2 + .25f_3 + (\gamma_3)^2$	$.7f_3$
4	1.00	35	$2f_4 + 2\gamma_4$	0
5	.99	25	$.35(f_5)^2 + .8f_5 + 9(\gamma_5)^2 + 3\gamma_5$	$.8f_5$
6	.99	40	$1.4f_6 + 4\gamma_6$	0
7	1.00	30	$.05(f_7)^2 + .1f_7 + (\gamma_7)^2$	$.7f_7$
8	.99	25	$.18(f_8)^2 + .4f_8 + 3(\gamma_8)^2 + 2\gamma_8$	$.8f_8$
9	1.00	40	$.85f_9 + 2.5\gamma_9$	0
10	.96	1,800	$.55(f_{10})^2 + 2f_{10} + 3(\gamma_{10})^2$	$.8f_{10}$
11	.94	1,600	$.45(f_{11})^2 + 2.5f_{11} + 2(\gamma_{11})^2$	$.7f_{11}$
12	.99	2,000	$.07(f_{12})^2 + .5f_{12} + 2(\gamma_{12})^2$	$.8f_{12}$
13	.99	1,600	$.06(f_{13})^2 + .4f_{13} + 1.5(\gamma_{13})^2$	$.7f_{13}$
14	1.00	36	$.9f_{14} + 3.5\gamma_{14}$	0
15	.99	40	$.25(f_{15})^2 + 2.8f_{15} + 4.5(\gamma_{15})^2 + 4.5\gamma_{15}$	$.8f_{15}$
16	.99	40	$.12(f_{16})^2 + 2.5f_{16} + 4(\gamma_{16})^2 + 5\gamma_{16}$	$.9f_{16}$
17	1.00	35	$1.1f_{17} + 2.5\gamma_{17}$	0

Link a	α_a	$\bar{u}_a$	$\hat{c}_a(f_a, \gamma_a)$	$\hat{z}_a(f_a)$
18	.98	260	$.11(f_{18})^2 + .3f_{18} + 2(\gamma_{18})^2$	$.6f_{18}$
19	.99	235	$.13(f_{19})^2 + .2f_{19} + (\gamma_{19})^2$	$.7f_{19}$
20	1.00	25	$f_{20} + .5(\gamma_{20})^2 + 4\gamma_{20}$	0
21	.99	35	$.09(f_{21})^2 + .5f_{21} + (\gamma_{21})^2 + 4\gamma_{21}$	$.8f_{21}$
22	.98	35	$.14(f_{22})^2 + .9f_{22} + 1.5(\gamma_{22})^2 + 7.5\gamma_{22}$	$.75f_{22}$
23	1.00	35	$.8f_{23} + 3\gamma_{23}$	0
24	.95	2,200	$.6(f_{24})^2 + 1.1f_{24} + 2.5(\gamma_{24})^2$	$.6f_{24}$
25	.96	2,000	$.85(f_{25})^2 + 1.5f_{25} + 3(\gamma_{25})^2$	$.7f_{25}$
26	.99	2,500	$.05(f_{26})^2 + .4f_{26} + (\gamma_{26})^2$	$.6f_{26}$
27	1.00	2,150	$.06(f_{27})^2 + .6f_{27} + 2(\gamma_{27})^2$	$.5f_{27}$
28	1.00	30	$.6f_{28} + 4\gamma_{28}$	0
29	.99	40	$.1(f_{29})^2 + .5f_{29} + 2(\gamma_{29})^2 + 5\gamma_{29}$	$.9f_{29}$
30	.99	35	$.4(f_{30})^2 + 1.3f_{30} + 2(\gamma_{30})^2 + 6\gamma_{30}$	$.7f_{30}$
31	1.00	40	$.5f_{31} + 2.5\gamma_{31}$	0

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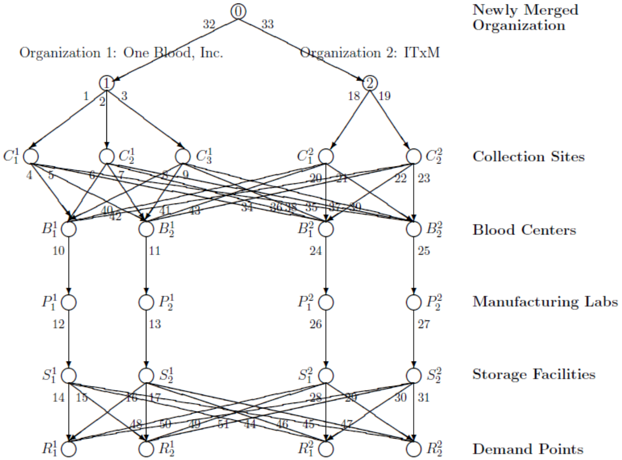
Solution Method

We implemented the **Euler method** for the variational inequality formulation (6) in the pre-merger problem.

We used **Matlab** to calculate the optimal values of **link flows, link frequencies, Lagrange multipliers**, among other quantities of interest for **every single link belonging to each organization**.

The convergence tolerance was $\epsilon = 10^{-5}$.

Case Study: Topology for the Post-Merger Problem



Case Study: Parameters for the **New Links** in the Post-Merger Problem

Link a	α_a	$\bar{u}_a$	$\hat{c}_a(f_a, \gamma_a)$	$\hat{z}_a(f_a)$
32	1.00	n/a	0	0
33	1.00	n/a	0	0
34	.99	30	$.4(f_{34})^2 + 1f_{34} + 9(\gamma_{34})^2 + 4\gamma_{34}$	$.75f_{34}$
35	.98	30	$.15(f_{35})^2 + 1.4f_{35} + 10(\gamma_{35})^2 + 5\gamma_{35}$	$.75f_{35}$
36	.99	30	$.5(f_{36})^2 + 2f_{36} + 8(\gamma_{36})^2 + 7\gamma_{36}$	$.9f_{36}$
37	.98	30	$.25(f_{37})^2 + 1f_{37} + 12(\gamma_{37})^2 + 6.5\gamma_{37}$	$.8f_{37}$
38	.98	30	$.3(f_{38})^2 + 1.5f_{38} + 9(\gamma_{38})^2 + 4\gamma_{38}$	$.75f_{38}$
39	.99	30	$.55(f_{39})^2 + 2f_{39} + 10(\gamma_{39})^2 + 4.5\gamma_{39}$	$.8f_{39}$
40	.99	25	$.17(f_{40})^2 + 1.5f_{40} + 7(\gamma_{40})^2 + 6\gamma_{40}$	$.75f_{40}$
41	1.00	25	$.15(f_{41})^2 + 2f_{41} + 7.5(\gamma_{41})^2 + 4\gamma_{41}$	$.6f_{41}$
42	.99	25	$.2(f_{42})^2 + 2f_{42} + 6(\gamma_{42})^2 + 6\gamma_{42}$	$.55f_{42}$
43	.98	25	$.25(f_{43})^2 + 2.5f_{43} + 8(\gamma_{43})^2 + 6\gamma_{43}$	$.7f_{43}$
44	.99	35	$.15(f_{44})^2 + 3f_{44} + 4.5(\gamma_{44})^2 + 6\gamma_{44}$	$.55f_{44}$
45	1.00	35	$.17(f_{45})^2 + 3f_{45} + 7(\gamma_{45})^2 + 5\gamma_{45}$	$.6f_{45}$
46	1.00	35	$.18(f_{46})^2 + 2.5f_{46} + 5(\gamma_{46})^2 + 4.5\gamma_{46}$	$.65f_{46}$
47	.99	35	$.16(f_{47})^2 + 3.5f_{47} + 4(\gamma_{47})^2 + 7\gamma_{47}$	$.65f_{47}$
48	1.00	32	$.35(f_{48})^2 + 3f_{48} + 2.5(\gamma_{48})^2 + 5\gamma_{48}$	$.55f_{48}$
49	.99	32	$.38(f_{49})^2 + 4f_{49} + 2(\gamma_{49})^2 + 6\gamma_{49}$	$.65f_{49}$
50	.98	32	$.4(f_{50})^2 + 1.8f_{50} + 3(\gamma_{50})^2 + 5.5\gamma_{50}$	$.5f_{50}$
51	1.00	32	$.35(f_{51})^2 + 1.5f_{51} + 2.5(\gamma_{51})^2 + 7\gamma_{51}$	$.55f_{51}$

Case Study: Observations

Under Normal Demand Scenario

- The majority of links in the post-merger problem have **maintained similar flows** to the pre-merger problem.
- A few links (mostly of distribution type) demonstrate some notable changes in the optimal weekly amount of blood to be distributed to their respective hospitals.
- **Only 3 out of the 18** newly added links play a relatively significant role in the post-merger problem.
- **Satisfaction of the hospital demand via the further blood center cannot be economically justified due to a significantly higher transportation cost [At most, between 10-20% of the demand can be satisfied via the new links.]**

Case Study: A Demand Surge Scenario

We used the same merger case to compare the resiliency of blood banks in the pre- and post-merger problems **during the response phase of a disaster**, which leads to a surge in demand.

Case Study: A **Demand Surge** Scenario

Assume a large-scale natural disaster has hit parts of Florida, resulting in an abrupt surge in demand for red blood cells immediately after the occurrence of the disaster. Assume the demand at the two Floridian hospitals during that week experiences an **increase by a factor of 10** as compared to the base scenario.

The demand at the other two hospitals (located in Chicago and Pittsburgh) **remains unchanged**.

We re-ran the algorithm to compare the performance of the blood banks in the pre- and post-merger problem under the new demand scenario.

Case Study: Observations

Under Raised Demand Scenario

In the pre-merger problem:

- The optimal link flows and frequencies on links corresponding to OneBlood have largely increased to be able to respond to the demand surge in the hospitals. The other organization **experiences no changes**, not surprisingly.

In the post-merger problem:

- Several links **across the supply chain network** experience increased flows and frequencies in the optimal solution.
- The two hospitals located in Chicago and Pittsburgh (over a thousand miles away from the impacted region) have **suffered drops** of 8.8% and 13.7% in their projected demand values.

Case Study: Discussion on **Synergy** of the Merger

	Status Quo Scenario			Disaster Scenario		
	Pre-Merger		Post-Merger	Pre-Merger		Post-Merger
	OneBlood, Inc.	ITxM		OneBlood, Inc.	ITxM	
Total Objective Value	$\$161,753.22$	$\$119,078.72$	$\$278,957.84$	$\$11,666,944.68$	$\$119,079.06$	$\$8,966,685.81$
Expected Total Shortage Cost	$\$6,044.32$	$\$3,570.41$	$\$9,528.83$	$\$2,932,952.43$	$\$3,570.03$	$\$1,606,741.21$
Expected Total Surplus Cost	$\$6,796.02$	$\$3,465.61$	$\$10,263.21$	$\$16,609.31$	$\$3,465.64$	$\$31,052.66$
$\mathcal{E}^{TC}$	0.67%			23.92%		
$\mathcal{S}^-$	0.67%			45.28%		
$\mathcal{S}^+$	-0.02%			-54.68%		

When the two merging blood banks are **geographically distant**, the synergy gained from the merger is **not significant** under **normal demand** situations.

In contrast, under a **demand surge** scenario, the merged organization will experience a **significant synergy**, both in terms of the total operational cost as well as the expected shortage penalty.

Game Theory and Blood Supply Chains

Competition and Blood Supply Chains

• An estimated 38% of the US population is eligible to donate blood at any given time. However, less than 10% of that eligible population actually donates blood each year. The percentage is even lower in some countries such as Britain and New Zealand.

• The different blood service organizations have to compete for this limited donor pool.

Competition and Blood Supply Chains

Along with a doctoral student, Pritha Dutta, we are developing game theory models to capture competition in blood supply chains. "Competition for Blood Donations: A Nash Equilibrium Framework," A. Nagurney and P. Dutta (2017).

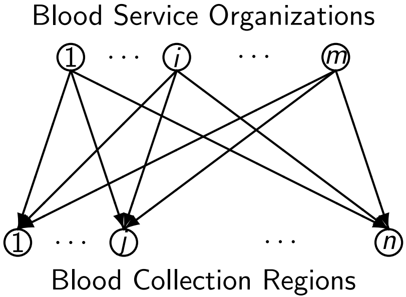
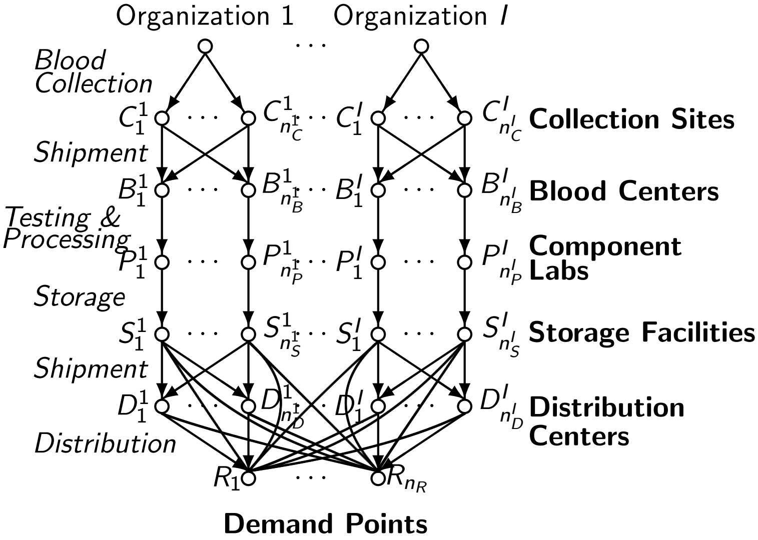


Figure: The Network Structure of the Game Theory Model for Blood Donations

Competition and Blood Supply Chains

Blood service organizations also compete to provide blood.



Summary and Conclusions

Summary and Conclusions

• Operations Research can provide assistance in blood supply chains, which is very much needed, given the characteristics of blood and the pressures in this industry.

• Blood is a perishable product and, hence, tools from OR are directly applicable.

• Moreover, the realities of M&As in this industry are amenable to analysis in terms of synergy via OR.

• Finally, the competition in this industry for both donors as well as for reduced prices, different contracts, and enhanced services for hospitals and medical centers allows us to utilize game theory in this area, which is quite novel.

• Further discussions with medical professionals is also unveiling issues in that younger blood may be better blood, opening up further directions for research.

Thank You!

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