Multitiered Blood Supply Chain Network Competition: Linking Blood Service Organizations, Hospitals, and Payers

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Introduction

This presentation is based on the paper:

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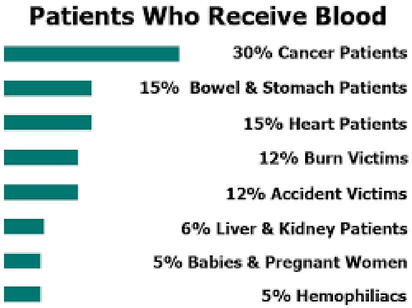
Outline

Background

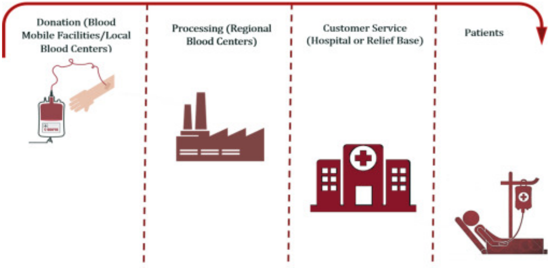
- In the United States nearly 21 million blood components; namely, red blood cells (RBCs), platelets and plasma, are transfused each year.
- Approximately 36,000 units of red blood cells are needed every day in the United States.
- Blood transfusions are integral parts of organ transplant surgeries, cardiovascular surgeries and treating trauma victims and diseases such as malaria.



Background

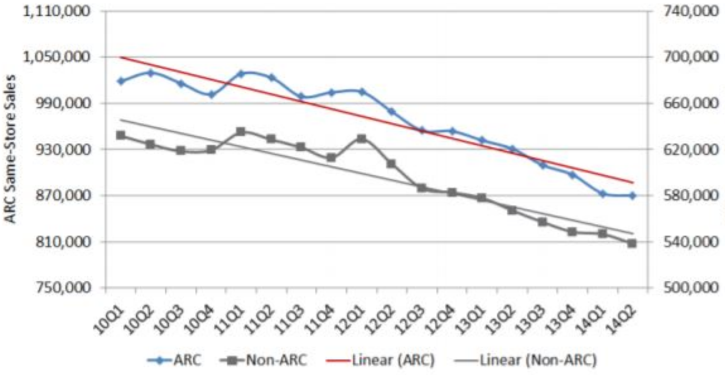
Blood supply chains comprise of:

- Blood service organizations
- Blood testing laboratories
- Hospitals and trauma centers
- Patients



Background

Various factors such as decrease in demand for blood, hospital consolidation, etc., have led to the increase in competition among blood suppliers.



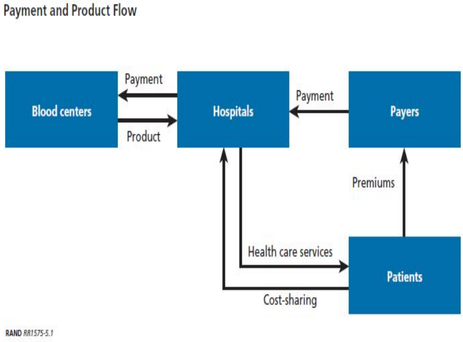
America's Blood Centers; January 2010-June 2014 DW Sales/Pricing Universe

Background

Two key economic relationships:

- Blood service organizations and hospitals
- Hospitals and payers

For several reasons the **economic sustainability** of the blood service organizations is under question.

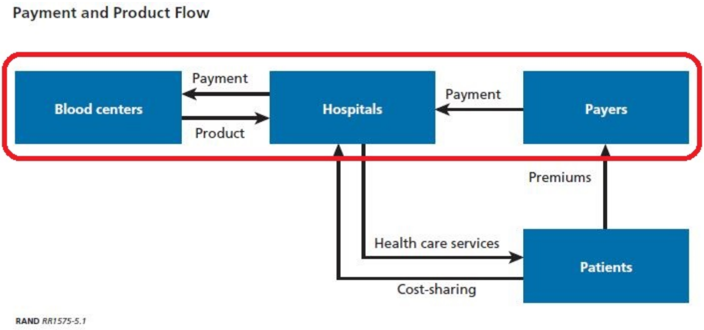


Background

- Operations maintained by blood service organizations are **capital intensive**.
- BSOs charge hospitals fee for their costs and hospitals in turn get reimbursed for their costs by patient payers such as insurance companies and government programs.
- There appears to be a **disconnect between the costs and payments received**.
- **Mulcahy et al. (2016)** suggested an alternative reimbursement policy that would take into account costs and units of blood transfused.

Background

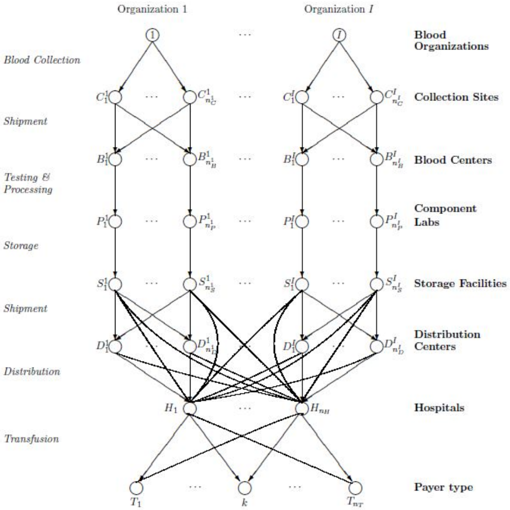
In this paper a multitiered game theory model is developed to determine the **optimal flow of RBCs** from blood suppliers to hospitals, **amount of RBC to be transfused** by hospitals to patients belonging to different payer groups, **prices** charged by BSOs and **reimbursements** received by hospitals from payers.



Literature Review

- **Nagurney, Dong, and Zhang (2002)** developed an equilibrium model for a competitive supply chain network with separate tiers for multiple manufacturers, multiple retailers, and multiple demand markets.
- **Bernstein and Federgruen (2005)** studied the equilibrium conditions in a two-echelon supply chain where a single supplier supplies materials to multiple competing retailers.
- **Mahmoodi and Eshghi (2014)** considered price competition between two-tiered supply chains consisting of manufacturers and retailers.
- **Nagurney, Masoumi, and Yu (2012)** developed a multicriteria optimization model taking into account all the major supply chain activities between a regional blood bank and its demand markets.
- **Nagurney and Dutta (2019)** developed an integrated network model to capture the competition among blood suppliers for donations as well as supply contracts with hospitals.

The Multitiered Blood Supply Chain Network Competition Model



Behavior of the Blood Service Organizations

The conservation of flow equation that has to hold for each BSO i; $i = 1, \ldots, I$, at hospital j; $j = H_1, \ldots, H_{n_H}$, is:

$$\sum_{p \in P_j^i} x_p \mu_p = q_{ij},$$

where x_p is the flow along path p, $\mu_p \equiv \prod_{a \in p} \alpha_a$; $p \in P$, denotes the multiplier corresponding to the percentage of throughput on path p.

Behavior of the Blood Service Organizations

Nonnegativity Constraint

Since the path flows must be nonnegative, we have that:

$$x_p \geq 0, \quad \forall p \in P.$$

Link and Path Flows

Let f_a denote the flow of blood on link a. Then, the following conservation of flow equations must hold:

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

Behavior of the Blood Service Organizations

Utility Function

The utility function of blood service organization i; $i = 1, \ldots, I$, denoted by U_i, can be expressed as:

$$U_i = \sum_{j=H_1}^{H_{n_H}} \rho_{ij}^{1*} q_{ij} + \omega_i \sum_{j=H_1}^{H_{n_H}} \gamma_{ij} q_{ij} - \sum_{a \in L^i} \hat{c}_a(f),$$

or, equivalently, in terms of path flows:

$$\hat{U}_i = \sum_{j=H_1}^{H_{n_H}} \rho_{ij}^{1*} \sum_{p \in P_j^i} x_p \mu_p + \omega_i \sum_{j=H_1}^{H_{n_H}} \gamma_{ij} \sum_{p \in P_j^i} x_p \mu_p - \sum_{a \in L^i} \tilde{\hat{c}}_a(x),$$

with $\tilde{\hat{c}}_a(x) \equiv \hat{c}_a(f)$, $\forall a \in L$.

Behavior of the Blood Service Organizations

Feasible Set

The feasible set for blood service organization i is defined as $K_i \equiv \{X_i | x_i \in R_+^{n_{P^i}}\}$.
X_i denotes the vector of path flows corresponding to blood service organization i; $i = 1, \ldots, I$:

$$X_i \equiv \{\{x_p\} | p \in P^i\}\} \in R_+^{n_{P^i}}$$

Behavior of the Blood Service Organizations

Optimality Conditions

The optimality conditions for all the blood service organizations simultaneously can be expressed as the following variational inequality (cf. Gabay and Moulin (1980), Nagurney (1999)): determine $x^* \in K^1, K^1 \equiv \prod_{i=1}^{I} K_i$, such that:

$$\sum_{i=1}^{I} \sum_{j=H_1}^{H_{n_H}} \sum_{p \in P_j^i} \left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} - \omega_i \gamma_{ij} \mu_p - \rho_{ij}^{1*} \mu_p \right] \times [x_p - x_p^*] \geq 0 \quad \forall x \in K^1,$$

where $\frac{\partial \hat{C}_p(x)}{\partial x_p}$ is for path $p \in P_j^i$ given by

$$\frac{\partial \hat{C}_p(x)}{\partial x_p} \equiv \sum_{a \in L^i} \sum_{b \in L^i} \frac{\partial \hat{c}_b(f)}{\partial f_a} \alpha_{ap}.$$

Behavior of the Hospitals

The total amount of blood transfused by hospital j; $j = H_1, \ldots, H_{n_H}$, cannot exceed the total amount it receives from its contracted suppliers. Therefore, the following condition must be satisfied

$$\sum_{k=T_1}^{T_{n_T}} q_{jk} \leq \sum_{i=1}^{I} q_{ij},$$

or, equivalently,

$$\sum_{k=T_1}^{T_{n_T}} q_{jk} \leq \sum_{i=1}^{I} \sum_{p \in P_j^i} x_p \mu_p.$$

Behavior of the Hospitals

Optimization Problem

The optimization problem for hospital j; $j = H_1, \ldots, H_{n_H}$, is

$$\text{Maximize} \quad \rho_j^{2*} \sum_{k=T_1}^{T_{n_T}} q_{jk} + \beta_j \sum_{k=T_1}^{T_{n_T}} \theta_{jk} q_{jk} - h_j\Big(\sum_{k=T_1}^{T_{n_T}} q_{jk}\Big) - \sum_{i=1}^{I} \rho_{ij}^{1*} \sum_{p \in P_j^i} x_p \mu_p,$$

subject to the constraint shown earlier and the nonnegativity constraints: $x_p \geq 0$, $\forall p \in P_j$, where P_j is the set of all paths terminating in j, and $q_{jk} \geq 0$ for all j and k.

- **Revenue**
- **Monetized altruism**
- **Inventory cost**
- **Procurement cost**

Optimality Conditions

Assuming that the holding cost for each hospital is convex and continuous, the optimality conditions for all hospitals, simutaneously, coincide with the solution of the variational inequality: determine $(x^*, q^*, \eta^*) \in K^2$ satisfying

$$\sum_{i=1}^{I}\sum_{j=H_1}^{H_{n_H}}\sum_{p\in P_j^i}\left[\rho_{ij}^{1*}\mu_p-\eta_j^*\mu_p\right]\times[x_p-x_p^*]+\sum_{j=H_1}^{H_{n_H}}\sum_{k=T_1}^{T_{n_T}}\left[-\rho_j^{2*}-\beta_j\theta_{jk}+\frac{\partial h_j(\sum_{k=T_1}^{T_{n_T}} q_{jk}^*)}{\partial q_{jk}}\right.$$

$$\left.+\eta_j^*\right]\times[q_{jk}-q_{jk}^*]+\sum_{j=H_1}^{H_{n_H}}\left[\sum_{i=1}^{I}\sum_{p\in P_j^i}x_p^*\mu_p-\sum_{k=T_1}^{T_{n_T}}q_{jk}^*\right]\times[\eta_j-\eta_j^*]\geq 0$$

$$\forall (x,q,\eta)\in K^2,$$

with the feasible set K^2 defined as:

$$K^2 \equiv \{(x,q,\eta)|x\in R_+^{n_P}, q\in R_+^{n_H n_T}, \eta\in R_+^{n_H}\}.$$

Behavior of the Payer Groups

Equilibrium Conditions

The equilibrium conditions are: For all hospitals j; $j = H_1, \ldots, H_{n_H}$, and payers $k = T_1, \ldots, T_{n_T}$:

$$\rho_j^{2*} + c_{jk}(q^*) \begin{cases} = \rho_{jk}^{3*} & \text{if} \quad q_{jk}^* > 0, \\ \geq \rho_{jk}^{3*} & \text{if} \quad q_{jk}^* = 0. \end{cases}$$

and

$$d_{jk}(\rho^{3*}) \begin{cases} = q_{jk}^* & \text{if} \quad \rho_{jk}^{3*} > 0, \\ \leq q_{jk}^* & \text{if} \quad \rho_{jk}^{3*} = 0. \end{cases}$$

where ρ_{jk}^3 is the reimbursement from payer k to hospital j, $d_{jk}(\rho^3)$ is the demand at hospital j from payer group k, and c_{jk} is the transaction cost.

Multitiered Blood Supply Chain Network Equilibrium

Multitiered Blood Supply Chain Network Equilibrium

The equilibrium state of the supply chain is one where the blood product (RBC) flows between the three distinct tiers of decision-makers coincide and the blood flows and prices satisfy the sum of the optimality conditions.

Variational Inequality Formulation

Theorem: Variational Inequality Formulation

The equilibrium conditions governing the supply chain model with competition are equivalent to the solution of the variational inequality problem given by: determine $(x^*, q^*, \eta^*, \rho^{3*}) \in K^4$ satisfying:

$$\sum_{i=1}^{I} \sum_{j=H_1}^{H_{n_H}} \sum_{p \in P_j^i} \left[\frac{\partial \hat{C}_p(x^*)}{\partial x_p} - \omega_i \gamma_{ij} \mu_p - \eta_j^* \mu_p \right] \times [x_p - x_p^*]$$

$$+ \sum_{j=H_1}^{H_{n_H}} \sum_{k=T_1}^{T_{n_T}} [c_{jk}(q^*) + \frac{\partial h_j(\sum_{k=T_1}^{T_{n_T}} q_{jk}^*)}{\partial q_{jk}} + \eta_j^* - \beta_j \theta_{jk} - \rho_{jk}^{3*}] \times [q_{jk} - q_{jk}^*]$$

$$+ \sum_{j=H_1}^{H_{n_H}} \left[\sum_{i=1}^{I} \sum_{p \in P_j^i} x_p^* \mu_p - \sum_{k=T_1}^{T_{n_T}} q_{jk}^* \right] \times [\eta_j - \eta_j^*] + \sum_{j=H_1}^{H_{n_H}} \sum_{k=T_1}^{T_{n_T}} [q_{jk}^* - d_{jk}(\rho^{3*})] \times [\rho_{jk}^3 - \rho_{jk}^{3*}] \geq 0$$

$$\forall (x, q, \eta, \rho^3) \in K^4,$$

where $K^4 \equiv \{(x, q, \eta, \rho^3) \in R_+^{n_P + 2n_H n_T + n_H}\}$.

Illustrative Examples

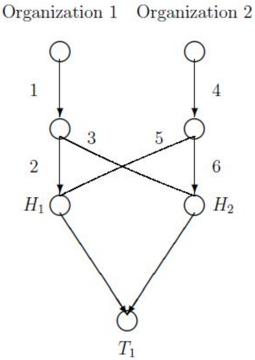


Figure 5.2. The Blood Supply Chain Network Topology for the Illustrative Examples

Paths: $p_1 = (1, 2)$, $p_2 = (1, 3)$, $p_3 = (4, 5)$, and $p_6 = (4, 6)$. The time horizon is assumed to be a week. μ_ps are all equal to 1, $\forall p$.

Example 1

Total Link Cost Functions

$$\hat{c}_1(f_1) = f_1^2 + 1.5f_1, \quad \hat{c}_2(f_2) = f_2^2 + 2f_2, \quad \hat{c}_3(f_3) = f_3^2 + 2.5f_3,$$
$$\hat{c}_4(f_4) = f_4^2 + 2f_4, \quad \hat{c}_5(f_5) = f_5^2 + 2f_5, \quad \hat{c}_6(f_6) = f_6^2 + 2.5f_6.$$

Altruism Components

$$\omega_1 = \omega_2 = \beta_{H_1} = \beta_{H_2} = 0.$$

Holding Cost Functions

$$h_{H_1}(q_{H_1T_1}) = 1.5 \times q_{H_1T_1}, \quad h_{H_2}(q_{H_2T_1}) = 1.5 \times q_{H_2T_1}.$$

Example 1

Transaction Cost Functions

$$c_{H_1T_1}(q_{H_1T_1}) = q_{H_1T_1} + 100, \quad c_{H_2T_1}(q_{H_2T_1}) = q_{H_2T_1} + 100.$$

Demand Price Functions

$$d_{H_1T_1} = -0.005\rho^3_{H_1T_1} + 0.002\rho^3_{H_2T_1} + 100,$$

$$d_{H_2T_1} = -0.005\rho^3_{H_2T_1} + 0.002\rho^3_{H_1T_1} + 100.$$

Example 1

Equilibrium Path Flows

$x^*_{p_1} = x^*_{p_2} = 49.29, x^*_{p_3} = x^*_{p_4} = 49.21.$

Equilibrium Prices Charged by the BSOs

$\eta^*_{H_1} = 299.25$ and $\eta^*_{H_2} = 299.75.$

Equilibrium Prices Charged by Hospitals

$\rho^{2*}_{H_1} = 300.75$ and $\rho^{2*}_{H_2} = 301.25.$

Quantities of Blood Transfused

$q^*_{H_1 T_1} = q^*_{H_2 T_1} = 98.50.$

Reimbursements from Payers

$\rho^{3*}_{H_1 T_1} = 499.25$ and $\rho^{3*}_{H_2 T_1} = 499.75$

Example 2

Network structure and input data remains same as Example 1 except here

$$\alpha_1 = 1, \quad \alpha_2 = 0.95, \quad \alpha_3 = 1, \quad \alpha_4 = 1, \quad \alpha_5 = 1, \quad \alpha_6 = 0.98.$$

Hence, the path multipliers are:

$$\mu_{p_1} = 1 \times 0.95 = 0.95, \quad \mu_{p_2} = 1, \quad \mu_{p_3} = 1, \quad \mu_{p_4} = 1 \times 0.98 = 0.98.$$

Example 2

Equilibrium Path Flows

$x^*_{p_1} = 48.35, x^*_{p_2} = 51.36, x^*_{p_3} = 52.53, x^*_{p_4} = 48.10.$

Equilibrium Prices charged by the BSOs

$\eta^*_{H_1} = 310.29$ and $\eta^*_{H_2} = 307.63.$

Equilibrium Prices Charged by Hospitals

$\rho^{2*}_{H_1} = 311.75$ and $\rho^{2*}_{H_2} = 307.63.$

Quantities of Blood Transfused

$q^*_{H_1 T_1} = 98.46$, and $q^*_{H_2 T_1} = 98.49.$

Reimbursements from Payers

$\rho^{3*}_{H_1 T_1} = 510.26$, and $\rho^{3*}_{H_2 T_1} = 506.12.$

Algorithm

Modified Projection Method

Step 0. Initialization
Initialize with $Y^0 \in \mathcal{K}$. Set $\tau = 1$ and select ψ, such that $0 < \psi \leq 1/L$, where L is the Lipschitz constant.

Step 1: Computation
Compute $\bar{Y}^\tau$ by solving the variational inequality subproblem:

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

Step 2: Adaptation
Compute Y^τ by solving the variational inequality subproblem :

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

Step 3: Convergence Verification
If $|Y^\tau - Y^{\tau-1}| \leq \epsilon$, for $\epsilon > 0$, a pre-specified tolerance level, then stop; otherwise, set $\tau := \tau + 1$, and go to Step 1.

Explicit Formulae for the Modified Projection Method

The closed form expression for the blood path flows at iteration τ is: For each path $p \in P^i_j, \forall i, j$, compute:

$$\bar{x}^\tau_p = \max\left\{0, x^{\tau-1}_p - \psi\left(\frac{\partial \hat{C}_p(x^{\tau-1})}{\partial x_p} - \omega_i \gamma_{ij} \mu_p - \eta^{\tau-1}_j \mu_p\right)\right\}.$$

The amount of blood transfused, q_{jk}, $\forall j, k$, at iteration τ, is computed according to:

$$\bar{q}^\tau_{jk} = \max\left\{0, q^{\tau-1}_{jk} - \psi\left(c_{jk}(q^{\tau-1}) + \frac{\partial h_j(\sum_{k=T_1}^{T_{n_T}} q^{\tau-1}_{jk})}{\partial q_{jk}} + \eta^{\tau-1}_j - \beta_j \theta_{jk} - {\rho^3_{jk}}^{\tau-1}\right)\right\}.$$

Explicit Formulae for the Modified Projection Method

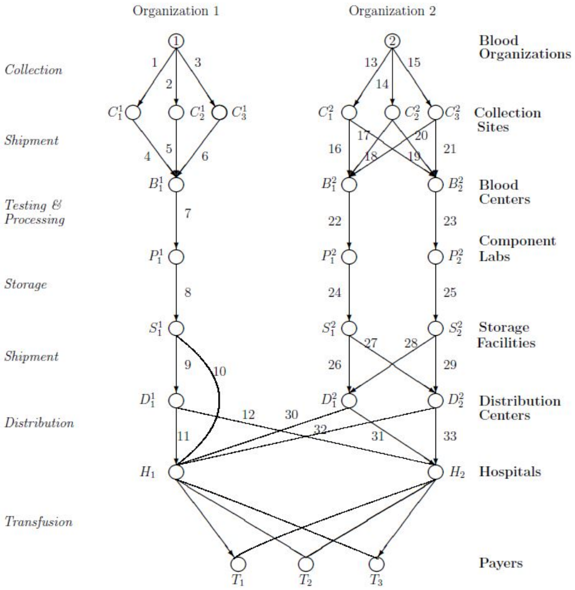
The Lagrange multipliers, η_j, $j = H_1, \ldots, H_{n_H}$, are computed at iteration τ using the formula:

$$\bar{\eta}_j^{\tau} = \max\left\{0, \eta^{\tau-1} - \psi\left(\sum_{i=1}^{I}\sum_{p\in P_j^i} x_p^{\tau-1}\mu_p - \sum_{k=T_1}^{T_{n_T}} q_{jk}^{\tau-1}\right)\right\}.$$

At iteration τ, the closed form expression for the demand prices, ρ_{jk}^3, $j = H_1, \ldots, H_{n_H}$; $k = T_1, \ldots, T_{n_T}$, is:

$$\bar{\rho}_{jk}^{3\tau} = \max\left\{0, {\rho^3}_{jk}^{\tau-1} - \psi\left(q_{jk}^{\tau-1} - d_{jk}({\rho^3}^{\tau-1})\right)\right\}.$$

Numerical Examples



Baseline Example

The network is stylized and the case study is loosely based on the blood banking landscape in Southern California.

Inventory Holding Costs

$$h_{H_1}(\sum_{k=T_1}^{T_3} q_{H_1 k}) = 23.6 \times (q_{H_1 T_1} + q_{H_1 T_2} + q_{H_1 T_3}),$$

$$h_{H_2}(\sum_{k=T_1}^{T_3} q_{H_2 k}) = 24 \times (q_{H_2 T_1} + q_{H_2 T_2} + q_{H_2 T_3}).$$

Transaction Costs for H_1

$$c_{H_1 T_1}(q_{H_1 T_1}) = 0.5 q_{H_1 T_1} + 10, \quad c_{H_1 T_2}(q_{H_1 T_2}) = 0.5 q_{H_1 T_2} + 9,$$

$$c_{H_1 T_3}(q_{H_1 T_3}) = 0.5 q_{H_1 T_3} + 8.$$

Baseline Example

Transaction Costs for H_2

$$c_{H_2T_1}(q_{H_2T_1}) = 0.5q_{H_2T_1} + 10, \quad c_{H_2T_2}(q_{H_2T_2}) = 0.5q_{H_2T_2} + 10,$$
$$c_{H_2T_3}(q_{H_2T_3}) = 0.5q_{H_2T_3} + 8.$$

Demand Price Functions for H_1

$$d_{H_1T_1} = -0.007\rho^3_{H_1T_1} + 0.001\rho^3_{H_2T_1} + 100,$$
$$d_{H_1T_2} = -0.007\rho^3_{H_1T_2} + 0.001\rho^3_{H_2T_2} + 50,$$
$$d_{H_1T_3} = -0.007\rho^3_{H_1T_3} + 0.001\rho^3_{H_3T_1} + 100.$$

Baseline Example

Demand Price Functions for H_2

$$d_{H_2 T_1} = -0.005\rho^3_{H_2 T_1} + 0.003\rho^3_{H_1 T_1} + 100,$$

$$d_{H_2 T_2} = -0.005\rho^3_{H_2 T_2} + 0.003\rho^3_{H_1 T_2} + 50,$$

$$d_{H_2 T_3} = -0.005\rho^3_{H_2 T_3} + 0.003\rho^3_{H_1 T_3} + 100.$$

Altruism Weights and Coefficients

$\omega_1 = \omega_2 = 1$, $\gamma_{1H_1} = 1, \gamma_{1H_2} = 1, \gamma_{2H_1} = 1, \gamma_{2H_2} = 1$. $\beta_{H_1} = \beta_{H_2} = 1$, $\theta_{H_1 T_1} = 1, \theta_{H_1 T_2} = 1, \theta_{H_1 T_3} = 2, \theta_{H_2 T_1} = 1, \theta_{H_2 T_2} = 1, \theta_{H_2 T_3} = 2$.

Baseline Example

Table: Definition of Links, Associated activity, Arc Multipliers, Total Operational Link Cost Functions, and Equilibrium Link Solution

Link a	From Node	To Node	Activity	α_a	$\hat{c}_a(f)$	f_a^*
1	1	C_1^1	Collection	1.00	$0.45_1^2 + 0.6f_1$	49.96
2	1	C_2^1	Collection	1.00	$0.35f_2^2 + 0.5f_2$	57.35
3	1	C_3^1	Collection	1.00	$0.32f_3^2 + 0.6f_3$	64.24
4	C_1^1	B_1^1	Shipment	1.00	$0.09f_4^2 + 0.36f_4$	49.96
5	C_2^1	B_1^1	Shipment	1.00	$0.12f_5^2 + 0.5f_5$	57.35
6	C_3^1	B_1^1	Shipment	1.00	$0.1f_6^2 + 0.35f_6$	64.24
7	B_1^1	P_1^1	Testing/ Processing	0.98	$0.5f_7^2 + 0.86f_7$	171.55
8	P_1^1	S_1^1	Storage	1.00	$0.12f_8^2 + 0.5f_8$	168.12
9	S_1^1	D_1^1	Shipment	1.00	$0.09f_9^2 + 0.5f_9$	64.36
10	S_1^1	H_1	Distribution	1.00	$0.05f_{10}^2 + 0.68f_{10}$	103.76
11	D_1^1	H_1	Distribution	1.00	$0.04f_{11}^2 + 0.8f_{11}$	0.00
12	D_1^1	H_2	Distribution	1.00	$0.06f_{12}^2 + 0.8f_{12}$	64.36
13	2	C_1^2	Collection	1.00	$0.3f_{13}^2 + 0.8f_{13}$	104.72
14	2	C_2^2	Collection	1.00	$0.25f_{14}^2 + 0.65f_{14}$	138.95
15	2	C_3^2	Collection	1.00	$0.32f_{15}^2 + 0.6f_{15}$	97.36
16	C_1^2	B_1^2	Shipment	1.00	$0.1f_{16}^2 + 0.28f_{16}$	82.57
17	C_1^2	B_2^2	Shipment	1.00	$0.15f_{17}^2 + 0.3f_{17}$	22.15
18	C_2^2	B_1^2	Shipment	1.00	$0.15f_{18}^2 + 0.35f_{18}$	33.17

Baseline Example

Table: Definition of Links, Associated activity, Arc Multipliers, Total Operational Link Cost Functions, and Equilibrium Link Solution

Link a	From Node	To Node	Activity	α_a	$\hat{c}_a(f)$	f_a^*
19	C_2^2	B_2^2	Shipment	1.00	$0.12f_{19}^2 + 0.45f_{19}$	105.78
20	C_3^2	B_1^2	Shipment	1.00	$0.16f_{20}^2 + 0.5f_{20}$	53.18
22	B_1^2	P_1^2	Testing/Processing	0.98	$0.4f_{22}^2 + 0.65f_{22}$	168.93
23	B_2^2	P_2^2	Testing/Processing	0.97	$0.45f_{23}^2 + 0.8f_{23}$	172.11
24	P_1^2	S_1^2	Storage	0.96	$0.02f_{24}^2 + 0.05f_{24}$	165.55
25	P_2^2	S_2^2	Storage	1.00	$0.04f_{25}^2 + 0.07f_{25}$	166.94
26	S_1^2	D_1^2	Shipment	1.00	$0.2f_{26}^2 + 0.4f_{26}$	80.61
27	S_1^2	D_2^2	Shipment	1.00	$0.18f_{27}^2 + 0.6f_{27}$	78.32
28	S_2^2	D_1^2	Shipment	1.00	$0.12f_{28}^2 + 0.45f_{28}$	99.96
29	S_2^2	D_2^2	Shipment	1.00	$0.15f_{29}^2 + 0.5f_{29}$	66.98
30	D_1^2	H_1	Distribution	1.00	$0.08f_{30}^2 + 0.5f_{30}$	75.12
31	D_1^2	H_2	Distribution	1.00	$0.1f_{31}^2 + 0.6f_{31}$	105.45
32	D_2^2	H_1	Distribution	1.00	$0.12f_{32}^2 + 0.35f_{32}$	66.75
33	D_2^2	H_2	Distribution	1.00	$0.16f_{33}^2 + 0.4f_{33}$	78.55

Baseline Example

Equilibrium Quantities

$$q^*_{H_1 T_1} = 98.46, \quad q^*_{H_1 T_2} = 48.61, \quad q^*_{H_1 T_3} = 98.55,$$
$$q^*_{H_2 T_1} = 99.43, \quad q^*_{H_2 T_2} = 49.53, \quad q^*_{H_2 T_3} = 99.41.$$

Equilibrium Prices

$$\rho^{3*}_{H_1 T_1} = 257.76, \quad \rho^{3*}_{H_1 T_2} = 231.83, \quad \rho^{3*}_{H_1 T_3} = 245.80,$$
$$\rho^{3*}_{H_2 T_1} = 268.39, \quad \rho^{3*}_{H_2 T_2} = 233.43, \quad \rho^{3*}_{H_2 T_3} = 266.37,$$

$$\rho^{1*}_{1H_1} = \rho^{1*}_{2H_1} = \eta^*_{H_1} = 184.92, \quad \rho^{1*}_{1H_2} = \rho^{1*}_{2H_2} = \eta^*_{H_2} = 194.67,$$
$$\rho^{2*}_{H_1} = 198.52, \quad \rho^{2*}_{H_2} = 208.67.$$

Baseline Example

Incurred Demands at Equilibrium Prices

$$d_{H_1T_1} = 98.46, \quad d_{H_1T_2} = 48.61, \quad d_{H_1T_3} = 98.55,$$

$$d_{H_2T_1} = 99.43, \quad d_{H_2T_2} = 49.53, \quad d_{H_2T_3} = 99.41.$$

Stakeholders	**BSO 1**	**BSO 2**	H_1	H_2
Utility	25,187.59	47,806.95	985.40	495.25

Variant 1

In Variant 1 the weights of the BSOs are all set to zero, that is, $\omega_1 = \omega_2 = 0$.

Equilibrium Quantities

$$q^*_{H_1T_1} = 97.87, \quad q^*_{H_1T_2} = 48.02, \quad q^*_{H_1T_3} = 97.96,$$
$$q^*_{H_2T_1} = 99.23, \quad q^*_{H_2T_2} = 49.33, \quad q^*_{H_2T_3} = 99.21,$$

Equilibrium Prices

$$\rho^{3*}_{H_1T_1} = 356.08, \quad \rho^{3*}_{H_1T_2} = 330.15, \quad \rho^{3*}_{H_1T_3} = 344.12,$$
$$\rho^{3*}_{H_2T_1} = 366.95, \quad \rho^{3*}_{H_2T_2} = 332.00, \quad \rho^{3*}_{H_2T_3} = 364.93.$$

Variant 1

Equilibrium Prices

$$\rho^{1*}_{1H_1} = \rho^{1*}_{2H_1} = \eta^*_{H_1} = 283.54, \quad \rho^{1*}_{1H_2} = \rho^{1*}_{2H_2} = \eta^*_{H_2} = 293.33,$$
$$\rho^{2*}_{H_1} = 297.14, \quad \rho^{2*}_{H_2} = 307.33.$$

Stakeholders	**BSO 1**	**BSO 2**	H_1	H_2
Utility	24,952.65	47,365.72	979.48	493.29

Variant 2

In Variant 2, only the weights associated with the hospitals are set to zero, that is, we have $\beta_{H_1} = \beta_{H_2} = 0$.

Equilibrium Quantities

$$q^*_{H_1 T_1} = 98.41, \quad q^*_{H_1 T_2} = 48.56, \quad q^*_{H_1 T_3} = 98.42,$$
$$q^*_{H_2 T_1} = 99.41, \quad q^*_{H_2 T_2} = 49.46, \quad q^*_{H_2 T_3} = 99.42.$$

Equilibrium Prices

$$\rho^{3*}_{H_1 T_1} = 267.54, \quad \rho^{3*}_{H_1 T_2} = 241.62, \quad \rho^{3*}_{H_1 T_3} = 265.55,$$
$$\rho^{3*}_{H_2 T_1} = 278.20, \quad \rho^{3*}_{H_2 T_2} = 253.33, \quad \rho^{3*}_{H_2 T_3} = 276.20.$$

Variant 2

Equilibrium Prices

$$\rho^{1*}_{1H_1} = \rho^{1*}_{2H_1} = \eta^*_{H_1} = 184.74,$$

$$\rho^{1*}_{1H_2} = \rho^{1*}_{2H_2} = \eta^*_{H_2} = 194.49,$$

$$\rho^{2*}_{H_1} = 278.20, \quad \rho^{2*}_{H_2} = 218.49.$$

Stakeholders	**BSO 1**	**BSO 2**	H_1	H_2
Utility	25,156.20	47,747.99	-0.02	0.01

Note: The entire supply chain of each BSO is captured in the model. As for the hospitals, the focus is on its blood supply operations, but each hospital engages in numerous other activities.
In the United States, blood transfusion costs account for 1% of a hospital's budget, typically, which is considerd to be high (Hemez (2016)).

Results for the Variants

Table: Links and Link Equilibrium Solution for Variant Examples

Link a	From Node	To Node	Variant 1 f_a^*	Variant 2 f_a^*	Variant 3 f_a^*
1	1	C_1^1	49.71	49.94	49.68
2	1	C_2^1	57.08	57.32	57.04
3	1	C_3^1	63.93	64.20	63.89
4	C_1^1	B_1^1	49.71	49.92	49.68
5	C_2^1	B_1^1	57.08	57.32	57.04
6	C_3^1	B_1^1	63.93	64.20	63.89
7	B_1^1	P_1^1	170.72	171.44	170.61
8	P_1^1	S_1^1	167.31	168.01	167.20
9	S_1^1	D_1^1	64.26	64.34	64.25
10	S_1^1	H_1	103.05	103.67	102.95
11	D_1^1	H_1	0.00	0.00	0.00
12	D_1^1	H_2	64.26	64.34	64.25
13	2	C_1^2	104.22	104.66	104.16
14	2	C_2^2	138.29	138.27	138.21
15	2	C_3^2	96.89	97.30	96.83
16	C_1^2	B_1^2	82.18	82.52	82.13

Results for the Variants

Table: Links and Link Equilibrium Solution for Variant Examples

Link a	From Node	To Node	Variant 1 f_a^*	Variant 2 f_a^*	Variant 3 f_a^*
17	C_1^2	B_2^2	22.04	22.13	22.03
18	C_2^2	B_1^2	33.01	33.15	32.99
19	C_2^2	B_2^2	105.28	105.72	105.21
20	C_3^2	B_1^2	52.93	53.15	52.90
21	C_3^2	B_2^2	43.96	44.15	43.94
22	B_1^2	P_1^2	168.12	168.82	168.02
23	B_2^2	P_2^2	171.29	172.00	171.18
24	P_1^2	S_1^2	164.76	165.45	164.66
25	P_2^2	S_2^2	166.15	166.84	166.04
26	S_1^2	D_1^2	80.23	80.56	80.18
27	S_1^2	D_2^2	77.94	78.27	77.89
28	S_2^2	D_1^2	99.49	99.90	99.42
29	S_2^2	D_2^2	66.66	66.94	66.62
30	D_1^2	H_1	74.53	75.04	74.45
31	D_1^2	H_2	105.18	105.42	105.15
32	D_2^2	H_1	66.28	66.68	66.22
33	D_2^2	H_2	78.33	78.52	78.30

Variant 3

In Variant 3, all the weights associated with altruism for all the BSOs and all the hospitals were identically equal to zero.

Equilibrium Quantities

$$q^*_{H_1T_1} = 97.82, \quad q^*_{H_1T_2} = 47.94, \quad q^*_{H_1T_3} = 97.83,$$
$$q^*_{H_2T_1} = 99.21, \quad q^*_{H_2T_2} = 49.26, \quad q^*_{H_2T_3} = 99.22,$$

Equilibrium Prices

$$\rho^{3*}_{H_1T_1} = 365.87, \quad \rho^{3*}_{H_1T_2} = 339.94, \quad \rho^{3*}_{H_1T_3} = 363.87,$$
$$\rho^{3*}_{H_2T_1} = 376.76, \quad \rho^{3*}_{H_2T_2} = 351.78, \quad \rho^{3*}_{H_2T_3} = 374.76,$$
$$\rho^{1*}_{1H_1} = \rho^{1*}_{2H_1} = \eta^*_{H_1} = 283.36, \quad \rho^{1*}_{1H_2} = \rho^{1*}_{2H_2} = \eta^*_{H_2} 293.15,$$
$$\rho^{2*}_{H_1} = 306.96, \quad \rho^{2*}_{H_2} = 317.15.$$

Variant 3

Stakeholders	**BSO 1**	**BSO 2**	H_1	H_2
Utility	24,921.40	47,307.50	-0.12	0.06

Note: In Toner at al. (2011), the authors report that the average cost of acquisition of one unit of RBCs in the West is **228.31** with a standard deviation of 42. According to Ellingson et al. (2017), the interquartile range for the price paid by hospitals in the United States for a unit of leukocyte-reduced RBCs in 2015 was **197 to 228**, while that of non-leukocyte-reduced RBCs was **185 to 205**.

Summary and Conclusion

- The model developed here captures the **decentralized nature** of the blood banking industry in the United States.
- To the best of our knowledge, this is the first supply chain network model to include the complex economic interplays between the different tiers of decision-makers in the blood supply chain.
- This work explores a cost-based pricing scheme for blood products that **bridges the disconnect** between actual costs of acquiring blood and the payments received by the hospitals and the blood suppliers.
- The equilibrium prices obtained reveal how the **prices increase** as the blood service organizations and hospitals **act less altruistically**.
- The results also show that the equilibrium prices increase in progression down the tiers, which ensures the **economic stability** of the blood supply chain.

Thank You !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