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Performance Analysis of Blood Bank Mergers in View of COVID-19 Pandemic and Beyond

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Abstract

During the COVID-19 pandemic, blood service organizations in the United States encountered unprecedented challenges, including reduced donation rates, staff shortages, and widespread burnout - factors that significantly strained their supply chain capacities. As societal activities resumed and demand for blood increased, these challenges were further compounded. Mergers and acquisitions, long considered a strategy for enhancing operational efficiency, had previously been explored in the blood banking sector prior to the pandemic. This study presents a supply chain network optimization model incorporating capacity overflow and outsourcing options to evaluate the effectiveness of blood bank mergers. The model is applied to a real-world case involving a 2015 merger between two California-based blood banks. Several supply and demand scenarios - representing pre-pandemic conditions, the early stages of the pandemic, and a return-to-normal period - are analyzed to compare the performance of the merged entity against a counterfactual scenario in which the two organizations remained independent. The findings indicate that regional blood bank mergers can offer significant advantages during periods of crisis, particularly in terms of operational cost reduction and supply stability.

Categories: Risk Management in Supply Chain Management, Strategic Supply Chain Management, Mergers and Acquisitions
Keywords: supply chains, blood banking, mergers and acquisitions, network optimization, covid-19 pandemic

Introduction

The COVID-19 pandemic severely disrupted global supply chains, and healthcare systems worldwide were no exception. Among the most critically affected components were blood services - an essential part of the healthcare infrastructure - which faced unprecedented challenges (Sahu et al., 2020). In their 2019 study titled "Competition for blood donations", Nagurney and Dutta describe blood as a unique, life-saving resource that cannot be synthetically manufactured or substituted, nor can it be stored for extended periods (Nagurney and Dutta, 2019). Regardless of the severity or frequency of COVID-19 surges in a given region, the demand for various blood products remained constant throughout the pandemic. On any given day, shortages in blood supply can lead to the postponement or cancellation of vital medical procedures, including treatments for traumatic injuries, sickle cell disease, certain cancers, and other chronic conditions. As such, disruptions in the delivery of blood to hospitals may result in serious medical complications or even fatalities (Pirabán et al., 2019).

Even prior to the pandemic, the U.S. blood banking industry faced a highly volatile environment, with challenges emerging as early as the beginning of the 21st century. While the years preceding 2008 saw a consistent annual increase in both blood collection and transfusion volumes, the period from 2008 to 2015 experienced a notable decline in both metrics, as documented by the National Blood Collection and Utilization Survey (Free et al., 2023). This downward trend was largely attributed to updated transfusion guidelines, advances in minimally invasive surgical techniques, and the widespread implementation of patient blood management programs. These developments placed significant financial strain on American blood service organizations (BSOs), many of which operated with minimal or even negative profit margins despite serving the largest demand market globally (Mulcahy et al., 2016). Although these declines began to stabilize around 2015, with projections suggesting a plateau by 2021 (Free et al., 2023), the onset of the COVID-19 pandemic ultimately disrupted this anticipated recovery.

During the early months of the pandemic, blood banks in the United States - and globally - experienced a substantial overall decline of 25% in blood collections (Kumar et al., 2023), with some regions reporting reductions of 40%-71% (Sahu et al., 2020) and (Esfandabadi et al., 2024). In response to this unprecedented nationwide shortage, the U.S. Surgeon General, in coordination with the Federal Emergency Management Agency (FEMA), classified blood donation as an essential activity to encourage healthy and eligible individuals to continue donating during the lockdown period (Vitalant, 2021). Concurrently, the U.S. Food and Drug Administration (FDA) revised its deferral guidelines for certain donor groups in an effort to mitigate the decline in the national blood supply (Vasavda et al., 2020).

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Hospitals and surgical centers also contributed to alleviation efforts by implementing strategies such as canceling elective procedures and reassessing the clinical necessity of blood transfusion requests (Sahu et al., 2020). Notably, the demand for blood products also declined by approximately 20% during the lockdown period, due in part to reduced trauma-related cases as a result of stay-at-home orders, as well as the widespread postponement of elective surgeries and non-urgent clinical treatments (Sahu et al., 2020) and (Esfandabadi et al., 2024).

Nagurney, in their study "Heading into the third year of the pandemic, the US blood supply is at a 10-year low" explain how the blood banks in the United States encountered yet another critical turning point after the rollout of COVID-19 vaccines in 2021 and the gradual lifting of pandemic-related restrictions (Nagurney, 2022). According to the American Red Cross, hospitals experienced an “atypically high rise in trauma cases and emergency room visits,” largely attributed to a surge in travel and outdoor activities following the reopening during the summer of 2021 (Jiménez, 2021) and (Vitalant, 2021). In addition, hospitals resumed elective surgeries and medical treatments that had previously been postponed due to the pandemic (American Red Cross, 2021). Some patients, having experienced delayed treatment, presented with more advanced stages of illness, necessitating a greater volume of blood transfusions (Jiménez, 2021). Consequently, in 2021, the American Red Cross reported a 10% increase in demand from trauma centers compared to 2019, contributing to the organization’s worst blood shortage in over a decade (American Red Cross, 2021).

This surge in demand unfortunately coincided with a prolonged and significant decline in blood donation rates. Although the U.S. government formally declared the end of the COVID-19 public health emergency in May 2023, blood donation levels took a long time to recover to pre-pandemic rates (PR Newswire, 2023). Even under normal conditions, only about 3% of the U.S. population donates blood annually, despite 38% being age-eligible (American Red Cross, 2021) and (Nagurney, 2020). The shift to remote work significantly impacted donation campaigns at workplaces, with business-hosted blood drives down by 50% in 2022 compared to 2019 (PR Newswire, 2023). Similarly, mobile blood drives hosted by religious institutions, schools, theaters, and seasonal festivals saw a marked decline in participation due to lingering pandemic-related concerns (Lapook, 2021). Compounding this trend, natural disasters such as wildfires and hurricanes led to the cancellation of numerous scheduled blood drives during the same period. Moreover, the emergence of highly transmissible COVID-19 variants, including Delta and Omicron, further suppressed donation rates in 2021-2022, as demonstarted by Nagurney in the study titled, "Labor and Supply Chain Networks" (Nagurney, 2022). Even in January 2024, the American Red Cross reported an emergency blood shortage, citing the lowest number of donors in the United States in over two decades (American Red Cross, 2024).

In light of these challenges, U.S. blood banks have continued to navigate a turbulent operational environment, seeking to balance financial sustainability with fluctuating demand. Among the strategic responses to this instability, mergers and acquisitions (M&As) gained prominence in the decade prior to the COVID-19 pandemic. America’s Blood Centers - the largest network of nonprofit blood banks in North America - reported nearly 20 partnerships and mergers among member organizations between 2009 and 2014, compared to just 19 throughout the entire 1990s (Masoumi et al., 2017). As a result of these consolidations, the number of non-hospital-based blood centers in the U.S. declined from 80 in 2015 to 53 by 2022 (Americas Blood Centers, 2022). These organizational restructurings varied widely in scale, geographic location, and the type of partnerships formed. Nonetheless, across all merger cases, the pursuit of improved operational efficiency and a more stable blood supply emerged as the predominant motivations cited by the participating organizations (Masoumi et al., 2017).

This study develops a supply chain network optimization model designed to evaluate mergers between blood banks. The model possesses the flexibility to represent various merger and acquisition configurations among regional blood service organizations of differing sizes and geographic distributions, contingent upon appropriate adjustments to the network structure. The model supports aggregation of collection zones on the supply side and clustering of demand regions on the demand side to comprehensively represent the supply chain network. To illustrate the proposed framework, the model is applied to a real-world case involving the 2015 merger of two blood banks located in Northern and Central California. A scenario-based analysis is conducted to compare the performance of the merged organization against a counterfactual in which the two entities had remained independent. Three supply/demand scenarios are examined, each reflecting a distinct phase of the COVID-19 pandemic: (i) a “baseline” pre-pandemic scenario, (ii) an early-pandemic “lockdown” scenario, and (iii) a “return-to-normal” scenario. The results from these scenarios are used to assess the merger’s synergies based on two key objectives: cost-related savings and the minimization of blood shortages at demand points.

The remainder of this paper is organized as follows. The next part reviews the relevant literature and highlights this study’s contributions to the blood banking field. Following that, we introduce the supply chain network model developed for analyzing blood bank mergers, including the associated optimization formulation and the variational inequality representations for both pre- and post-merger problems. We then present the case study of the blood bank merger in California, along with a detailed description of three pandemic-related supply and demand scenarios. This is followed by a presentation of the optimal solutions and corresponding performance metrics for each scenario, as well as the results of a sensitivity analysis. The paper concludes with a summary of findings and suggestions for future research.

Literature review

This part of the paper reviews two main streams of relevant scholarly literature. It begins with an overview of studies on M&As from a supply chain perspective, followed by a detailed examination of research focused on the blood banking supply chain. The latter includes literature addressing the challenges faced by blood supply chains during the COVID-19 pandemic. The review concludes with a discussion of this study's contributions and how it aims to bridge existing gaps in the literature.

Mergers and Acquisitions literature

M&As have garnered sustained interest not only from industry stakeholders but also from researchers across various sectors of the economy in both the United States and internationally. This body of research spans numerous industries, including technology, financial services, retail, and, notably, healthcare.

Several studies have examined M&As through the lens of supply chain networks. Mattsson emphasized the critical role of supply chain structures in determining the success or failure of global integrations (Mattsson, 2003). Öberg explored post-merger shifts in managerial sense-making and networking activities (Öberg et al., 2007). Nagurney proposed a system-optimization framework to evaluate the strategic benefits of horizontal mergers (Nagurney, 2009). Building on this, Liu and Nagurney introduced a supply chain network model incorporating cost synergies and risk reduction via a mean-variance approach to assess the value of mergers (Liu and Nagurney, 2011). More recently, Shao developed a methodology to quantitatively classify M&A cases using network transaction data (Shao et al., 2021).

In the context of healthcare supply chains, several studies have addressed the impact of mergers. Harris and co-authors identified significant improvements in hospital efficiency following mergers, particularly in terms of input utilization (Harris et al., 2000). Zuckerman analyzed the broader forces reshaping healthcare systems, with a focus on insurance consolidation amid a wave of organizational mergers (Zuckerman, 2011). Beaulieu evaluated hospital performance pre- and post-acquisition, finding a modest decline in patient experience but no substantial change in readmission or mortality rates (Beaulieu et al., 2020).

Beyond healthcare, Comez-Dolgan and Tanyeri investigated the long-term effects of mergers on firms' inventory turnover (Comez-Dolgan and Tanyeri, 2015). Yuan examined the implications of horizontal mergers within a Cournot oligopoly, analyzing the roles of competition effects, yield uncertainty, and cost synergies. Their study also assessed the social welfare outcomes associated with merger-induced uncertainty (Yuan et al., 2020). Yang-Sun found that firms involved in M&As tend to reduce the size of their supply base post-merger to enhance operational performance - an effect particularly pronounced in horizontal integrations (Yang-Sun et al., 2024).

Despite the critical role of blood banks within healthcare, there remains a notable gap in the literature concerning mergers and acquisitions in this sector from a supply chain perspective. This gap is addressed in greater detail in the subsequent parts of the review.

Blood supply chain literature

Perishable products - particularly human blood - have been the focus of research for over half a century. Key areas of investigation in the classical blood banking literature include ordering policies, inventory management, location-allocation decisions, and the transportation and distribution of blood products. Several scholars have conducted comprehensive reviews of this body of work, examining it through various modeling and methodological lenses. Notable contributions include those by Karaesmen et al. (Karaesmen et al., 2011), Belien and Force (Belien and Force, 2012), Osorio et al.(Osorio et al., 2015), Pirabán et al. (Pirabán et al., 2019), Williams et al. (Williams et al., 2020), and Torrado and Barbosa-Póvoa (Torrado and Barbosa-Póvoa, 2022). Table *1* provides a summary of selected recent studies focused on blood supply chain networks.

Article	No. of BSOs	Echelons	Blood Products	Scope of the Research	Modeling/Solution Method
(Abdolazimi et al., 2023)	1	C, P, I, D	WB	Supply chain configuration under COVID-19	TOPSIS algorithm
(Blake and Hardy, 2014)	1	P, I, D	WB/RBC	Inventory management of a regional bank	Simulation-optimization
(Coelho and Laporte,					Branch-and-cut

2014)	1	C, I, D	N/A	Replenishment and inventory management	algorithm
(Dillon et al., 2017)	1	C, P, I, D	RBC	Optimal policies for inventory management	Stochastic programming
(Duan and Liao, 2014)	1	P, I, D	RBC	Supply chain inventory management	Simulation-optimization
(Dutta and Nagurney, 2019)	N	C, S, P, I, D, T	RBC	Interactions b/w BSOs, hospitals, payer groups	Variational inequalities
(Esmaeili et al., 2023)	1	C, P, I, D	WB	Location, inventory and routing problem	Mixed-integer programming
(Fahimnia et al., 2017)	1	C, S, P, I, D	WB	Supply chain design model for disaster relief	Stochastic programming
(Fallahi et al., 2024)	1	C, P, I, D	PLAS	Design of convalescent plasma network	Mixed-integer linear programming
(Gunpinar and Centeno, 2015)	1	C, P, I, D	RBC, PLT	Two-level supply chain with cross-matching	Stochastic integer programming
(Haeri et al., 2020)	1	C, P, I, D	RBC, PLAS, PLT, C	Motivational social aspects of donation	Interactive fuzzy approach
(Haijema, 2014)	1	I	WB, PLT	Optimal ordering, disposal, issuance policies	Stochastic dynamic programming
(Hamdan and Diabat, 2019)	1	C, S, P, I, D	RBC	Production, inventory, location decisions	Stochastic programming
(Heidari and Pasandideh, 2018)	1	C, P, I, D	RBC, PLAS, PLT	Design of a sustainable supply chain network	Robust optimization
(Hosseinifard et al., 2019)	1	C, P, I, D	WB/RBC	Impact of a call for blood after a disaster	Markov chain
(Hu et al., 2024)	1	P, I, D	PLT	Inventory allocation under supply uncertainty	Simulation-optimization
(Jabbarzadeh et al., 2014)	1	C, P, I, D	WB	Network design during and after disasters	Robust optimization
(Katsaliaki and Brailsford, 2007)	1	C, P, I, D	RBC	Blood inventory management in a hospital	Simulation
(Kenan and Diabat, 2022)	1	C, P, I, D	RBC, PLAS, PLT	Supply/demand uncertainty after a disaster	Stochastic programming
(Ma et al., 2019)	1	C, I, D	RBC, PLAS	Allocation of blood to disaster-impacted areas	Mixed-integer linear programming
(Masoumi et al., 2017)	N	C, S , P, I, D	WB/RBC	BSO mergers with activity frequencies	Variational inequalities
(Mustafee et al., 2009)	1	C, S, P, I, D	RBC, PLT	Ordering policies at a national blood service	Simulation
(Nagurney and Dutta, 2019)(a)	N	C	WB	Competition over blood donations	Variational inequalities
(Nagurney and Dutta, 2019)(b)	N	C, S, P, I, D	WB/RBC	Competition over donations and hospitals	Variational inequalities
(Nagurney and Dutta, 2021)	1	C	PLAS	Plasma donations in the COVID-19 pandemic	Variational inequalities
(Nagurney and Masoumi, 2012)	1	C, S, P, I, D	WB/RBC	Blood supply chain network design	Variational inequalities
(Nagurney et al., 2012)	1	C, S, P, I, D	WB/RBC	Operations of a blood supply chain	Variational inequalities
(Paul et al., 2019)	1	P, I, D	WB	Socially optimal contracting with hospitals	Optimization

(Pierskalla, 2004)	1	C, P, I, D	WB/RBC	Blood centers' optimal target inventory levels	Optimization
(Puranam et al., 2017)	1	C, P, I, D	WB	Blood inventory with multiple supply sources	Dynamic programming
(Rytilä and Spens, 2006)	1	C, P, I, D	RBC, PLAS, PLT, C	Increase efficiency in the supply chain	Simulation
(Samani and Hosseini-Motlagh, 2021)	1	C, P, I, D	RBC	Capacity sharing to handle COVID-19 demand	Optimization
(Samani et al., 2019)	1	C, P, I, D	WB/RBC, PLAS, PLT	Supply chain network design	Robust optimization
(Sarhangian et al., 2018)	1	C, P, I, D	WB/RBC	Inventory management policy	Simulation
(Shirazi et al., 2021)	1	C, P, I, D	PLAS	Plasma supply chain in COVID-19 pandemic	MOIWO
(Yang et al., 2024)	1	C, P, I, D	RBC	Blood supply chain optimization in COVID-19	Stochastic programming
(Zahiri and Pishvaee, 2016)	1	C, P, I, D	RBC	Supply chain network design	Robust possibilistic optimization
(Zahiri et al., 2015)	1	C, S, P, I, D	WB	Location-allocation model	Robust possibilistic optimization
(Zhang et al., 2023)	1	P, I, D	PLT	Platelet inventory sharing	Optimization
This study	**N**	**C, S, P, I, D**	**WB/RBC**	**Performance analysis of a merger between blood banks during COVID-19**	**Variational inequalities**

TABLE 1: A Summary of Selected Recent Publications in the Area of Blood Supply Chains. Blood Supply Chain Echelons: C = Collection, S = Shipment, P = Processing, I = Inventory, D = Distribution, T = Transfusion. Blood Products: WB = Whole Blood, RBC = Red Blood Cells, PLAS = Plasma, PLT = Platelets, C = Cryoprecipitates

BSO, blood service organization

(Nagurney and Dutta, 2019)(a): Nagurney A, Dutta P: Competition for blood donations. Omega. 2019, 85:103-14. 10.1016/j.omega.2018.06.001

(Nagurney and Dutta, 2019)(b): Nagurney A, Dutta P: Supply chain network competition among blood service organizations: a Generalized Nash Equilibrium framework. Annals of Operations Research. 2019, 275:551-86. 10.1007/s10479-018-3029-2

Optimization models - spanning a range of forms, scopes, and methodologies - have been extensively employed by blood bank researchers to develop cost-efficient ordering policies. Pierskalla introduced algorithms to determine optimal target inventory levels for community blood centers within a region (Pierskalla, 2004). Coelho presented an integrated model for the replenishment, delivery, and inventory management of perishable products, solved using an exact branch-and-cut algorithm (Coelho and Laporte, 2014). Gunpinar developed an integer programming model to minimize total costs, shortages, and wastage at the hospital level (Gunpinar and Centeno, 2015). Zahiri applied a mixed-integer linear programming model to support strategic and tactical decision-making in blood banking systems over a multi-period planning horizon (Zahiri et al., 2015). Puranam constructed a multi-period dynamic programming model for a large medical center sourcing blood from multiple suppliers (Puranam et al., 2017). Paul modeled a regional blood bank as a social planner aiming to minimize the total cost of shortages and outdates, suggesting that offering subsidies for shortages could incentivize hospitals to report demand more accurately (Paul et al., 2019). Zhang developed a two-echelon transshipment model to manage shared platelet inventory and reduce product wastage (Zhang et al., 2023). More recently, Esmaeili proposed a mixed-integer mathematical framework for designing a blood supply chain that minimizes both shortages and operational costs (Esmaeili et al., 2023).

The application of queuing theory and stochastic programming to model uncertainties in blood banking systems dates back to some of the earliest research in the field (Nahmias and Pierskalla, 1973). More recently, Haijema employed a stochastic dynamic programming model to determine optimal age-dependent policies for ordering, issuing, and disposing of blood units (Haijema, 2014). Dillon proposed a two-stage stochastic programming model to identify optimal periodic review policies for red blood cell

(RBC) inventories (Dillon et al., 2017). Sarhangian investigated threshold-based allocation strategies to evaluate trade-offs between the age of transfused blood and RBC availability at hospitals (Sarhangian et al., 2018). Hamdan developed a two-stage stochastic model that considered both the number of outdated blood units and delivery times to demand points (Hamdan and Diabat, 2019).

Over the past two decades, several researchers have used simulation and hybrid simulation-optimization approaches to address the complexities of inventory management and blood distribution in supply chains. Blake utilized a simulation-optimization framework to evaluate inventory policies across a network of regional blood distribution centers (Blake and Hardy, 2014). Osorio presented an integrated model combining discrete-event simulation and integer linear optimization to tackle production planning issues at both strategic and operational levels (Osorio et al., 2017). Elalouf developed a simulation-based model for transporting collected units across a three-echelon blood supply chain (Elalouf et al., 2021). More recently, Hu proposed a simulation-optimization approach to determine near-optimal order-up-to levels under dynamic supply scenarios (Hu et al., 2024). Additional examples of such methodologies can be found in the following articles: (Rytilä and Spens, 2006), (Katsaliaki and Brailsford, 2007), (Mustafee et al., 2009), and (Duan and Liao, 2014).

The increasing frequency and severity of natural disasters, along with their associated fatalities, have drawn significant attention from researchers in recent years. Numerous studies have addressed the distribution of blood in the context of preparedness, mitigation, and response phases of large-scale, highly uncertain events. Notable contributions in this domain include the works of Jabbarzadeh et al. (Jabbarzadeh et al., 2014), Fahimnia et al. (Fahimnia et al., 2017), Hosseinifard et al. (Hosseinifard et al., 2019), and Ma et al. (Ma et al., 2019), all of which focus on blood banking within disaster relief operations. For a comprehensive review of quantitative models in blood supply chains with an emphasis on disaster response, see Asadpour et al. (Asadpour et al., 2022).

Network theory, valued for its robust modeling capabilities and computational efficiency, has also attracted growing interest among blood supply chain researchers. Nagurney employed a generalized supply chain network model with arc multipliers to represent the operations management of a regionalized blood bank (Nagurney et al., 2012). Building on this approach, subsequent studies - including those by Nagurney and Masoumi (Nagurney and Masoumi, 2012), Zahiri and Pishvaee (Zahiri and Pishvaee, 2016), Heidari and Pasandideh (Heidari and Pasandideh, 2018), Samani et al. (Samani et al., 2019), and Haeri et al. (Haeri et al., 2020) - utilized network models to design or redesign blood supply chains under demand uncertainty, with a focus on maximizing cost-efficiency. More recently in their study titled, "Labor and Supply Chain Networks", Nagurney extended the framework to incorporate labor constraints and capacity bounds across the various operational activities of a blood service organization (Nagurney, 2022).

Recent studies have also begun to explore interactions among multiple blood service organizations, as illustrated in several publications summarized in Table *1*. Masoumi developed a quantitative model to analyze blood bank mergers, using blood quantity and activity frequency as decision variables (Masoumi et al., 2017). In their studies, " Competition for blood donations" and " Supply chain network competition among blood service organizations: a Generalized Nash Equilibrium framework.", Dutta and Nagurney (Nagurney and Dutta, 2019) introduced game-theoretic network models to capture competitive dynamics among blood service entities across different tiers of the supply chain, including donor centers and hospitals. In contrast to these studies, the present paper proposes a framework for evaluating the outcomes of an actual blood bank merger using scenario analysis to assess the resilience and effectiveness of a U.S.-based merger.

In recent years, numerous researchers in the field of blood supply chains have turned their attention to the unprecedented challenges posed by the COVID-19 pandemic, which disrupted both the supply and demand for blood worldwide. Several studies have addressed these issues from various modeling perspectives. Samani proposed a two-stage model to mitigate declining donation rates during the pandemic's peak through capacity sharing between demand regions (Samani and Hosseini-Motlagh, 2021). Accordingly, multiple research studies, such as Nagurney and Dutta (Nagurney and Dutta, 2021), Shirazi et al. (Shirazi et al., 2021), and Fallahi et al. (Fallahi et al., 2024) developed supply chain models focused on the procurement and distribution of convalescent plasma as a treatment for COVID-19 patients. Kenan introduced a two-stage stochastic programming model to promote equitable distribution of blood products among hospitals during pandemic-related disruptions (Kenan and Diabat, 2022). Tirkolaee formulated a mixed-integer linear programming model that minimized operational costs while maximizing employment opportunities within the blood supply chain under pandemic constraints (Tirkolaee et al., 2023). Abdolazimi proposed a multi-level supply chain network to address blood bank location decisions under uncertainty caused by COVID-19 (Abdolazimi et al., 2023). Esfandabadi developed a multi-objective model aimed at improving the appeal of blood centers amid declining donations, while also minimizing operating costs and product shortages (Esfandabadi et al., 2024). Finally, Yang presented a supply chain design model to alleviate blood shortages resulting from pandemic-related disruptions, supported by a case study in China (Yang et al., 2024).

Contributions of this research

As noted earlier, organizational restructuring in various forms and scales has been widely undertaken within the blood banking industry over the past two decades. Despite the growing attention of supply chain researchers to this sector, scholarly work specifically addressing mergers among blood banks remain limited. This gap in the literature is further accentuated by the impacts of the COVID-19 pandemic, which imposed both financial and operational resilience challenges on blood service organizations. To the best of the authors' knowledge, this study is the first to evaluate the effectiveness of mergers and acquisitions in a healthcare supply chain context using scenarios inspired by pandemic-related disruptions.

The proposed model integrates the notion of capacity overflow within the blood banking industry - a topic previously examined in the literature, albeit typically through alternative modeling frameworks such as activity frequency analysis. In contrast, this study formulates capacity overflow as a soft constraint that permits normal capacity to be exceeded at an additional cost, modeled as a non-linear function of the overflow associated with each link/activity in the supply chain. This formulation better reflects real-world conditions in which demand exceeds standard capacity, particularly under the "return-to-normal" scenario analyzed in this paper. Furthermore, the study underscores the role of outsourcing blood procurement to external organizations, where the ability to access outsourced blood during periods of heightened demand emerges as a direct consequence of organizational consolidation. Although outsourcing is a well-established practice within the blood banking sector, it has received limited attention in the academic literature.

In summary, the main contributions of this research are summarized as follows:

- The study introduces models that represent the supply chain networks of multiple blood service organizations before and after a merger, using cost and shortage metrics to assess the merger's effectiveness.

- The model incorporates the option for blood banks to outsource the procurement of processed and tested blood to an external entity when demand levels justify such an arrangement - a scenario that has occurred in several U.S. blood banks.

- It captures the concept of capacity overflow, allowing for the analysis of how gradual increases or sudden surges in demand affect the entire supply chain.

- The case study presented in this paper replicates a completed, real-world merger between two U.S.-based blood banks and draws upon insider data, information, and insights provided by former and current officials of the organizations involved.

- A numerical scenario analysis evaluates the performance of the merger under three distinct supply and demand conditions, each corresponding to different stages of the COVID-19 pandemic. The analysis is further supported by a sensitivity study on demand volatility.

The following section introduces the supply chain network model developed to analyze the blood bank merger.

Research Method

The supply chain network model of a blood bank merger with outsourcing, capacity overflow, aggregated collection, and clustered demand

In this section, supply chain network models are presented for the pre-and post-merger problems between two (or any number of) blood service organizations, following a brief overview of the activities involved in a blood bank supply chain. A mathematical framework to solve each model is also presented in this section.

Blood bank merger: the pre-merger supply chain network model and formulation

Blood banks in the United States, as in many other countries, typically operate on a non-profit basis (Nagurney et al., 2012). The national blood supply is primarily managed by the American Red Cross, in coordination with 53 community blood centers and 90 hospital-based blood centers (Americas Blood Centers, 2022). BSOs do not charge partner hospitals for the blood itself; instead, they recover costs associated with the various supply chain activities involved in the collection, processing, testing, and distribution of blood, as detailed later in this section. Figure *1* illustrates the supply chain network topology for the pre-merger scenario, consisting of I regional BSOs.

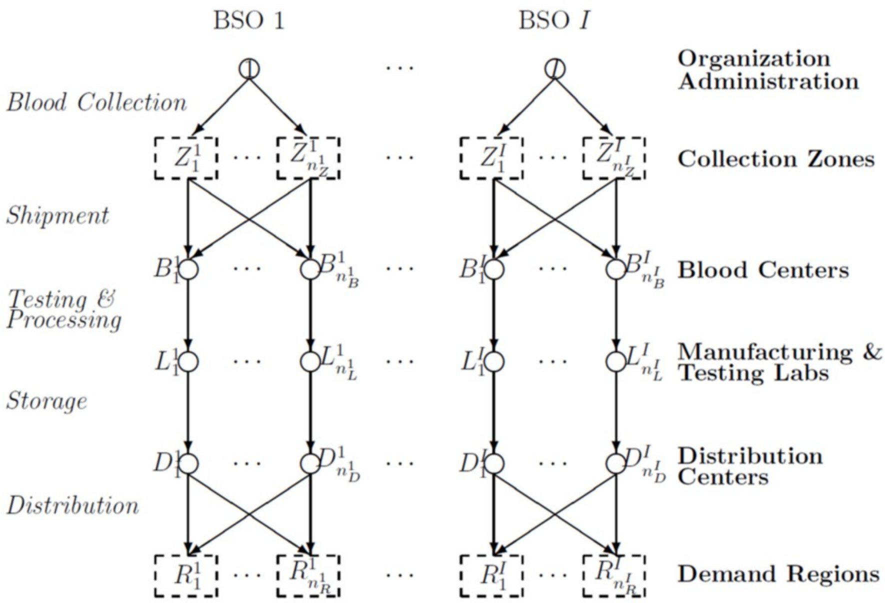

FIGURE 1: Supply Chain Network Topology for I Blood Service Organizations in the Pre-Merger Problem

Source: supply chain network model developed by the authors

The top level node (origin) of each BSO represents the *organization administration*. Every other node within the network of each organization denotes a facility in the system. The only exceptions are at the second as well as the sixth level where nodes represent zones or regions rather than facilities. More specifically, at the second level of nodes, each organization *i* is assumed to collect blood in n_Z^i *collection zones* each of which is composed of a number of adjacent permanent or mobile collection (donor) centers. Similarly, each organization *i* is assumed to serve n_R^i *demand regions* composed of a number of its partner hospitals and medical surgical centers located in the same geographical cluster. Further information on how these zones/regions can be defined is provided in the subsequent sections of the paper (case study).

For every organization $i \in \{1, \ldots, I\}$ there exist one or more *path*s, connecting the corresponding origin node *i* to one of its destination nodes. Every path consists of a sequence of directed links/arcs representing the following five supply chain network activities: (1) collection of whole blood (WB) at donor centers; (2) shipment of collected blood to blood centers; (3) testing of all collected units, as well as fractionating into components; (4) storage of processed and tested blood; (5) distribution of RBCs to the under-contract hospitals.

It should be noted that certain facilities belonging to one BSO may physically coincide with some others of the same organization. Next, we present the mathematical model that captures the pre-merger problem consisting of *I* blood service organizations, beginning with the formulation notations displayed in Table 2.

Type	Notation	Definition
Sets	L_i^0	The set of directed links representing the activities associated with each BSO $i; i = 1, \ldots, I$ in the pre-merger problem (Figure 1).
	L^0	The set of links in the topology for the pre-merger problem. n_{L^0} denotes the number of all pre-merger links.
	L^1	The set of links in the topology for the post-merger problem (Figure 2). n_{L^1} denotes the number of all post-merger links.
	$\mathcal{P}^0_{R_k^i}$	The set of pre-merger paths joining the top node of each BSO i to a specific demand region; i.e., the origin/destination pair $R_k^i; i = 1, \ldots, I \text{ and } k = 1, \ldots, n_R^i.$
	$\mathcal{P}^1$	The set of all paths in the pre-merger problem. $n_{\mathcal{P}^0}$ denotes the number of all pre-merger paths.
	$\mathcal{P}^1_{R_k^i}$	The set of post-merger paths joining the supernode (of the merged organization) to a specific demand region $R_k^i; i = 1, \ldots, I \text{ and } k = 1, \ldots, n_R^i.$

	$\mathcal{P}^0$	The set of all paths in the post-merger problem. $n_{\mathcal{P}^1}$ denotes the number of all post-merger paths.
Parameters	d_{ik}	The stochastic parameter representing the actual demand for red blood cells (RBC) at demand region $R_k^i; i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$ during the time period of one week.
	$\bar{u}_a$	The effective (weekly) capacity of link $a; a \in L^0$, pre-merger (or, $a \in L^1$, post-merger).
	o_a^{max}	Upper bound on the (weekly) overflow of link a relative to its effective capacity; $a \in L^0$, pre-merger (or, $a \in L^1$, post-merger).
	δ_{ap}	$\delta_{ap}=1$, if link a is contained in path p and $\delta_{ap}=0$, otherwise; $a \in L^0$ and $p \in \mathcal{P}^0$ for the pre-merger problem (or, $a \in L^1$ and $p \in \mathcal{P}^1$ for the post-merger problem).
	α_a	The arc multiplier associated with link a, which represents the percentage of throughput on link a. $\alpha_a \in (0,1]; a \in L^0$, pre-merger (or, $a \in L^1$, post-merger).
	α_{ap}	The arc-path multiplier, which is the product of the multipliers of the links on path p that precede link $a; a \in L^0$ and $p \in \mathcal{P}^0$, pre-merger (or, $a \in L^1$ and $p \in \mathcal{P}^1$, post-merger); that is, $\alpha_{ap} \equiv \delta_{ap} \prod_{b \in \{a'<a\}_p} \alpha_b$, where $\{a'<a\}_p$ denotes the set of the links preceding link a in path p. For the links located in the first tier, $\alpha_{ap} \equiv \delta_{ap}$.
	μ_p	The multiplier corresponding to the percentage of throughput on path $p; i.e., \mu_p \equiv \prod_{a \in p} \alpha_a; p \in \mathcal{P}^0$, pre-merger (or, $\mathcal{P}^1$, post-merger).
	sc_{ik}	The unit shortage penalty assigned by BSO i to demand region R_k^i representing the social cost of a death or a severe injury of a patient due to a blood shortage at that region; $i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$.
	ec_{ik}	The unit disposal cost of outdated supply surplus at demand region $R_k^i; i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$.
Decision Variables	v_{ik}	The projected demand for RBC at the demand region $R_k^i; i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$ during the time period of one week. We group the projected demands into the $\sum_{i=1}^{I} n_R^i$-dimensional vector v.
	x_p	The nonnegative flow of RBC on path p $p \in \mathcal{P}^0$, pre-merger (or, $\mathcal{P}^1$ post-merger). We group the path flows into the $n_{\mathcal{P}^0}$-dimensional vector x, pre-merger (or, $n_{\mathcal{P}^1}$, post-merger).
	f_a	The initial flow of WB or RBC on link $a; a \in L^0$, pre-merger (or, L^1, post-merger). We group the link flows into the n_{L^0}-dimensional vector f, pre-merger (or, n_{L^1}, post-merger).
	o_a	The amount of product overflow on link $a; a \in L^0$, pre-merger (or, L^1, post-merger), with regards to its existing capacity, $\bar{u}_a$, in the (weekly) time period. We group the capacity overflows into the n_{L^0}-dimensional vector o, pre-merger (or, n_{L^1}, post-merger).
Functions	$\hat{c}_a=\hat{c}_a(f_a)$	The total operational cost on link a which is assumed to be a function of the product flow on that link; $a \in L^0$, pre-merger (or, $a \in L^1$, post-merger).
	$\hat{z}_a=\hat{z}_a(f_a)$	The total discarding cost function associated with the product flow on link $a; a \in L^0$, pre-merger (or, $a \in L^1$, post-merger).
	$\hat{\gamma}_a=\hat{\gamma}_a(o_a)$	The total overflow penalty function on link $a; a \in L^0$, pre-merger (or, $a \in L^1$, post-merger).
	$\mathcal{F}_{ik}(t)$	The probability density function of the actual demand at demand region $R_k^i; i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$
	$P_{ik}(v_{ik})$	The cumulative distribution function of d_{ik}; that is, $P_{ik}(v_{ik})=P_{ik}(d_{ik} \leq v_{ik})=\int_0^{v_{ik}} \mathcal{F}_{ik}(t)d(t); \quad i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$.
	$s_{ik}=s_{ik}(v_{ik})$	The shortage of RBC at demand point R_k^i; that is, $s_{ik} \equiv \max\{0, d_{ik}-v_{ik}\}$; $i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$. The expected shortage is given by $E(s_{ik})=\int_{v_{ik}}^{\infty}(t-v_{ik})\mathcal{F}_{ik}(t)d(t)$.
	$e_{ik}=e_{ik}(v_{ik})$	The surplus of RBC at demand point R_k^i; that is, $e_{ik} \equiv \max\{0, v_{ik}-d_{ik}\}$; $i=1,\ldots,I \text{ and } k=1,\ldots,n_R^i$. The expected surplus is given by

$$E(e_{ik}) = \int_0^{v_{ik}} (v_{ik} - t)\mathcal{F}_{ik}(t)d(t).$$

TABLE 2: Notations for the Pre-Merger and Post-Merger Blood Banking Problems

Our model uses arc (link) multipliers, α_a, to represent the throughput of product flow; that is, units of collected WB or RBC, subject to perishability/waste/loss associated with that activity on each link a in the supply chain network. Note that the flow on links belonging to tiers 1-3 (i.e., blood collection, shipment, as well as testing and processing) represents the number of units of WB. In contrast, flow on the remaining links (tiers 4 and 5, i.e., storage and distribution of tested/processed blood) represents the number of units of RBC. This assumption is due to the fact that one unit (one pint) of collected WB can be separated into one unit of RBC in addition to plasma, platelets, and other by-products of blood. It should be emphasized that our model solely focuses on RBC, which constitutes the majority of transfusions among all derivatives of blood.

The model assumes an effective capacity for every link of the blood supply chain network under normal circumstances over the planning horizon, denoted by $\bar{u_a}; a \in L^0$. These capacities reflect a "soft" upper bound on the volume of various activities - collection, shipment, testing and processing, and so forth. Accordingly, decision variable o_a is defined as a cushion to allow surpassing the aforementioned effective capacity on each link a of the network should a demand surge necessitates that. Such overflow includes, for instance, the overtime operation (of blood collection facilities, testing labs, and so forth), or conducting extra trips and/or operating larger vehicles (for transportation/shipment links). Additionally, $\o_a^{\max},\ a \in L^0$, is defined to represent a "hard" upper bound on the amount of output increase (overage), o_a, relative to the effective capacity, $\bar{u}_a$, for each blood bank activity. A total overflow penalty function, $\hat{\gamma_a}$ is then defined for each link which is a function of overflow variable, o_a, on that link.

Each BSO aims to improve its operational efficiency and stable its blood supply. Such a multi-criteria decision-making problem can be formulated as follows: for each BSO $i = 1, \ldots, I,$

$$\text{Minimize} \quad \sum_{a \in L_i^0} \left[\hat{c}_a(f_a) + \hat{z}_a(f_a) + \hat{\gamma}_a(o_a)\right] + \sum_{k=1}^{n_{iR}} ec_{ik}E(e_{ik}), \qquad (1)$$

$$\text{Minimize}_{k=1,\ldots,n_{iR}} \quad E(s_{ik}). \qquad (2)$$

Objective function (1) captures the operational efficiency by minimizing the total operating costs of the entire organization, including the regular operational cost $\hat{c_a}(f_a)$, the discarding cost of waste $\hat{z_a}(f_a)$, the overflow cost $\hat{\gamma_a}(o_a)$ associated with each supply chain activity (link) $o_a^{\max}$, $a \in L^0$, as well as the disposal cost of expected outdated (surplus) blood at each demand region R_k^i, calculated through $ec_{ik}E(e_{ik})$.

Objective function (2) minimizes the expected supply shortage at each demand region R_{ik}, denoted by $E(s_{ik})$. A unit shortage penalty, denoted by sc_{ik}, is assigned by BSO i to demand region R_k^i, representing the social cost of a death or a severe injury of a patient due to a blood shortage in that region. Accordingly, a nonpreemptive multi-objective programming approach is applied to this problem to construct a single weighted-sum objective function, i.e.,

$$\text{Minimize} \quad \sum_{a \in L_i^0} \left[\hat{c}_a(f_a) + \hat{z}_a(f_a) + \hat{\gamma}_a(o_a)\right] + \sum_{k=1}^{n_{iR}} \left[ec_{ik}E(e_{ik}) + sc_{ik}E(s_{ik})\right]. \quad (3)$$

Note that each organization is operating independently prior to the merger, which implies that each of their optimization problems is independent of the others. Therefore, the following optimization problem generates the optimal solution for each organization over the course of the planning horizon of the pre-merger model (i.e., one week):

$$\text{Minimize} \quad \sum_{i=1}^{I} \sum_{a \in L_i^0} \left[\hat{c}_a(f_a) + \hat{z}_a(f_a) + \hat{\gamma}_a(o_a)\right]$$

$$+\sum_{i=1}^{I}\sum_{k=1}^{n_{iR}}\Big[ec_{ik}E(e_{ik})+sc_{ik}E(s_{ik})\Big], \tag{4}$$

subject to:

$$v_{ik}=\sum_{p\in\mathcal{P}^0_{R_{ik}}} x_p\mu_p, \qquad i=1,\dots,I;\ k=1,\dots,n_{iR}, \tag{5}$$

$$f_a=\sum_{k=1}^{n_{iR}}\sum_{p\in\mathcal{P}^0_{R_{ik}}} x_p\alpha_{ap}, \qquad \forall a\in L^0_i;\ i=1,\dots,I, \tag{6}$$

$$f_a\le \bar{u}_a+o_a, \qquad \forall a\in L^0_i,\ i=1,\dots,I. \tag{7}$$

$$o_a\le o_a^{\max}, \qquad \forall a\in L^0_i,\ i=1,\dots,I. \tag{8}$$

$$x_p\ge 0, \qquad \forall p\in\mathcal{P}^0_{R_{ik}};\ i=1,\dots,I;\ k=1,\dots,n_{iR}. \tag{9}$$

$$o_a\ge 0, \qquad \forall a\in L^0_i,\ i=1,\dots,I. \tag{10}$$

Constraint (5) indicates that the shipment amounts of blood product for each organization is determined based on the projected demand at its own demand regions subject to the throughput factor on corresponding paths. Constraint (6) is of conservation of flow type, which means that the initial product flow (excluding waste/perishability/loss) on link a is the sum of the product flows along paths which contain that link, subject to the consideration of potential losses in the preceding activities. Constraint (7) limits the flow of product (i.e., blood) on link a to the existing effective capacity on that link, $\bar{u}_a$, while, as mentioned earlier, allowing an overflow variable of o_a, driven by the demand. Constraint (8) guarantees that capacity overflow on each link does not exceed the maximum increase allowed. Constraints (9) and (10) are non-negativity constraints.

All cost and penalty functions are assumed to be convex and continuously differentiable. Therefore, objective function (4), the sum of convex functions, is convex. Associated with constraint (7), a set of new variables, $\eta_a;\, a\in L^0$ is defined as the Lagrange multipliers which are grouped into the n_{L^0}-dimensional vector η. Such multipliers can be interpreted as the set of shadow prices corresponding to the effective (soft) capacity constraints on each link, representing the monetary value of the capacity on that link.

The variational inequality (VI) formulation of the above pre-merger optimization problem, in terms of path flows as well as link flows, is presented next, followed by the proof of the formulation.
The VI formulation allows utilization of an effective structure for computational purposes. See, Nagurney (Nagurney, 1999), Dupuis and Nagurney (Dupuis and Nagurney, 1993) and the references therein.

Variational Inequality Formulation of the Pre-Merger Problem
Optimization problem (4), subject to constraints (5) through (10), is equivalent to the VI problem: determine the vector of optimal path flows, the vector of optimal capacity overflows, and the vector of Lagrange multipliers, $(x^*,o^*,\eta^*)\in K$, such that:

$$\sum_{i=1}^{I}\sum_{k=1}^{n_{iR}}\sum_{p\in\mathcal{P}^0_{R_{ik}}}\left[\frac{\partial\hat{C}_p(x^*)}{\partial x_p}+\frac{\partial\hat{Z}_p(x^*)}{\partial x_p}+ec_{ik}\mu_p P_{ik}\left(\sum_{q\in\mathcal{P}^0_{R_{ik}}} x^*_q\mu_q\right)\right.$$

$$\left.-sc_{ik}\mu_p\left(1-P_{ik}\left(\sum_{q\in\mathcal{P}^0_{R_{ik}}} x^*_q\mu_q\right)\right)+\sum_{a\in L^0_i}\eta^*_a\alpha_{ap}\right]\times[x_p-x^*_p]$$

$$+\sum_{i=1}^{I}\sum_{a\in L^0_i}\left[\frac{\partial\hat{\gamma}_a(o^*_a)}{\partial o_a}-\eta^*_a\right]\times[o_a-o^*_a]$$

$$+\sum_{i=1}^{I}\sum_{a\in L_i^0}\left[\bar{u}_a+o_a^*-\sum_{q\in\mathcal{P}^0}x_q^*\alpha_{aq}\right]\times[\eta_a-\eta_a^*]\geq 0,\quad \forall(x,o,\eta)\in K, \quad (11)$$

where $K\equiv\{(x,o,\eta)|x\in R_+^{n_{\mathcal{P}^0}},0\leq o_a\leq o_a^{\max};\forall a\in L^0,\eta\in R_+^{n_{L^0}}\}$ and for each path $p;p\in\mathcal{P}_{R_{ik}}^0;i=1,\ldots,I;k=1,\ldots,n_{ik},$

$$\frac{\partial\hat{C}_p(x)}{\partial x_p}\equiv\sum_{a\in L_i^0}\frac{\partial\hat{c}_a(f_a)}{\partial f_a}\alpha_{ap},\ \text{and} \quad (12a)$$

$$\frac{\partial\hat{Z}_p(x)}{\partial x_p}\equiv\sum_{a\in L_i^0}\frac{\partial\hat{z}_a(f_a)}{\partial f_a}\alpha_{ap}. \quad (12b)$$

Variational inequality (11) can be rewritten in terms of link flows as: determine the vector of optimal link flows, the vector of optimal projected demands, the vector of optimal link capacity overflows, and the vector of Lagrange multipliers, $(f^*,v^*,o^*,\eta^*)\in K^1$, such that:

$$\sum_{i=1}^{I}\sum_{a\in L_i^0}\left[\frac{\partial\hat{c}_a(f_a^*)}{\partial f_a}+\frac{\partial\hat{z}_a(f_a^*)}{\partial f_a}+\eta_a^*\right]\times[f_a-f_a^*]$$

$$+\sum_{i=1}^{I}\sum_{k=1}^{n_{ik}}[ec_{ik}P_{ik}(v_{ik}^*)-sc_{ik}(1-P_{ik}(v_{ik}^*))]\times[v_{ik}-v_{ik}^*]$$

$$+\sum_{i=1}^{I}\sum_{a\in L_i^0}\left[\frac{\partial\hat{\gamma}_a(o_a^*)}{\partial o_a}-\eta_a^*\right]\times[o_a-o_a^*]$$

$$+\sum_{i=1}^{I}\sum_{a\in L_i^0}[\bar{u}_a+o_a^*-f_a^*]\times[\eta_a-\eta_a^*]\geq 0,\quad\forall(f,v,o,\eta)\in K^1, \quad (13)$$

where $K^1\equiv\{(f,v,o,\eta)|(5)-(10)\ \text{hold, and}\ \eta\geq 0\}.$

Proof of the Variational Inequality Formulation

Let TC_{i^0} denote that part of objective function (3) corresponding to BSO $\forall i=1,\ldots,I,\ TC_{i_0}$ is assumed to be convex and continuously differentiable, and feasible set K be closed and convex. Based on the Karush-Kuhn-Tucker conditions and the classical theory of VIs (Nagurney, 1999) and (Kinderlehrer and Stampacchia, 1980), the optimal solution to (3) is equivalent to the solution to the following VI: determine $(x^*,o^*,\eta^*)\in K$, such that:

$$\sum_{i=1}^{I}\sum_{k=1}^{n_{iR}}\sum_{p\in\mathcal{P}_{R_{ik}}^0}\left[\frac{\partial TC_i^0}{\partial x_p}+\sum_{a\in L_i^0}\eta_a^*\alpha_{ap}\right]\times[x_p-x_p^*]+\sum_{i=1}^{I}\sum_{a\in L_i^0}\left[\frac{\partial TC_i^0}{\partial o_a}-\eta_a^*\right]\times[o_a-o_a^*]$$

$$+\sum_{i=1}^{I}\sum_{a\in L_i^0}\left[\bar{u}_a+o_a^*-\sum_{q\in\mathcal{P}^0}x_q^*\alpha_{aq}\right]\times[\eta_a-\eta_a^*]\geq 0,\quad\forall(x,o,\eta)\in K. \quad (14)$$

For each path $p;p\in\mathcal{P}_{R_{ik}}^0$, the partial derivative of the objective function with respect to the flow on that path is calculated as follows:

$$\frac{\partial TC_i^0}{\partial x_p}=\frac{\partial\left\{\sum_{a\in L_i^0}[\hat{c}_a(f_a)+\hat{z}_a(f_a)+\hat{\gamma}_a(o_a)]+\sum_{k=1}^{n_{iR}}[ec_{ik}E(e_{ik})+sc_{ik}E(s_{ik})]\right\}}{\partial x_p}$$

$$=\sum_{a\in L_i^0}\frac{\partial\hat{c}_a(f_a)}{\partial x_p}+\sum_{a\in L_i^0}\frac{\hat{z}_a(f_a)}{\partial x_p}+\sum_{a\in L_i^0}\frac{\hat{\gamma}_a(o_a)}{\partial x_p}+\sum_{k=1}^{n_{iR}}ec_{ik}\frac{\partial E(e_{ik})}{\partial x_p}+\sum_{k=1}^{n_{iR}}sc_{ik}\frac{E(s_{ik})}{\partial x_p}$$

$$= \sum_{a \in L_i^0} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \frac{\partial f_a}{\partial x_p} + \sum_{a \in L_i^0} \frac{\hat{z}_a(f_a)}{\partial f_a} \frac{\partial f_a}{\partial x_p} + \sum_{k=1}^{n_{iR}} ec_{ik} \frac{\partial E(e_{ik})}{\partial v_{ik}} \frac{\partial v_{ik}}{\partial x_p} + \sum_{k=1}^{n_{iR}} sc_{ik} \frac{E(s_{ik})}{\partial v_{ik}} \frac{\partial v_{ik}}{\partial x_p}$$

$$= \sum_{a \in L_i^0} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \alpha_{ap} + \sum_{a \in L_i^0} \frac{\hat{z}_a(f_a)}{\partial f_a} \alpha_{ap} + \sum_{k=1}^{n_{iR}} ec_{ik} \frac{\partial E(e_{ik})}{\partial v_{ik}} \mu_p + \sum_{k=1}^{n_{iR}} sc_{ik} \frac{E(s_{ik})}{\partial v_{ik}} \mu_p. \tag{15}$$

Following Leibniz's integral rule, the below can be derived:

$$\frac{\partial E(e_{ik})}{\partial v_{ik}} = P_{ik}(v_{ik}) = P_{ik}\left(\sum_{q \in \mathcal{P}^0_{R_{ik}}} x_q \mu_q\right), \qquad i = 1, \dots, I; \quad k = 1, \dots, n_{iR}. \tag{16a}$$

$$\frac{\partial E(s_{ik})}{\partial v_{ik}} = P_{ik}(v_{ik}) - 1 = P_{ik}\left(\sum_{q \in \mathcal{P}^0_{R_{ik}}} x_q \mu_q\right) - 1, \qquad i = 1, \dots, I; \quad k = 1, \dots, n_{iR}, \tag{16b}$$

For each link $a \mid a \in L_i^0$, the partial derivative of the objective function with respect to the overflow on that link is:

$$\frac{\partial TC_i^0}{\partial o_a} = \frac{\partial \left\{ \sum_{a \in L_i^0} [\hat{c}_a(f_a) + \hat{z}_a(f_a) + \hat{\gamma}_a(o_a)] + \sum_{k=1}^{n_{iR}} [ec_{ik} E(e_{ik}) + sc_{ik} E(s_{ik})] \right\}}{\partial o_a}$$

$$= \sum_{a \in L_i^0} \frac{\partial \hat{c}_a(f_a)}{\partial o_a} + \sum_{a \in L_i^0} \frac{\hat{z}_a(f_a)}{\partial o_a} + \sum_{a \in L_i^0} \frac{\hat{\gamma}_a(o_a)}{\partial o_a} + \sum_{k=1}^{n_{iR}} ec_{ik} \frac{\partial E(e_{ik})}{\partial o_a} + \sum_{k=1}^{n_{iR}} sc_{ik} \frac{E(s_{ik})}{\partial o_a}$$

$$= \sum_{a \in L_i^0} \frac{\hat{\gamma}_a(o_a)}{\partial o_a}. \tag{17}$$

By making use of the definitions in (12a) and (12b) and the results in (16a) and (16b), variational inequality (11) is immediate. In addition, the equivalence between VIs (11) and (13) can be proved with (5) and (6).

Blood bank merger: the post-merger supply chain network model and formulation

In this section, we present the model corresponding to the situation where the I individual blood organizations have merged to form a new organization (Figure 2). Supernode 0 represents the newly merged blood banking organization, and the links connecting node 0 and node $i; \quad i = 1, \dots, I$ reflect the merger of those blood organizations. Please note that the focus of this model is comparing the day-to-day operational aspects of the pre- and post-merger models, and thus, we do not take into account the total costs associated with the merging process (i.e., the total cost functions on the newly added links are assumed to be zero).

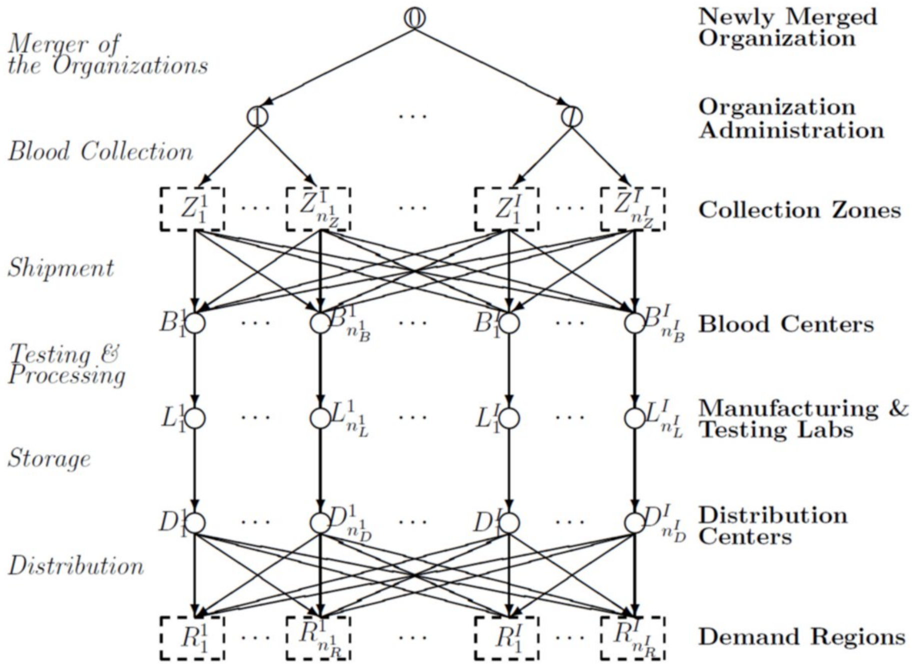

FIGURE 2: Supply Chain Network Topology for the Post-Merger Problem

Source: supply chain network model developed by the authors

Completion of the merger (or acquisition) enables the collection zones of Organization i (which no longer exists as an individual entity) to have their collected units of WB transported to the blood centers of the other organization(s) for subsequent testing, processing, and so forth, if and only if it is economically viable. In fact, the optimal solution to the model will determine whether or not such an option leads to cost-saving for the merged organization. In Figure 2, the newly added cross-organizational links connecting the third and the fourth tiers of nodes denote such feature of our model. Similarly, the newly added links between the last two tiers of nodes in the network represent the situation where Organization i (fully or partially) serves the under-contract hospitals/regions of the other blood provider(s). This, clearly, occurs only if the optimal solution to the problem recommends so.

As for the formulation of the post-merger problem, let L^1 be the set of all links in Figure 2 with n_{L^1} denoting the number of such post-merger links in this set. Let $\mathcal{P}^1_{R_{ik}}$ denote the set of the paths joining supernode 0 with demand region $R^i_k; i=1,\ldots,I$ and $k=1,\ldots,n_{iR}$. $\mathcal{P}^1$ and $n_{\mathcal{P}^1}$ denote the set of all the paths and the number of all paths in the post-merger problem, respectively. Therefore, the total cost minimization problem for the merged organization can be expressed as:

$$\text{Minimize} \quad \sum_{a\in L^1_i}\Big[\hat{c}_a(f_a)+\hat{z}_a(f_a)+\hat{\gamma}_a(o_a)\Big]$$

$$+\sum_{i=1}^{I}\sum_{k=1}^{n_{iR}}\Big[ec_{ik}E(e_{ik})+sc_{ik}E(s_{ik})\Big], \tag{18}$$

subject to:

$$v_{ik}=\sum_{p\in\mathcal{P}^1_{R_{ik}}}x_p\mu_p, \qquad i=1,\ldots,I;\ k=1,\ldots,n_{iR}, \tag{19}$$

$$f_a=\sum_{p\in\mathcal{P}^1}x_p\alpha_{ap}, \qquad \forall a\in L^1, \tag{20}$$

$$f_a\leq \bar{u}_a+o_a, \qquad \forall a\in L^1, \tag{21}$$

$$o_a\leq o_a^{\max}, \qquad \forall a\in L^1. \tag{22}$$

$$x_p \geq 0, \qquad \forall p \in \mathcal{P}^1, \tag{23}$$

$$o_a \geq 0, \qquad \forall a \in L^1. \tag{24}$$

The solution to the post-merger total cost minimization problem, similar to the pre-merger, can be obtained as a solution to a variational inequality problem akin to (11) (or (13)) where $a \in L^1, p \in \mathcal{P}^1_{n_{ik}}$, for $i = 1, \ldots, I$, and $k = 1, \ldots, n_{iR}$, and the vectors f, x, v, o, η have identical definitions as before, but are re-dimensioned accordingly. Set K is then replaced by $K^2 \equiv \{(x, o, \eta) | x \in R_+^{n_{\mathcal{P}^1}}, 0 \leq o_a \leq o_a^{max}; \forall a \in L^1, \eta \in R_+^{n_{L^1}}\}$; and set K^1 is replaced by $K^3 \equiv \{(f, v, o, \eta) | (19) - (24) \text{ hold, and } \eta \geq 0\}$.

Results And Discussion

Case study: a merger between two blood banks

The case to be considered for the performance analysis of a blood bank operation consolidation is the merger between Blood Centers of the Pacific (BCP) and BloodSource. First announced in December 2015, this merger was claimed to form the largest supplier of blood in Northern and Central California (Robertson, 2015). Interestingly, both of the two BSOs involved in the merger have been subject to a series of M&As, re-branding, and other organizational reforms prior to and even after the 2015 merger, all of which have been excluded from the analysis. The focus of this case study is solely on the 2015 merger between BCP and BloodSource, utilizing the developed mathematical framework, while conducting a performance analysis under three scenarios inspired by the COVID-19 pandemic in the 2020-21 period.

Figure *3* illustrates the pre-merger geographic distribution of the major operational sites of BCP and BloodSource in the northwestern United States. According to organizational representatives, the primary objective of the 2015 merger was to enable closer collaboration between two neighboring, long-standing community blood banks. However, ongoing financial pressures appear to have played a significant - if not predominant - role in motivating the consolidation, as noted by a local spokesperson for BCP (Robertson, 2015).

FIGURE 3: Geographical Distribution of Major Facilities of Blood Centers of the Pacific and BloodSource Prior to the 2015 Merger

Source: authors (location of the facilities provided by the officials of the blood banks involved in the merger)

As part of the 2015 deal, Blood Source, Inc., became a member of the Scottsdale, Arizona-based Blood Systems, Inc. (BSI), one of the oldest and largest nonprofit community blood providers in the nation serving a total of more than 700 hospitals in 24 states at the time of merger. The other organization involved with the merger, BCP, was already affiliated with BSI prior to the merger (Robertson, 2015). In September 2018, BSI announced that its 10 blood center brands would unite as one cohesive brand under the new name *Vitalant*, in order to enhance the effectiveness of advertising efforts of the organization in their competition over potential donors with the other blood banks (Vitalant, 2018).

Unless otherwise noted, the information presented in this section was provided by officials from the two blood banks interviewed for this study (see Acknowledgements).

The Pre-Merger Supply Chain Network Structure of the Case Study

Prior to the 2015 merger, the San Francisco-based Blood Centers of the Pacific provided blood components to more than 50 hospitals across Northern California. Similarly, the Sacramento-based BloodSource served over 40 hospitals throughout Northern and Central California, the San Francisco Bay Area, and Northern Nevada.

Figure *4* depicts the supply chain network topology for both BCP and BloodSource in the pre-merger problem. It should be noted that certain facilities (locations) of these two blood banks are represented by more than one node in the topology due to the multiple roles they play in the supply chain.

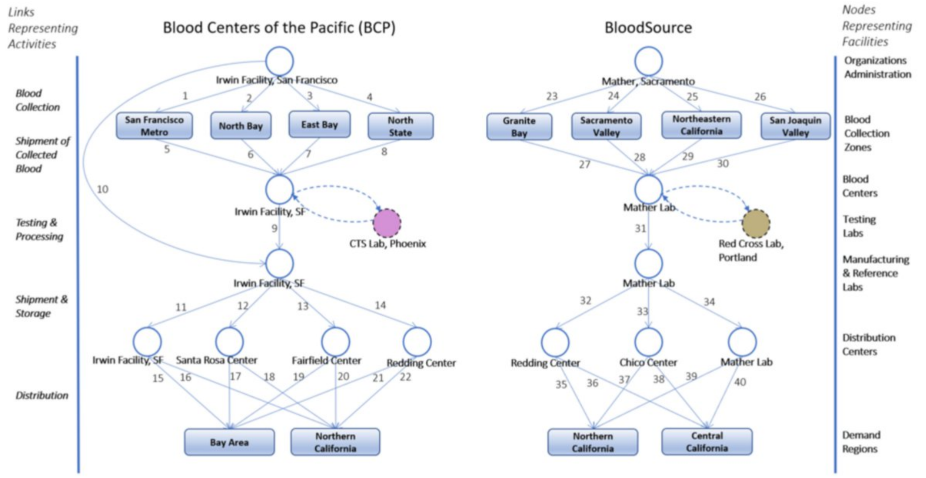

FIGURE 4: Supply Chain Network Topology of Blood Centers of the Pacific (BCP) and BloodSource in the Pre-Merger Problem

Source: supply chain network model developed by the authors for the case study

Each collection zone in the model is composed of a number of adjacent permanent or mobile collection (donor) centers. These zones are formed based on the proximity of donor centers (to each other) as well as their distance to their corresponding immediate destination node. Each of the two BSOs is assumed to have four collection zones as displayed in Figure *4*.

All BCP's collected blood units are sent to their Irwin facility in San Francisco, while the blood units collected by BloodSource are sent to Mather Lab in Sacramento.

Before the merger, BCP outsourced their testing to Creative Testing Solutions (CTS), which was operated by BSI, and located in Phoenix, Arizona. BloodSource, on the other hand, outsourced the testing of its collected blood units for infectious diseases to the closest American Red Cross lab in Portland, Oregon, before the merger. It should be noted that the two testing labs used in the pre-merger problem (denoted by dashed circles in Figure *4*) did not belong to the BSOs. Yet tier 3 links (Link 9 for BCP and Link 31 for BloodSource) represent both activities of testing (at various levels) as well as processing. Thus, the total cost functions corresponding to these two links represent the costs of testing and processing, combined.

As shown in Figure *4*, the partner hospitals of each BSO are grouped into two *demand regions (clusters)*. For BCP, these clusters are labeled as "Region 1" and "Region 2," representing the *Bay Area* and *Northern California*, respectively. For BloodSource, "Region 3" and "Region 4," respectively, represent *Northern California* and *Central California*. Each region contains several adjacent hospitals served via certain distribution centers. In addition to proximity and distance factors earlier mentioned for the collection zones, the population of communities to be served is taken into consideration as well as the geographical distribution of hospitals while determining these demand clusters.

The supply chain structure of BCP poses another notable feature from an analytical perspective. In the pre-merger model, thanks to being part of Blood Systems, Inc., BCP is able to obtain tested and processed blood units directly from its parent organization once a need arises. In other words, if there ever exists excess demand for blood products such that BCP is not able to meet, BSI comes to help by providing red blood cell units. Such supplemental units have been collected, tested and processed by the other members blood banks of the parent organization, and are ready to be distributed, albeit at a higher cost, to BCP. Link 10 in Figure *4* represents such a situation where BCP "outsources" the collection, testing and processing of blood when they are unable to satisfy the demand using their own resources, subject to the capacity on this link.

Parameters of the Pre-Merger Problem

This section provides parameters of the case study corresponding to the pre-merger problem, including the cost functions, the capacity values, as well as the demand information. It should be noted here that the values of these parameters and total cost functions were determined based on: (1) information provided by the blood bank officials (See Acknowledgements); (ii) information available on the organizations' websites shortly after the 2015 merger; (iii) average historical data for the American Red Cross Blood Services (Masoumi et al., 2017).

The weekly demand for RBCs at each of the four clusters is assumed to follow a continuous uniform distribution with different ranges (representing the lower and upper bounds of their respective uncertain weekly demand in the baseline scenario). The below values of the uniform distribution ranges are based on how these demand clusters are defined for each BSO, i.e., the population of each cluster as well as the number of under-contract hospitals in that region. In addition, the reported total weekly outputs for each organization have been taken into account in the determination of the below ranges:

- For BSO 1 (BCP):
Region 1 (Bay Area): [1675, 2100]
Region 2 (Northern California): [340, 420]

- For BSO 2 (BloodSource):
Region 3 (Northern California): [115, 140]
Region 4 (Central California): [1800, 2200]

The unit shortage penalty values, which quantify the relative severity of the consequences associated with a single RBC unit shortage in each demand region, are presented below for both the pre-merger and post-merger models. The severity of these shortage penalties reflects the extent to which unmet demand in a given region can feasibly be fulfilled by alternative blood banks operating within that region.

- For BSO 1 (BCP):
Region 1: 1450
Region 2: 1500

- For BSO 2 (BloodSource):
Region 3: 1475
Region 4: 1500

Similarly, the cost (penalty) corresponding to the excess units of unused/outdated RBC at the hospitals in each demand region are:

- For BSO 1 (BCP):
Region 1: 5.0
Region 2: 4.0

- For BSO 2 (BloodSource):
Region 3: 4.5
Region 4: 5.0

Next, the parameters corresponding to Organization 1 (BCP) and Organization 2 (BloodSource) are displayed in Table *3* and Table *4*, respectively.

Link a	α_a	$\bar{u}_a$	o_a^{max}	$\hat{c}_a(f_a)$	$\hat{z}_a(f_a)$	$\hat{\gamma}_a(o_a)$
1	1.000	1,500	150	$.020(f_1)^2 + .200f_1$	$.700f_1$	$.200(o_1)^2$
2	1.000	600	60	$.030(f_2)^2 + .250f_2$	$.700f_2$	$.250(o_2)^2$
3	1.000	750	75	$.028(f_3)^2 + .200f_3$	$.800f_3$	$.250(o_3)^2$
4	1.000	500	50	$.023(f_4)^2 + .320f_4$	$.800f_4$	$.300(o_4)^2$
5	0.990	1,700	170	$.008(f_5)^2 + .100f_5$	$.700f_5$	$.100(o_5)^2$
6	0.980	1,000	100	$.015(f_6)^2 + .100f_6$	$.700f_6$	$.100(o_6)^2$
7	0.990	800	80	$.016(f_7)^2 + .080f_7$	$.600f_7$	$.100(o_7)^2$
8	0.970	600	60	$.022(f_8)^2 + .140f_8$	$.800f_8$	$.200(o_8)^2$
9	0.950	1,800	180	$.088(f_9)^2 + .700f_9$	$.500f_9$	$.250(o_9)^2$
10	0.990	2,000	200	$300.000f_{10}$	$.800f_{10}$	$.100(o_{10})^2$
11	1.000	1,500	150	$.005(f_{11})^2 + .150f_{11}$	$.500f_{11}$	$.120(o_{11})^2$
12	1.000	750	75	$.010(f_{12})^2 + .200f_{12}$	$.600f_{12}$	$.150(o_{12})^2$
13	1.000	750	75	$.010(f_{13})^2 + .170f_{13}$	$.700f_{13}$	$.150(o_{13})^2$
14	0.990	1,200	120	$.010(f_{14})^2 + .230f_{14}$	$.700f_{14}$	$.180(o_{14})^2$
15	1.000	1,450	145	$.008(f_{15})^2 + .400f_{15}$	$.600f_{15}$	$.200(o_{15})^2$
16	0.990	-	-	$.200(f_{16})^2 + .900f_{16}$	$.700f_{16}$	$.350(o_{16})^2$
17	1.000	400	40	$.010(f_{17})^2 + .800f_{17}$	$.600f_{17}$	$.200(o_{17})^2$
18	0.990	-	-	$.180(f_{18})^2 + .650f_{18}$	$.700f_{18}$	$.250(o_{18})^2$
19	1.000	450	45	$.010(f_{19})^2 + .450f_{19}$	$.700f_{19}$	$.200(o_{19})^2$
20	0.990	-	-	$.200(f_{20})^2 + .750f_{20}$	$.700f_{20}$	$.250(o_{20})^2$
21	0.980	-	-	$.023(f_{21})^2 + .550f_{21}$	$.800f_{21}$	$.300(o_{21})^2$
22	0.990	1,200	120	$.010(f_{22})^2 + .320f_{22}$	$.600f_{22}$	$.150(o_{22})^2$

TABLE 3: Throughput Multipliers, Weekly Capacities, Upper Bounds on Capacity Overflows, Regular Operational Cost Functions, Total Discarding Cost Functions, and Total Overflow Penalty Functions for Organization 1 (Blood Centers of the Pacific) (Links 1-22) in the Pre-Merger Problem under the Baseline Scenario

Link a	α_a	$\bar{u}_a$	O_a^{max}	$\hat{c}_a(f_a)$	$\hat{z}_a(f_a)$	$\hat{\gamma}_a(o_a)$
23	1.000	750	75	$.020(f_{23})^2 + .150f_{23}$	$.700f_{23}$	$.170(o_{23})^2$
24	1.000	1,250	125	$.029(f_{24})^2 + .200f_{24}$	$.700f_{24}$	$.150(o_{24})^2$
25	1.000	750	75	$.031(f_{25})^2 + .300f_{25}$	$.750f_{25}$	$.200(o_{25})^2$
26	1.000	750	75	$.028(f_{26})^2 + .300f_{26}$	$.800f_{26}$	$.200(o_{26})^2$
27	1.000	900	90	$.008(f_{27})^2 + .100f_{27}$	$.700f_{27}$	$.150(o_{27})^2$
28	1.000	1,250	125	$.017(f_{28})^2 + .150f_{28}$	$.700f_{28}$	$.150(o_{28})^2$
29	0.980	1,000	100	$.022(f_{29})^2 + .150f_{29}$	$.800f_{29}$	$.150(o_{29})^2$
30	0.970	1,000	100	$.016(f_{30})^2 + .200f_{30}$	$.800f_{30}$	$.120(o_{30})^2$
31	0.960	2,600	260	$.090(f_{31})^2 + .600f_{31}$	$.550f_{31}$	$.350(o_{31})^2$
32	0.990	1,200	120	$.013(f_{32})^2 + .450f_{32}$	$.800f_{32}$	$.200(o_{32})^2$
33	0.990	1,500	150	$.007(f_{33})^2 + .250f_{33}$	$.600f_{33}$	$.170(o_{33})^2$
34	1.000	1,750	175	$.004(f_{34})^2 + .100f_{34}$	$.500f_{34}$	$.150(o_{34})^2$
35	0.990	500	50	$.009(f_{35})^2 + .300f_{35}$	$.600f_{35}$	$.150(o_{35})^2$
36	0.980	-	-	$.028(f_{36})^2 + .800f_{36}$	$.700f_{36}$	$.250(o_{36})^2$
37	1.000	200	20	$.014(f_{37})^2 + .700f_{37}$	$.700f_{37}$	$.200(o_{37})^2$
38	1.000	1,500	150	$.010(f_{38})^2 + .650f_{38}$	$.700f_{38}$	$.200(o_{38})^2$
39	0.990	-	-	$.018(f_{39})^2 + .650f_{39}$	$.750f_{39}$	$.250(o_{39})^2$
40	1.000	1,750	175	$.012(f_{40})^2 + .500f_{40}$	$.600f_{40}$	$.200(o_{40})^2$

TABLE 4: Throughput Multipliers, Weekly Capacities, Upper Bounds on Capacity Overflows, Regular Operational Cost Functions, Total Discarding Cost Functions, and Total Overflow Penalty Functions for Organization 2 (BloodSource) (Links 23-40) in the Pre-Merger Problem under the Baseline Scenario

The Post-Merger Supply Chain Network Structure of the Case Study

Figure *5* displays the supply chain network model corresponding to the merged BSO after the completion of the 2015 merger between the two Californian blood banks. As explained earlier, as a result of the merger, BloodSource became part of Blood Systems, Inc., an alliance of 10 independent blood banks across the United States at the time of the merger. The Arizona-based organization allowed both blood banks to keep their names and operations (at the levels of collection and shipment to blood centers) until their national brand unification in 2018 took place. The new supernode labeled "BCP & BloodSource'" represents the merged BSO, and the links connecting this supernode with the existing BSOs reflect the unified management of the organization operations once the merger process has been completed.

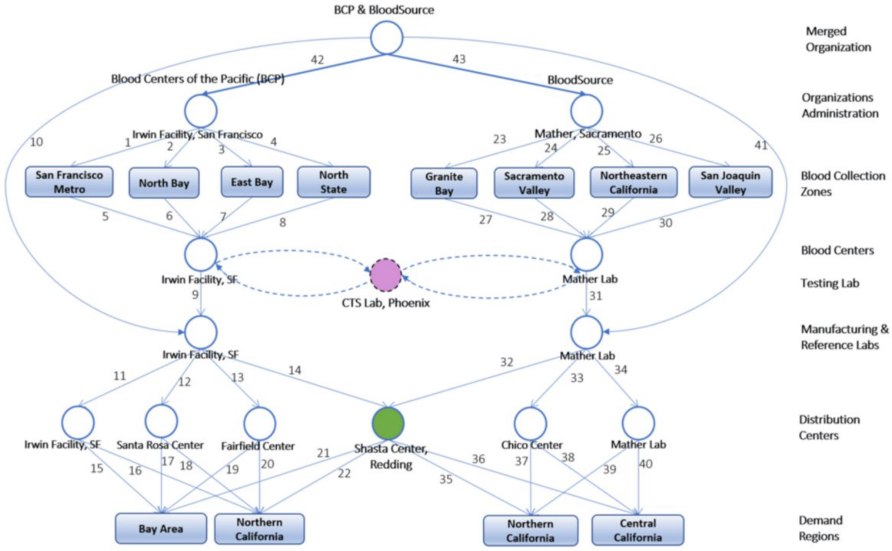

FIGURE 5: Supply Chain Network Topology of the Newly Formed Blood Service Organization in the Post-Merger Problem

Source: supply chain network model developed by the authors for the case study

Each hospital in the post-merger model is assumed to continue being served by its pre-merger partner organization. Though, a number of changes were made in the supply chain of the new organization during or shortly after the merger as follows:

- BloodSource now gets the testing of their collected blood samples for certain infectious diseases conducted at the CTS Lab in Phoenix (Compare the testing lab nodes in Figure 4 and Figure 5).

- BloodSource now has the option to purchase processed/tested blood directly from BSI (represented by newly added Link 41; that is, outsourcing of blood procurement should the excess demand necessitate such a case).

- BloodSource and BCP combined their own distribution facilities in Redding, California, into one (represented by a shared node at the distribution level in Figure 5). Blood banks also combined their collection centers in Redding.

Parameters of the Post-Merger Problem

Table 5 displays the new values of the parameters for the post-merger problem. The links not displayed here are assumed to have the same values as those in Table 3 and Table 4.

Link a	α_a	$\bar{u}_a$	O_a^{max}	$\hat{c}_a(f_a)$	$\hat{z}_a(f_a)$	$\hat{\gamma}_a(o_a)$
4	1	500	50	$.017(f_4)^2 + .230f_4$	$.800f_4$	$.200(o_4)^2$
8	0.97	500	50	$.020(f_8)^2 + .100f_8$	$.800f_8$	$.150(o_8)^2$
9	0.95	1800	180	$.080(f_9)^2 + .500f_9$	$.500f_9$	$.150(o_9)^2$
14	0.99	1000	100	$.006(f_{14})^2 + .200f_{14}$	$.650f_{14}$	$.150(o_{14})^2$
22	0.99	900	90	$.007(f_{22})^2 + .290f_{22}$	$.600f_{22}$	$.130(o_{22})^2$
25	1	700	70	$.028(f_{25})^2 + .250f_{25}$	$.750f_{25}$	$.120(o_{25})^2$
29	0.98	900	90	$.020(f_{29})^2 + .130f_{29}$	$.800f_{29}$	$.130(o_{29})^2$
31	0.955	2600	260	$.082(f_{31})^2 + .500f_{31}$	$.450f_{31}$	$.170(o_{31})^2$
32	0.99	1100	110	$.010(f_{32})^2 + .250f_{32}$	$.800f_{32}$	$.180(o_{32})^2$
35	0.99	400	40	$.008(f_{35})^2 + .280f_{35}$	$.600f_{35}$	$.130(o_{35})^2$
41	0.99	1500	150	$310.000f_{41}$	$.750f_{41}$	$.120(o_{41})^2$
42	1	unlimited	unlimited	0	0	0
43	1	unlimited	unlimited	0	0	0

TABLE 5: New Values of Throughput Multipliers, Weekly Capacities, Upper Bound on Capacity Overflows, Total Operational Cost, Total Discarding Cost, and Total Overflow Penalty Functions for the Merged Blood Service Organization in the Post-Merger Problem under the Baseline Scenario

Scenario Analysis

In this section we present three scenarios, inspired by the operations of blood banks in the United States during the COVID-19 pandemic, to compare the performance of the merged BSO with the individual blood banks had the merger not taken place in 2015-16. The first scenario replicates the status of the merged blood banks in September-October 2019, referred to as the "baseline pre-COVID scenario." The second one represents the operations of these two BSOs during the mid March - mid April of 2020 during the early weeks of the pandemic in California; referred to as the "lockdown period scenario." The last one captures the landscape of the two blood bank operations during the September-October 2021; labeled as the "return-to-normal scenario."

For each scenario, an algorithm based on the Euler method is utilized to solve VI (11). Thus, the optimal values of product flows, capacity overflows, as well as the Lagrange multipliers are obtained corresponding to all links belonging to BCP and BloodSource under each of the three scenarios for the pre- and post-merger problems. The potential savings in the total operating cost of the BSOs associated with the merger is measured for each scenario, as well as the potential savings in the shortage penalty at the demand regions resulted from the merger.

Baseline Pre-COVID Scenario: September-October 2019

This scenario replicates the supply/demand status of the merged BSO in the pre-pandemic era, specifically during the September-October 2019 period, and compares its performance measures with those of the individual blood banks assuming they were operating independently during that period. The optimal solution to the pre-merger problem under the baseline scenario is displayed in Table 6.

Organization 1 (BCP)				Organization 2 (BloodSource)			
Link a	f_a*	o_a*	η_a*	Link a	f_a*	o_a*	η_a*
1	519.14	0	0	23	770.46	20.46	6.96
2	319.01	0	0	24	543.5	0	0
3	330.59	0	0	25	459.6	0	0
4	312.11	0	0	26	546.59	0	0
5	519.14	0	0	27	770.46	0	0
6	319.01	0	0	28	543.5	0	0
7	330.59	0	0	29	459.6	0	0
8	312.11	0	0	30	546.59	0	0
9	1,456.61	0	0	31	2,294.56	0	0
10	1,038.03	0	0	32	134.09	0	0
11	1,100.29	0	0	33	922.04	0	0
12	427.43	0	0	34	1,146.65	0	0
13	473.23	0	0	35	132.75	0	0
14	410.48	0	0	36	0	0	415.05
15	1,100.29	0	0	37	0	0	0
16	0	0	130.66	38	912.82	0	0
17	427.43	27.4	10.92	39	0	0	86.96
18	0	0	128.81	40	1,146.65	0	0
19	473.23	23.28	9.36				
20	0	0	124.76				
21	0	0	297.02				
22	406.38	0	0				

TABLE 6: Optimal Values of Weekly Link Flows, Capacity Overflows on Links, and Lagrange Multipliers for Organization 1 (BCP) (Links 1-22) and Organization 2 (BloodSource) (Links 23-40) in the Pre-Merger Problem under the Baseline Scenario

Similarly, the optimal solution to the post-merger problem under the baseline scenario can be found in Table 7.

Organization 1 (BCP)				Organization 2 (BloodSource)			
Link a	f_a^*	o_a^*	η_a^*	Link a	f_a^*	o_a^*	η_a^*
1	543.33	.00	.00	23	585.23	.00	.00
2	333.91	.00	.00	24	355.79	.00	.00
3	345.98	.00	.00	25	331.90	.00	.00
4	399.29	.00	.00	26	356.24	.00	.00
5	543.33	.00	.00	27	585.23	.00	.00
6	333.91	.00	.00	28	355.79	.00	.00
7	345.98	.00	.00	29	331.90	.00	.00
8	399.29	.00	.00	30	356.24	.00	.00
9	1,594.97	.00	.00	31	1,611.83	.00	.00
10	1,043.41	.00	.00	32	.00	.00	.00
11	1,100.28	.00	.00	33	968.91	.00	.00
12	427.37	.00	.00	34	1,142.59	.00	.00
13	473.31	.00	.00	35	135.77	.00	.00
14	547.24	.00	.00	36	.00	.00	417.93
15	1,100.28	.00	.00	37	.00	.00	.00
16	.00	.00	114.53	38	959.23	.00	.00
17	427.37	27.41	10.93	39	.00	.00	108.91
18	.00	.00	113.57	40	1,142.59	.00	.00
19	473.31	23.26	9.34	41	577.98	.00	.00
20	.00	.00	110.44	42	1,622.52	.00	.00
21	.00	.00	324.49	43	1,629.16	.00	.00
22	406.00	.00	.00				

TABLE 7: Optimal Values of Weekly Link Flows, Capacity Overflows on Links, and Lagrange Multipliers for the Merged Blood Service Organization in the Post-Merger Problem under the Baseline Scenario

Comparing the optimal solutions to the pre- and post-merger problems under the baseline pre-COVID scenario (Table *6* and Table *7*) reveals the following outcomes:

Firstly, Link 10 (representing BCP's option of outsourcing the procurement of processed and tested blood to BSI) sees a significant weekly flow of over 1,000 RBC units in the baseline scenario, pre- and post-merger alike. Similarly, BloodSource enjoys a weekly flow of nearly 578 units on link 41 in the post-merger problem, thanks to the newly added outsourcing option to BloodSystems, Inc. This highlights the importance of the role the parent organization plays in overseeing the procurement of blood, given the demand scenario.

Secondly, the aforementioned structural changes during the merger process has resulted in load changes for certain supply chain activities. In the collection and shipment activities, the merger has moved a fraction of BloodSource's load to BCP. To be more specific, Links 1-8 (corresponding to BCP's collection and shipment) experience an average flow increase of over 10%, whereas Links 23-30 (corresponding to BloodSource's collection and shipment) see an average reduction of 30% in product flow. Moreover, shipment/storage Links 14 and 32, respectively, connecting the manufacturing labs of BCP and BloodSource to the newly merged Shasta distribution center in Redding have been subject to flow changes. That is, while BCP sees a 33% increase in shipping to the Redding distribution center, BloodSource stops using it for distribution purposes after the merger in the baseline scenario. The remaining three activities (testing/processing, shipment/storage, and distribution) have maintained almost the same product flows.

Additionally, we analyze the performance of the merger in the baseline scenario from a synergy perspective in Table 8 and Table 9.

Objective Function Value	Pre-Merger			Post-Merger
	BCP	BloodSource	Both BSOs Combined	Merged Organization
Total Operating Cost	$557,312.24	$575,810.59	$1,133,122.83	$1,043,644.09
Regular Operational Costs	$549,720.45	$567,965.46	$1,117,685.91	$1,028,941.07
Discarding Cost on Links	$6,611.27	$7,328.91	$13,940.18	$13,120.47
Capacity Overflow Penalty	$258.47	$71.17	$329.64	$258.42
Expected Discarding Cost at Demand Points	$722.04	$445.05	$1,167.09	$1,324.13
Total Shortage Penalty	$19,668.13	$39,200.34	$58,868.47	$38,069.84

TABLE 8: Comparison of the Weekly Total Operating Costs ($) As Well as the Total Shortage Penalty ($) of the BSOs in the Pre- and Post-merger Problems for the Baseline Scenario

BSO, blood service organization; BCP, Blood Centers of the Pacific

From a monetary perspective, *Cost Synergy*, defined as the percentage change in the total operating cost; i.e., objective function (1), with respect to the pre- and post-merger problems is equal to 7.90%. For the baseline demand scenario, the above cost synergy is equivalent of a cost saving of $89,478.74 over a period of just one week, or roughly 4.6 million dollars in one year. The projected cost synergy is mainly due to savings from operational costs, and less from discarding costs and capacity overflow penalties, as broken down in Table 8.

Similarly, *Shortage Synergy*, defined as the percentage change in the shortage penalty; i.e., objective function (2), at the demand points with respect to the two problems is equal to 35.33%. The above shortage synergy translates to a significant reduction in the disruption of treatments or surgeries at the hospitals in the four demand regions after the completion of the merger. This shortage synergy can also be interpreted as a type of "risk-pooling" between the two blood banks as a result of the merger, while the newly merged BSO is backed by the parent organization (BSI).

Projected Value (RBC Units)	Pre-Merger			Post-Merger
	BCP	BloodSource	Both BSOs Combined	Merged Organization
Supplied Amount	2,403.00	2,190.00	4,593.00	4,639.00
Capacity Overage	50.67	20.46	71.13	50.67
Outsourced Amount	1,038.03	N/A	1,038.03	1,621.39

TABLE 9: Comparison of the weekly projected supplied blood (RBC units), capacity overage (RBC units), as well as the outsourced amount (RBC units) of the BSOs in the pre- and post-merger problems for the baseline scenario

BSO, blood service organization; BCP, Blood Centers of the Pacific; RBC, red blood cells

Also, in terms of the weekly units of supplied RBC to the demand points, as seen in Table 9, the merged BSO (4,639) sees a 1% increase compared to the combined number of the two BSOs (4,593) in the pre-merger problem. Accordingly, in terms of the capacity overage, the merged organization sees a 29% reduction in the overflow amount. A significant part of this improvement is due to a 56% increase in the number of outsourced units to BSI, which was not available to BloodSource prior to the merger.

Sensitivity Analysis of Synergy Measures

We now conduct sensitivity analysis of the two synergy measures against the changes in the expected value as well as the variability of demand. This analysis not only helps with the validation of the proposed merger model, but also allows the blood bank officials to evaluate the robustness of gains from the merger against likely fluctuations in the demand market, a phenomenon almost all blood banks have faced during the past 10 years.

Sensitivity Analysis against Expected Value of Demand

We start our sensitivity analysis by varying the expected value of demand for RBC at each of the four demand regions while keeping the variability of demand constant. We use the existing demand values used in the pre- and post -merger problems of the baseline scenario. Then, we decrease the expected value of the uniform distribution of demand at each region from 5% below to 25% below the base scenario in the increments of 5%. Similarly, we increase the expected value of demand from 5% to 25%. Thus, we have a total of 11 demand scenarios each of which is examined for the cost synergy as well as the shortage synergy in the pre- and post-merger problems. Figure 6 displays the impact of varying the expected values of demand on these synergy measures.

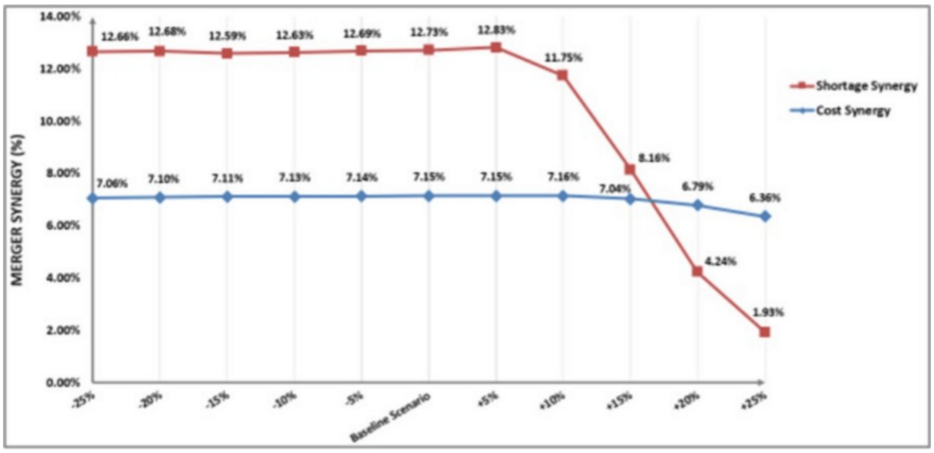

FIGURE 6: Sensitivity Analysis of Cost and Shortage Synergies Associated with the 2015 Merger between BCP and BloodSource against the Change in the Expected Value of Demand Relative to the Baseline Pre-COVID Scenario

Source: chart developed by the authors based on the results of the numerical analysis. BCP, Blood Centers of the Pacific

As seen in Figure 6, the merged organization is likely to enjoy a relatively robust 6-7% gain in the cost synergy associated with the merger over all the above demand scenarios. As for the other synergy measure, i.e., that of the shortage, our analysis shows a projected synergy of at least 11-12% when the demand increase is less than 10% compared to the baseline pre-COVID scenario. For further increases in the expected value of demand, the shortage synergy shows a sharp drop which essentially means no significant gain from the merger given the current structure of their supply chains under such an extreme demand surge.

Sensitivity Analysis against Demand Variability

We now examine the impact of varying the variability of demand at each region while keeping the expected value of each uniform distribution constant. Similar to the above sensitivity analysis against changes in the expected demand, here we have 11 scenarios starting from 25% decrease in demand range (compared to the baseline scenario) up to 25% increase, and calculate the same two synergy measures in the pre- and post-merger problems. As seen in Figure 7, neither of the two synergies of cost and shortage experienced a significant change as a result of manipulating the demand variability as long as the expected value of demand stays unchanged. In other words, the synergy gained from the merger is relatively robust with respect to the changes in demand variability.

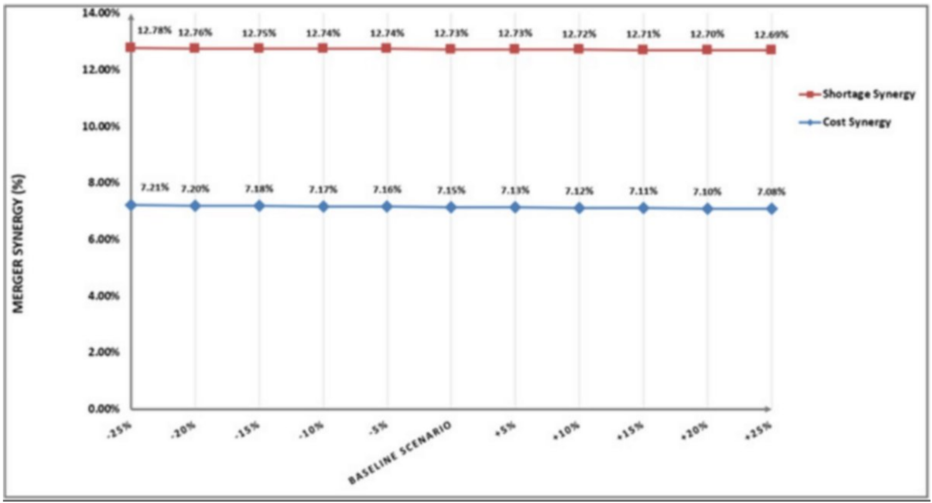

FIGURE 7: Sensitivity Analysis of Cost and Shortage Synergies Associated with the 2015 Merger between BCP and BloodSource Against the Changes in Demand Ranges Corresponding to the Baseline Pre-COVID Scenario

Source: chart developed by the authors based on the results of the numerical analysis. BCP, Blood Centers of the Pacific

Lockdown Period Scenario: March-April 2020

This section analyzes the supply and demand scenarios governing the blood banks during the first few weeks of the COVID-19 pandemic in the West Coast of the U.S. The Californian blood bank mega-merger was completed roughly 3 years prior to the emergence of the pandemic. Nonetheless, the developed framework allows analyzing the performance of the merged organization during any situations, and compare that with those of the individual BSOs involved in the merger in the hypothetical setting that the merger had not taken place.

The first peak of the COVID-19 pandemic in the United States (i.e., mid March through mid April of 2020) significantly impacted the upstream (collection) side of blood supply chains despite all the efforts made by healthcare officials to maintain the national supply of this highly critical product. In the analysis, this negative impact is captured by applying a 40% reduction in the capacity of all collection (as well as outsourcing) links. All other links were assumed to experience a 5% reduction as a result of the strict safety guidelines imposed on healthcare facilities, as well as the shortage of essential workforce caused by sickness and quarantine. Accordingly, the maximum overload allowed (o_a^{max}) over collection links was set to zero, and 5% over all other links in the network. Similarly, a 10% increase is applied on all regular operational as well as discarding costs, mainly caused by additional safety protocols throughout the supply chain including but not limited to the use of disinfecting products and personal protective equipment (PPE) supplies in their facilities.

The demand side of blood supply chains, including hospitals and surgical medical centers were no less affected during that period. Similar to the other regions of the United States, a stay-at-home order in the state of California in March 2020 resulted in a considerably lower number of trauma patients in need of blood transfusions. Furthermore, the majority of elective surgeries and a significant fraction of chronic disease treatments were canceled/postponed during the first peak of the pandemic, contributing to a major drop in demand for blood in that period (Sahu et al., 2020). In the quantitative analysis of the lockdown period scenario, a 20% reduction is assumed to the lower and upper bounds of the uniform probability distribution corresponding to the demand for red blood cells in each of the four regions.

The obtained optimal solution to the pre- and post-merger problems of the lockdown period scenario demonstrates a major reduction between 19% and 21% in the supplied units of blood, as compared to those of the baseline. From a synergy perspective, the newly merged organization enjoys a cost synergy of 6.10%, and a shortage synergy of 11.99%.

Return-to-Normal Scenario: September-October 2021

In this section, the landscape of the Californian blood bank operations during the late summer through late fall of 2021 period is investigated, a period referred to as a "return-to-normal" scenario in this research.

As mentioned earlier in the paper, the above time period coincided with a continued period of hesitancy to donate blood, resulting in lower than normal donation rates for American blood banks. In the analysis of the scenario, a 90% capacity on collection (and outsourcing) links, as seen in the study titled, "Heading into the third year of the pandemic, the US blood supply is at a 10-year low" by Nagurney (Nagurney, 2022), and 98% on all other links are assumed (as compared to the baseline scenario). The maximum overage caps on these links were set to 0% and 5%, respectively. All regular operational, overage penalty, and discarding cost functions, as well as shortage penalties were assumed to remain the same as the lockdown period.

As for the demand side, an accelerated demand for RBC caused by a sharp increase in travels and outdoor activities as well as an increasing resumption of postponed treatments, have been further challenging blood banks in balancing the supply/demand to the date. In the analysis of the scenario, the ranges of the probability distribution of demand at each region were set 10% higher than the baseline scenario (i.e., 35-40% higher than the lockdown period).

Our results show a 9.2-9.5% increase in the supplied units of blood across all regions in both pre- and post-merger problems of the return-to-normal scenario; that is, 35.0-37.5% higher than those of the lockdown period. In terms of the synergy of the merger, the merger demonstrates a significant cost synergy of 7.75%, and a notable shortage synergy of 35.50%.

Scenario Analysis Discussion

This section compares the performance of the individual blood banks involved in the merger with that of the merged organization under each of the three COVID-19 scenarios described earlier.

Figure *8a* summarizes the comparison of the weekly operating costs; i.e., objective function (1), of BCP and BloodSource with the merged BSO across the three above scenarios.

FIGURE 8: Comparison of Weekly Operating Costs of the BSOs in the Pre-merger and Post-merger Problems Across Three Different Scenarios

Source: chart developed by the authors based on the results of the numerical analysis. BSO, blood service organization

As seen in Figure *8a*, the merged organization is likely to see a relatively significant gain in the total operating cost savings, regardless of the supply/demand scenario. The dollar value of this savings depends on the scenario though. The larger the volume of blood supplied by the BSOs, the more significant the dollar value of this weekly savings becomes: $89,479 in the baseline scenario, $48,428 in the lockdown scenario, and $105,393 in the return-to-normal scenario. Accordingly, the calculated cost synergy values corresponding to the percentages of change in total operating costs are 7.90%, 6.10%, and 7.75%, respectively, showing a robust gain in cost savings across all three COVID-related scenarios.

Similarly, Figure *8b* shows a comparison of the supply shortage cost (penalty); i.e., objective function (2), of BCP and BloodSource with that of the merged BSO across the three above scenarios. The analysis shows a projected shortage synergy of 35.33% in the baseline scenario (equivalent to a $20,798 weekly shortage penalty), 11.99% in the lockdown period ($4,741), and 35.50% ($27,981) in the return-to-normal scenario.

As seen from the above numbers and charts, the merger would result in significant cost savings as well as an increased shortage synergy for the merged organization before, during, and after the emergence of

COVID-19 pandemic. In other words, from monetary and nonmonetary perspectives, both blood banks in addition to their under-contract hospitals considerably benefit from the merger. It should be emphasized that the cost efficiency and the stability of blood supply are often regarded as the primary motives for mergers, acquisitions, and other forms of organizational restructuring in the blood banking industry.

Based on the analysis, officials of the two BSOs involved in this merger could expect the merged organization to continue outperforming the two individual banks when faced with demand surge scenarios (e.g., the return-to-normal).

It should be noted that the scope of the proposed merger analysis framework is solely the day-to-day operations of blood banks in the pre- and post-merger problems. Thus, the real estate-related cost savings resulted from the consolidation of collection and distribution facilities as well as savings in administrative costs are excluded from the analysis. On the other hand, each merger is prone to a number of potential risks, including the communication gap between the merged organizations, job losses, as well as litigation issues. For a more thorough analysis of the merger, these additional factors should also be taken into consideration, upon the availability of such information.

Conclusions

Blood banking industry, a key component of the healthcare system in the United States, has been subject to a volatile landscape over the past decade. Emergence of COVID-19 contributed to the challenges blood banks face on both ends of these supply chains. Despite the ending declaration of the public health emergency by the U.S. government in May 2023, American blood banks continue experiencing operational inefficiencies at the same intensity, if not higher, than the first two years of the pandemic.

Blood banks have long been seeking operational cost efficiency as well as a more stabilized supply of blood through a number of ways, including mergers and acquisitions. In this research, a generalized supply chain network optimization framework was developed to analyze the effectiveness of blood bank mergers including the following features.

- The possibility of outsourcing the procurement of tested and processed blood by one blood service organization to another, under certain demand conditions, is captured in the model.
- The model allows the concept of capacity overflow corresponding to various activities of blood supply chains at the time of demand surge.
- The framework considers aggregation of blood collection zones on the supply side, as well as clustering the hospitals and surgical centers on the demand side, which allows for capturing the operations of large-scale, real-world blood supply chains.
- The model captures the amount of loss/waste/perishability of blood associated with each activity in the supply chain network through the use of arc multipliers representing the throughput of product flow on the corresponding links.
- A variational inequality approach is utilized to solve the system-optimization problem which provides computational effectiveness upon the solution of large-scale network problems.
- The solution to the model yields the optimal flow of WB/RBC on all links in the networks as well as the amount of capacity overflows so as to minimize the total cost in the pre- and post-merger problems while satisfying the uncertain demand for blood as closely as possible.

This framework was then utilized to analyze a case of merger between two blood banks in Northern/Central California that took place in 2015. Using three different supply/demand scenarios representing various stages of the COVID-19 pandemic in the United States, synergy measures were calculated to evaluate the extent of the merger success. The merger was shown to result in a robust "cost synergy" across the analyzed stages of the pandemic. Furthermore, an enhanced "shortage synergy," caused by the risk-pooling capability between blood banks, would guarantee a more stable supply of blood for the involved BSOs and their partner hospitals.

While this developed framework is sufficiently general to capture any other case of merger or acquisition between two or more blood banks, the following can be considered for future research. First and foremost, an updated performance analysis using the latest supply/demand scenarios governing the blood banking industry in the United States and elsewhere in the world would be necessary. From a modeling perspective, the situation where the capacity of a specific facility is shareable between two cooperating BSOs is worth further investigating. Accordingly, sharing demand points, that is, a cooperative effort by blood banks to collectively satisfy the demand of all their under-contract hospitals can be taken into consideration. Lastly, examining the competition between nonprofit and for-profit blood service organizations over the hospitals located in a demand region would be noteworthy.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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