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Resilient Blood Supply Systems under Demand Surges: A Scenario-Based Robust Inverse Data Envelopment Analysis Approach

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ABSTRACT

Objective: This study proposes an approach to maintain the efficiency of the blood transfusion system in response to increasing demand caused by disruptive events. The primary objective is to determine the necessary input adjustments for the blood transfusion system to accommodate the expected increase in its output.

Methodology: To achieve the study objectives, an inverse data envelopment analysis (IDEA) model is extended to a scenario-based robust counterpart. Considering different scenarios with increasing blood demands and specified probabilities of occurrence, the model is formulated to maintain the efficiency levels while preserving the optimality and feasibility of the model under the considered scenarios.

Results: The proposed model is applied to a real case in the provinces of Iran. After identifying the system inputs and outputs, a set of scenarios was defined to represent an increase in blood demand. Solving the model illustrates that the system requires an increase in the number of donation centers in a range of 0 to 46 across different provinces, while the percentage of donors to the province's population must increase by at most 18% in some provinces. These adjustments help preserve the current level of blood transfusion efficiency.

Conclusion: The present study proposes a novel scenario-based robust inverse data envelopment analysis (DEA) framework for evaluating the efficiency of blood transfusion centers under varying scenarios of increased demand. By analyzing multiple disruption levels, the proposed framework enables decision-makers to determine the necessary resource adjustments to maintain operational efficiency and develop effective plans for managing uncertainty.

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Introduction

The blood supply system is considered one of the most critical and complex components of the healthcare system because it must continuously balance blood supply and demand under uncertain conditions (Pirabán-Ramírez, Guerrero, Labadie, & Sotaquirá-Gutiérrez, 2026), as blood and blood products are used in complex surgeries, the treatment of specific diseases, and emergencies (Raykar, et al., 2021). Blood and its components, including red blood cells, white blood cells, plasma, and platelets, are essential for a wide range of medical treatments and emergency healthcare services (Moshtagh, Zhou, & Verma, 2026). Several studies have shown that blood shortages in the healthcare system result from various factors (Chien, Yao, Chen, & Ho, 2025). Studies have also shown that crises such as the COVID-19 pandemic have further exposed the vulnerability of the blood supply system (Kazemi Matin, Azadi, & Farzipoor Saen, 2022).

In recent years, the demand for blood and blood products has increased significantly, which highlights the importance of balancing blood supply and demand at the national level. From a management perspective, achieving a balance between blood supply and demand reflects the ability of the blood system to ensure the timely availability of safe blood products while minimizing shortages and wastage (Ghahremani-Nahr, Kian, Sabet, & Akbari, 2022). The blood supply-demand balance is affected by two major sources of uncertainty. The first category is supply-related uncertainties (Imamoglu, Topcu, & Aydin, 2023). Owing to the specific characteristics of blood, such as perishability, limited shelf life, blood safety, complete dependence on voluntary donors, and absence of substitution with synthetic products, the balance between blood supply and demand is constantly threatened by the supply side (Arani, Momenitabar, Ebrahimi, & Liu, 2021). In addition, the number of people eligible to donate blood is decreasing in many countries (Kazemi Matin, Azadi, & Farzipoor Saen, 2022). According to official reports and reliable statistics, there is a considerable variation between blood donation and supply across different provinces of the country, which further highlights the importance of managing blood supply and demand at the provincial level. In recent years, increasing numbers of traffic accidents, major surgeries, and age-related medical conditions have placed greater pressure on blood supply systems. On the other hand, geopolitical crises such as war and climate-related threats have reduced public participation in blood donation and increased the demand for blood. Some studies suggest that an increase in surgeries and diseases in the elderly has increased the demand for blood products. In some countries, more than half of the recipients of blood and blood products are older than 60, which has caused additional pressure on the blood demand sector (Ghahremani-Nahr, Kian, Sabet, & Akbari, 2022; Kazemi Matin, Azadi, & Farzipoor Saen, 2022; Fariman, et al., 2024).

Another factor disrupting the supply and demand in the blood system is the lack of coordination between blood transfusion centers and hospitals. Research has proven that independent decision-making by each of these institutions leads to orders exceeding actual needs, excessive blood collection in unnecessary situations, and, as a result, increased waste. This reduces the amount of available blood in conditions of increasing demand (Imamoglu, Topcu, & Aydin, 2023). The imbalance between blood supply and demand has wide-ranging consequences at the social and economic levels. Blood and blood product shortages are a major challenge in health systems worldwide (Ghahremani-Nahr, Kian, Sabet, & Akbari, 2022) and may lead to a significant increase in patient mortality in emergency, surgical, obstetric, and gynecological care units (Arani, Momenitabar, Ebrahimi, & Liu, 2021). In addition, the World Health Organization (WHO) has reported that a lack of access to safe blood is a leading cause of preventable death among patients with acute bleeding and anemia in low- and lower-middle-income countries (World Health Organization, 2025). Blood supply shortages also lead to longer hospital stays, which increase costs (Oliveira & Reis, 2020). In this context, according to the WHO's 2025 annual report, World Health Assembly Resolution WHA63.12 calls on Member States to support sustainable national blood programs to achieve self-sufficiency (WHO, 2025).

Given these consequences, blood supply systems must ensure adequate blood availability under normal conditions and maintain acceptable performance during disruptions and unexpected crises. In this regard, resilience in blood supply systems refers to the ability of the system to maintain acceptable performance levels and recover from disruptions caused by crises such as pandemics, wars, natural disasters, and seasonal or sudden fluctuations in blood supply and demand. Thus, maintaining the balance between blood supply and demand can be considered an important manifestation of resilience in healthcare systems. In fact, resilience is essential, especially for perishable products such as blood and blood products (Kazemi Matin, Azadi, & Farzipoor Saen, 2022). Enhancing the resilience of the blood supply chain is essential to ensure the continuous availability and safety of blood and blood products in the face of increasing crises (Viennet, et al., 2025).

Data envelopment analysis (DEA), one of the most widely used nonparametric efficiency assessment methods, has been used to measure the performance of decision-making units (DMUs) when multiple inputs and outputs are present. In the health sector, DEA is considered one of the most important performance assessment tools and has been widely used in the efficiency analysis of hospitals, health systems, health services, and health resource allocation (Kohl, Schoenfelder, Fügener, & O. Brunner , 2019). This method enables the comparison of various decision-making units, allowing for the identification of efficient units and sources of inefficiency, as well as the determination of a relative efficiency score for each unit; consequently, it is widely used to evaluate the performance of companies and various economic sectors (Jafarzadeh et al., 2026).

Conventional Data Envelopment Analysis (DEA) models assess the performance of Decision-Making Units (DMUs) under best-case scenarios. However, because these models focus on the most favorable or optimistic conditions, they may fail to provide a precise evaluation of DMU efficiency. To achieve a more realistic assessment, the Inverse Data Envelopment Analysis model can be employed, as it adopts a pessimistic approach. In this pessimistic approach, weights are assigned to inputs and outputs in such a way that the DMU's performance is minimized relative to other units (Ahmadpour-Samani et al., 2022).

Despite the advantages of DEA, its conventional models mainly focus on measuring relative efficiency and are less responsive to the needs of managerial decision-making, especially in situations where managers are forced to change resources or service levels owing to unpredictable changes in outputs. In the blood supply system, questions such as how much adjustment in inputs is necessary to maintain the efficiency level of provinces in the event of an increase in blood demand are important. In such situations, the inverse data envelopment analysis (IDEA) approach can be a suitable complement to conventional DEA. This method allows for estimating the required changes in inputs and outputs while maintaining the efficiency level (Wei, Zhang, & Zhang, 2000).

Despite numerous studies on performance evaluation of blood supply systems, most research based on DEA has focused on efficiency evaluation, performance comparison of blood transfusion centers, and productivity analysis, and the application of the inverse DEA approach in this field is still very limited. In addition, previous studies have paid less attention to the simultaneous effects of disturbances and uncertainties caused by supply and demand fluctuations, especially during crises and geopolitical tensions. Therefore, the development of a robust scenario-based inverse DEA approach can address these research gaps and assess the resilience of the blood supply system to these disturbances.

Therefore, the main objective of the current study is to determine the required level of changes in the inputs of the provincial blood supply system under the condition that, due to some geopolitical or natural disasters, the demand for blood and its products is increased in a way that the efficiency of the system is preserved. To this end, a robust scenario-based IDEA (RIDEA) is developed. The proposed RIDEA approach is solved under different scenarios of increasing blood demand, and the required changes in the system’s inputs are determined.

This study makes three main contributions: theoretical, methodological, and practical. From a theoretical perspective, this study expands the application of inverse data envelopment analysis to blood supply systems, thereby closing the gap between efficiency assessment and decision-making under changing demand conditions. From a methodological perspective, a robust scenario-based inverse data envelopment analysis framework is presented that allows for the simultaneous assessment of the impact of demand fluctuations and uncertain conditions and offers greater flexibility in analyzing system performance compared to conventional approaches. From a practical perspective, the research results can help blood transfusion managers in resource planning, increasing the resilience of the blood supply system, and making effective decisions in the face of crises and demand fluctuations.

The remainder of this paper is organized as follows. In Section 2, related literature is reviewed with a focus on data envelopment analysis and inverse DEA. The proposed model is developed in Section 3 and is then applied in the provinces of Iran. The obtained results are discussed in Section 4. Finally, the paper is concluded in Section 5 with some suggestions for future studies.

Literature Review

This study proposes a robust inverse DEA model to preserve the efficiency of the blood transfusion system in Iran's provinces under scenarios of increased blood demand resulting from disruptive events. In the following sections, first, DEA is reviewed with a focus on its applications in the blood supply system. Then, the inverse DEA is reviewed. Efficiency is one of the main fundamental concepts in management theory, referring to the ability of organizations to achieve goals (Mykhailenko, 2018). Its evaluation provides valuable information for resource allocation, process optimization, and operational benchmarking (Peykani, Seyed Esmaili, Pishvaee, Rostamy-Malkhalifeh, & Hosseinzadeh Lotfi, 2024). DEA is regarded as one of the most powerful and versatile nonparametric methods to evaluate the efficiency of a set of homogeneous decision-making units (Peykani, Mahmoodirad, & Amirteimoori, 2025) and was initially introduced by Charnes, Cooper, and Rhodes (1978). In terms of theoretical and economic foundations, DEA is based on production theory, the concept of the efficient frontier, and the measurement of relative efficiency. DEA develops this idea using linear programming and, without the need to assume a specific form for the production function, measures the efficiency of decision-making units based on the production possibility set and the concept of Pareto optimality, where efficient units form the efficiency frontier and other units are measured against it (Charnes, Cooper, & Rhodes, 1978). Some notable advantages of DEA can be stated as follows (Cook & Seiford, 2009; Xie, Zhu, Shang, & Li, 2021):

- Flexibility in dealing with complex and multidimensional data,
- Addressing qualitative and quantitative data.
- And consequently directing management attention toward the areas that require improvement.

In the literature on operations management and operations research, DEA has been widely used to measure the efficiency of banks, hospitals, universities, manufacturing companies, and even countries in the context of sustainable development (Cook & Seiford, 2009). Panwar, Olfati, Pant, and Snasel (2022) reviewed 40 years of DEA applications. They found approximately 4,000 studies in various areas that applied the DEA. They also determined banking and education as two main application areas of DEA. Specific applications of DEA have also been examined in various fields. Recent reviews on the DEA also demonstrated the growing trend of its applications in different areas (Mergoni, Emrouznejad, & De Witte, 2025). Tsaples and Papathansiou (2021) reviewed the applications of DEA in sustainability. Their study illustrates that the social dimension of sustainability is still underrepresented.

One of the main areas of DEA applications is healthcare. DEA has become one of the most widely used tools for assessing the relative efficiency of health units in the field of healthcare, as the health system usually has multiple inputs and outputs, conflicting objectives, and a lack of transparent market prices. Without assuming a specific production function, DEA allows for comparison of the performance of hospitals, health centers, health insurance, health networks, and even national health systems, and identifies which units generate greater outputs with similar resources or achieve the same output with fewer resources (Hollingsworth, 2008; Kohl, Schoenfelder, Fügener , & O. Brunner, 2019).

The most important application of DEA in healthcare is the evaluation of hospital efficiency. In this field, DEA is used to measure the technical efficiency, scale, and productivity of hospitals based on inputs such as the number of doctors, nurses, beds, costs, and equipment, and outputs such as the number of hospitalizations, surgeries, days in hospital, discharges, patient satisfaction, or quality of care indicators. Recent studies have shown that DEA is used not only to rank hospitals, but also to identify "peer units" and provide improvement targets to inefficient facilities. DEA has also been combined with methods such as regression, bootstrap, and the Malmquist index to analyze efficiency dynamics over time (Sun, Ye, Zhang, Xue, & Shang, 2023; Zubir, et al., 2024).

Another important application of DEA is in primary healthcare and healthcare networks. At this level, the efficiency of health centers, health homes, and referral systems is measured based on indicators such as vaccination coverage, chronic disease control, access to services, referrals, and health outcomes. Recent worldwide research using DEA to compare the efficiency of primary healthcare systems in various countries shows that several factors, such as the characteristics of governance, financing, and health system structure, may affect efficiency. (Moran, Suhrcke, & Nolte, 2023)

In recent years, DEA has also been used in more specialized areas, such as evaluating the efficiency of digital health, telemedicine, health service value chains, and smart hospital performance (Kohl, Schoenfelder, Fügener, & O. Brunner , 2019; Samut, 2023).

The blood supply is a critical component of the health system and plays a fundamental role in ensuring the continuity of medical services and saving patients' lives, particularly during disruptions such as earthquakes, pandemics, etc. (Pirabán, Guerrero, & Labadie, 2019; Imamoglu, Topcu, & Aydin, 2023). Any inefficiency in the blood supply chain can have consequences beyond increasing operating costs and can lead to blood shortages, increased waste, delayed treatments, and reduced quality of medical services. Consequently, assessing blood supply chain efficiency as a tool to identify inefficiencies, improve resource allocation, and enhance decision-making performance has become an important research topic in the health operations management literature (Kazemi Matin, Azadi, & Farzipoor Saen, 2022).

Despite the growing number of studies related to the blood supply chain, a review of the literature shows that previous studies are heterogeneous in terms of the scope of analysis, the level of modeling, and the way environmental complexities are represented. Given its critical importance, researchers usually focus on the optimal design of the blood supply chains. Agac, Baki, and Murat Ar (2024) reviewed more than 80 studies on blood supply chain network design. This line of research has continued to evolve since 2024, with several studies extending the existing literature (Abdolazimi, et al., 2025; Imamoglu, Ayyildiz, Aydin, & Topcu, 2025; Moshtagh, Zhou, & Verma, 2026).

While DEA has been extensively applied to evaluate healthcare systems, its applications in blood supply systems remain limited. DEA has been applied to assess the relative efficiency of different centers and components of this system. At the level of blood transfusion centers and blood banks, DEA has been used to compare the efficiency of decision-making units with similar input-output structures, and usually inputs such as human resources, working hours, equipment, and the number of blood collections, and outputs such as red blood cell and platelet production have been included in the modeling (Laspa & Priporas, 2008; Veihola, Aroviita, Kekomäki, Linna, & Sintonen, 2008). Previous studies have shown that DEA is a suitable tool for comparing the efficiency of blood centers in different countries and identifying performance gaps between them (Veihola, Aroviita, Linna, Sintonen, & Kekomäki, 2006). A summary of DEA applications in the blood supply field is presented in Table 1.

Table 1. Applications of DEA in the blood supply

NO	Author/Year	Objectives	Model	uncertainty	input	output
1	Veihola et al. (2006)	Technical evaluation and comparison of blood product preparation units in Europe	CCR	-	- Working hours - Equipment and premises - Whole blood (WB) collections	- Red blood cells (RBCs) units produced - Platelets (PLTs) units produced
2	Pereira (2006)	Examining the hypothesis of economies of scale in American blood transfusion centers	CCR	-	- Cost structure	- Production level - Service area characteristics
3	Veihola et al. (2007)	Investigating the impact of blood product waste on the technical efficiency of blood preparation centers	CCR	-	- Collected WB units - PLTs derived - Discarded units - Discarded PLT units	- RBC units produced - PLT units produced
4	Laspa and Priporas (2008)	Operational evaluation and comparison of blood banks to examine the performance of blood transfusion services	CCR	-	- Donor recruitment ratio	- Blood units' sufficiency ratio - Wastage rate - Transfusion reactions
5	Veihola, et al. (2008)	Examining the efficiency of blood banks	CCR	-	- Working hours - Total costs	- Produced RBCs - Produced PLTs
6	Nielsen and Nielsen (2016)	Evaluating the operational scale of blood transfusion centers to increase efficiency	CCR	-	- Budget - Full-time staff - Part-time staff - Service population	- Units produced of RBCs, plasma, PLTs
7	Moslemi and Mirzazadeh (2017)	Evaluating the efficiency and performance of the four-stage blood supply chain	Network DEA		- Donors' attraction - Intellectual capital, space and facilities, and costs of the blood donation center - Intellectual capital, space, facilities,	- Environmental and social actions, waste management, donor satisfaction, and loss rate in the blood donation center

NO	Author/Year	Objectives	Model	uncertainty	input	output
					and costs of the blood bank - Intellectual capital, space, facilities, and costs of the hospital - The number of donors - Hospital satisfaction from blood bank - Quality in the blood bank	- Social and environmental actions, management of financial resources, inventory, and waste management, recording and archiving, quality, and loss rate in the blood bank - Environmental and social actions, revenues, loss rate, patient satisfaction, quality, and inventory management in the hospital - Partnership and cooperation between the blood bank and the hospital - Satisfaction of the blood donation center with the blood bank - Blood bank satisfaction with the hospital
8	Kazemi Matin, Azadi, Farzipoor Saen (2022)	Simultaneous assessment of blood supply chain sustainability and resilience	Directional Distance Function	-	- Advertisement cost - The number of donors - Transportation costs - Research and development costs - Blood production costs - Environmental costs - Holding cost of products - Cost of work safety and labor health - The number of personnel	- Waste of blood - Transportation delay - The sent blood - Received blood for patients - profit
9	Agac, Baki, and Atici (2023)	Evaluating the efficiency of blood product	CCR	-	- Blood center - Number of doctors	- Total blood collection

NO	Author/Year	Objectives	Model	uncertainty	input	output
		collection in Türkiye and identifying factors affecting the performance of blood transfusion centers			- Number of Phlebotomists - Total number of mobile stations - Total number of permanent stations - Service population	
10	Hamisheh Bahar, Akhavan Niaki, and Khdemati (2026)	Optimizing the blood supply chain to forecast demand and increase resilience using a hybrid model.	Dynamic DEA	Robust	- Supplier costs (Eco design, inventory management, regulatory, raw material) - Blood bank (inventory management cost, blood donors, budget, Eco design cost, personnel cost) - Hospital costs - Laboratory costs	- Collected blood - Waste blood - Recovered patients

According to the reviewed studies, it is evident that while a limited set of studies have addressed this topic, these studies do not consider the effects of disruptions on the blood supply – demand balance. Furthermore, most existing studies focus on the classic CCR model, whereas IDEA has not yet been applied to the blood transfusion system. From a methodological perspective, new trends in health research show that traditional DEA has evolved into Network DEA, Dynamic DEA, Fuzzy DEA, Bootstrap DEA, and Two-stage DEA models to overcome the limitations of conventional DEA, such as its inability to assess service quality, data uncertainty, and environmental factors. Additionally, the integration of DEA with machine learning methods, spatial analysis, and health econometrics has expanded considerably and contributes to evidence-based decision-making in the health system (Zhou, et al., 2023; Zubir, et al., 2024).

While conventional DEA studies primarily focus on efficiency assessment, an important stream of research has extended DEA to support managerial planning and resource allocation decisions. In this context, Inverse Data Envelopment Analysis (IDEA) was introduced as an extension of conventional DEA to address decision-making problems that arise after efficiency has been evaluated. While traditional DEA measures the relative efficiency of decision-making units based on available data, Inverse DEA estimates the changes required in the remaining variables to maintain a certain level of efficiency or reach a target level if some inputs or outputs change. This approach was first introduced by Wei, Zhang, and Zhang (2000). Their research provided a mathematical framework for estimating the required changes in inputs and outputs while preserving efficiency and paved the way for the development of subsequent studies. Subsequently, researchers extended IDEA to settings involving constant and variable returns to scale, fuzzy environments, uncertainty, network structures, and dynamic data. Systematic reviews show that over the past two decades, IDEA has evolved from a theoretical tool to an applied approach for decision support in various fields, including banking, education, energy, manufacturing, supply chains, environment, and public services (Emrouznejad, Amin, Ghiyasi, & Michali, 2023).

In the healthcare sector, inverse DEA has been particularly useful in conditions of resource constraints and increasing demand (Emrouznejad, Amin, Ghiyasi, & Michali, 2023).

Based on the literature review, the main research gap can be summarized as follows: (1) In the field of blood and blood transfusion services, DEA studies have mainly focused on assessing the efficiency of blood transfusion centers, comparing regional performance, and analyzing productivity, but the Inverse DEA has rarely been applied in this field. However, the characteristics of blood supply systems, including resource constraints, demand fluctuations, the need for sustainable supply, and regional differences, make the Inverse DEA particularly valuable in this context. This approach can determine the changes in inputs and outputs required to maintain efficiency under changes in blood demand. Therefore, the use of Inverse DEA in the field of blood supply can reduce the gap between efficiency assessment and managerial decision-making while providing robust analytical support for policymaking and resource planning. (2) Previous DEA studies have not considered the effect of disruptions on either the demand or supply side of blood supply systems. Given the increasing number of geopolitical tensions in recent years, assessing the resiliency of blood supply systems to such disruptions has become essential. Therefore, a robust scenario-based IDEA is proposed to address these research gaps and is described in the following section.

Materials and Methods

DEA is a nonparametric mathematical programming approach widely used to evaluate the relative efficiency of entities referred to as decision-making units (DMUs) that use multiple inputs and outputs (Cooper, Seiford, & Zhu, 2011). Unlike parametric techniques, DEA does not require a predefined production function and empirically determines the efficient frontier based on observed data. In the present study, the provinces are considered DMUs within the blood transfusion system. The objective is to evaluate the operational efficiency of each province in converting collected blood into usable blood units while meeting regional blood demand. Among the DEA models, the CCR model proposed by Charnes, Cooper, and Rhodes (1978) assumes constant returns to scale (CRS) and evaluates the relative efficiency of DMUs by comparing weighted outputs to weighted inputs. Since the present study focuses on minimizing resource utilization while maximizing the production of safe and usable blood products, an input-oriented CCR model is employed.

Suppose that there are n DMUs (here, provincial blood transfusion systems), $j = 1,2, \dots, n$, to be evaluated and consider the oth province $o \in \{1,2, \dots, n\}$. Each DMU consumes varying amounts of m inputs, $x_{ij}, i = \{1,2, \dots, m\}$, and produces different s outputs, $y_{rj}, r = \{1,2, \dots, s\}$. The fractional form of the CCR model is formulated as follows for evaluating DMUo.

$$\text{Max}\, z = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}}$$

subject to

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \; for \; j = 1, \dots, n \tag{1}$$

$$u_r, v_i \geq 0$$

where $u_r, r = 1,2, \dots, s$ and $v_i, i = 1,2, \dots, m$ denote the weights assigned to the outputs and inputs, respectively. The above fractional programming model provides a generalized definition of efficiency without requiring predetermined weights. By applying the Charnes-Cooper (1962) transformation, the above model can be converted into the following linear programming model:

$$\max z = \sum_{r=1}^{s} u_r y_{ro}$$

subject to

$$\sum_{i=1}^{m} v_i x_{io} = 1 \tag{2}$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0$$

$$\mu_r, v_i \geq 0$$

The dual linear programming of the above model is formulated as follows.

$$\theta^* = \min \theta \tag{3}$$

subject to

$$\sum_{j=1}^{n} x_{ij}\lambda_j \le \theta x_{io} \qquad i = 1,2,\dots,m$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j \ge y_{ro} \qquad r = 1,2,\dots,s$$

$$\lambda_j \ge 0 \qquad j = 1,2,\dots,n$$

While conventional DEA evaluates the relative efficiency of DMUs based on observed inputs and outputs, it does not identify the resource adjustments required when operating conditions change. In the context of blood transfusion systems, managers often face fluctuating blood demand caused by pandemics, military conflicts, natural disasters, and large-scale accidents. Under such circumstances, determining the additional blood collection capacity required to maintain existing efficiency levels is more valuable than measuring the current performance.

To address this limitation, Inverse Data Envelopment Analysis (IDEA) is employed. IDEA extends the conventional DEA framework by estimating the necessary changes in inputs or outputs while preserving a predetermined efficiency score. In the context of the present study, each province was considered a DMU. When blood demand changes, the inverse DEA model determines the minimum additional inputs required for each province to maintain its existing efficiency level. The use of IDEA is particularly appropriate for blood supply systems because blood demand is highly uncertain and may vary significantly across regions and under different operating conditions. By preserving efficiency while accommodating changes in demand, the model concentrates on decision support for capacity planning and management, donor outreach strategies, and crisis preparedness. Consequently, IDEA serves as a bridge between efficiency assessment and strategic resource planning within the blood supply network.

To formulate the model, it is assumed that for province o, $E_0 = \theta_o^*$ and the amount of rth output is changed, that is, $\hat{y}_{ro} = y_{ro} + \Delta y_r$ which, Δy_r in this study, it represents the additional demand for blood or blood products. The decision variable is $\Delta x_i, i = 1,2,\dots,m,$ which represents the required increase in input i. The inverse CCR model is formulated as follows (Wei, Zhang, & Zhang, 2000).

$$\min \sum_{i=1}^{m} \Delta x_i \tag{4}$$

subject to

$$\sum_{j=1}^{n} x_{ij}\lambda_j \leq E_0(x_{io} + \Delta x_i) \qquad i = 1,2,\dots,m$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{ro} + \Delta y_r \qquad r = 1,2,\dots,s$$

$$\lambda_j \geq 0 \qquad j = 1,2,\dots,n$$

$$\Delta x_i \geq 0$$

Given the critical role of blood availability during disruptive conditions such as pandemics, military conflicts, and other emergencies, conventional DEA may not provide an adequate framework for assessing both operational performance and system robustness under varying supply and demand conditions. To address the issue of uncertainty arising from disruptive events in blood transfusion, the IDEA framework will be extended to a scenario-based robust IDEA model. Different scenarios representing varying blood supply and demand conditions will be incorporated into the model. This extension enables the evaluation of provincial performance not only under normal operating conditions but also under uncertain and high-risk environments, thereby providing a more comprehensive assessment of blood supply and demand robustness and resilience.

In the current study, it is assumed that some variables, that is, $\tilde{x}_{ij}$ and, $\tilde{y}_{rj}, \forall i, j$ are subject to uncertainty. To formulate the robust counterpart of the model, the scenario-based approach developed by Mulvey et al. (1995) is used. The problem can be formulated as follows:

$$\begin{aligned} & Min\ c^T x + d^T y \\ & Ax = b \\ & Bx + Cy = e \\ & x, y \geq 0, x \in R^{n_1}, y \in R^{n_2} \end{aligned} \qquad (5)$$

where x represents the set of structural variables with fixed coefficients, and y is the set of control variables with uncertain coefficients. The model is formulated under a set of scenarios $\Omega = \{1,2,\dots,S\}$ with a corresponding probability vector, $\{p_1, p_2, \dots, p_S\}$, $\sum_{s=1}^{S} p_s = 1$ where p_s denotes the probability of the sth scenario. Under each scenario $s \in \Omega$, the coefficients are defined as $\{d_s, B_s, C_s, e_s\}$. In its general form, Mulvey et al. (1995) presented the robust counterpart of the model in Eq. (5), as shown in Eq. (6), by introducing the concepts of solution robustness and model robustness.

$$Min\ \sigma(x, y_1, y_2, \dots, y_s) + w\rho\sigma(z_1, z_2, \dots, z_s)$$

S.T.

$$Ax = b \tag{6}$$

$$B_s x + C_s y_s + z_s = e_s, \forall s \in \Omega$$

$$x \geq 0, y_s \geq 0, \forall s \in \Omega$$

where $\{y_1, y_2, \dots, y_s\}$ represents the set of control variables in different scenarios, and $\{z_1, z_2, \dots, z_s\}$ are defined as the set of error variables measuring the allowable infeasibility of control constraints under the sth scenario. σ and ρ denote the solution and model robustness parameters, respectively, to ensure the optimality and feasibility of the solutions across different scenarios. More details can be found in Razavi Hajiagha et al. (2022).

In model (4), the uncertain parameters appear only in the constraints. Therefore, a model robustness term must be added to the objective function to ensure solution feasibility. This model robustness term is formulated as $\sum_{s \in S} p_s.\theta_s + \sum_{s \in S} p_s.\delta_s$ and is added to the objective function with a corresponding weight w. δ_s is a penalty term for infeasibilities of the solutions under the sth scenario and is defined as $B_s.x + C_s.y + \delta_s = e_s, \forall s \in \Omega$.

$$\min E = \sum_{s \in S} p_s \theta_s + \sum_{s=1}^{S} p_s \delta_{po}^{s-} + \sum_{j=1}^{n} \sum_{s=1}^{S} p_s \delta'^{s+}_{pj}$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij}^s \leq \theta^s x_{io}^s + \delta_i^s \qquad \forall s, i \tag{7}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^s \geq y_{ro}^s - \delta_r^s \qquad \forall s, r$$

$$\lambda_j, \delta_i^s, \delta_r^s \geq 0$$

Consequently, the robust inverse model is defined as follows:

$$\min E = \sum_{s \in S} p_s \Delta x_i^s + \sum_{s=1}^{S} p_s \delta_o^{s-} + \sum_{j=1}^{n} \sum_{s=1}^{S} p_s \delta'^{s+}_j \tag{8}$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij}^s \leq E_0(x_{io}^s + \Delta x_i^s) + \delta_i^s \qquad \forall s, i$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^s \geq y_{ro}^s + \Delta y_r^s - \delta_r^s \qquad \forall s, r$$

$$\lambda_j, \Delta x_i^s, \delta_i^s, \delta_r^s \geq 0$$

Unlike classical probability-based robust optimization models, the proposed framework does not rely on predefined probability distributions for different disruption scenarios or optimize all scenarios simultaneously. This is mainly due to the lack of reliable probability estimates for various levels of demand increase in the studied context. Instead, each demand-increase scenario is evaluated independently to determine the corresponding resource adjustments required to maintain efficiency. Therefore, the robustness of the proposed framework is reflected in its capability to provide decision-makers with feasible resource adjustment strategies across a range of plausible disruption conditions. In contrast to conventional scenario analysis, which primarily explores possible outcomes under alternative assumptions, the proposed approach combines scenario-based uncertainty assessment with inverse DEA to quantify the necessary adjustments in resources and support proactive decision-making under uncertain conditions.

Results

The blood supply in Iran is managed as a fully centralized national system under the management of the Iranian Blood Transfusion Organization (IBTO). This organization is the only official authority for blood collection, testing, processing, and distribution in the country, and the IBTO screens all donated blood for important blood-transmitted infections, such as HBV, HIV, HCV, and syphilis (Cheraghali, 2012). Regarding the need for blood in Iran, a statistical survey shows that blood donation is always needed in the country because Iran is located in the "thalassemia belt" and annually has a significant number of babies with thalassemia. Patients with thalassemia are the largest group of blood recipients. Blood is also used for many other medical and therapeutic needs, such as treating a large number of cancer patients, performing surgeries, or treating severe bleeding (Abolghasemi, et al., 2007; WHO, 2025).

Hence, maintaining a reliable and efficient blood supply chain is a vital component of the Iranian healthcare system (Soodejani, Haghdoost, Sedaghat, Baneshi, & Zolala, 2019). According to official statistics and reports from the country, the average blood donation rate in Iran is 26 per 1000 people, which places the country in a favorable position among other countries. More than

95% of donors are male, and most donors are regular donors (Tehran Times Straight Truth, 2024). According to statistics published in 2025, between January and August 2024, a total of 1,621,911 Iranians donated blood (Tehran Times Straight Truth, 2025). Almost all the needs of hospitals are met through the national network. After blood is collected in provincial centers, it is distributed to blood banks and then to hospitals. There is no private blood market in the country, and the supply chain is a completely state-owned system. According to official reports for 1403, Tehran province has the highest share in blood donation in the country, with more than 16%, and Fars province has more than 7%. In addition, the highest growth rate of blood donation in 1405 was in Lorestan province, with a 22% increase. North Khorasan and Kohgiluyeh and Boyer-Ahmad provinces ranked second and third, with a 16% and about a 13% increase, respectively. In addition, some provinces have performed more favorably in terms of overall blood donation indicators, such that Semnan, Yazd, and Qom provinces have ranked higher than other provinces with 69, 64, and 63 percent, respectively (Tehran Times Straight Truth, 2024).

A review of statistics published in 1404 also shows that the pattern of blood donation among the provinces of the country continues to be accompanied by significant differences. This year, the provinces of Zanjan, Sistan and Baluchestan, and Fars experienced the highest growth in blood donation, respectively. Tehran province accounted for approximately 17% of the country's total blood donation, while Fars and Isfahan provinces also had a significant share in the country's blood supply (Tehran Times Straight Truth, 2025). These differences indicate regional imbalances in the blood collection process and increase the importance of assessing blood supply efficiency at the provincial level.

On the other hand, critical situations such as natural disasters, wars, or epidemics present serious challenges to the blood supply, including a possible decrease in donors, blood shortages, and disruptions in collection centers. During the COVID-19 pandemic, blood donations decreased between 20 and 30 percent in the early weeks, negatively affecting the global blood supply. In such critical situations, due to the restrictions imposed by governments, blood donation systems experience severe operational disruptions due to movement restrictions, donor anxiety, and reduced access to collection centers (Shokouhifar & Ranjbarimesan, 2022). Risk management of the blood supply chain, as a preventive approach, plays an important role in reducing shortages, preventing blood loss, and increasing the reliability of the blood supply network.

Given that the focus of the present study is on assessing the ability to maintain service levels and meet demand under conditions of uncertainty and demand changes resulting from disruptions and crises, in which blood shortages can lead to treatment delays, postponement of surgeries, and increased adverse outcomes for patients (National Blood Resource Education Program Expert Panel, 1990; Osorio, Brailsford, & Smith, 2015), the proposed model was used to assess the extent of resource changes at the provincial level of the country. The input and output indicators defined for the provinces are as follows:

Inputs:

-Number of blood transfusion centers in the province (x_1);

-Ratio of blood donors to the province's population (x_2);

-Provincial-produced RBCs per year (x_3);

-Provincial-produced plasma per year (x_4);

-Provincial platelets produced per year (x_5).

Outputs:

-Provincial RBC demand per year (y_1);

-Provincial plasma demand per year (y_2);

-Provincial platelet demand per year (y_3).

The indicators selected to evaluate the performance of the blood transfusion system in the provinces of Iran were determined based on the logic of transforming capacity and resources into response to treatment demand. In the input section, the number of blood transfusion centers as a proxy for infrastructure capacity and access to services, the ratio of blood donors to the province's population as an indicator of the capacity for sustainable blood supply, and the annual production of packed red blood cells (RBC), plasma, and platelets as indicators of operational throughput in the collection, processing, and preparation of blood products were selected. According to the World Health Organization guidelines, the adequacy of the blood transfusion system depends on the existence of appropriate infrastructure, continuous participation of volunteer donors, and sufficient capacity to produce blood components needed by the health system (WHO, 2025). In addition, performance evaluation studies in health services emphasize that input indicators should represent physical and human resources and service production capacity (Ozcan, 2008).

In the output section, the annual provincial demand for packed RBCs, plasma, and platelets was considered the system output because the main goal of the blood transfusion system is to provide timely, safe, and adequate medical care to patients. Each of these blood components has a different therapeutic use, and their demand patterns reflect the health needs and disease burdens of each province. From the perspective of performance assessment, the output based on the met demand indicates the effectiveness of the system in converting resources into the required services (Sherman, 1984; WHO, 2025).

The statistical yearbook of the Blood Transfusion Organization was used to collect data on blood donation centers, the number of donors, and blood products. However, data related to per capita consumption of blood products were estimated based on different per capita figures mentioned in the sources, owing to the lack of accurate reporting (Omidikhoda, Amini Kafi-Abad, Pourfatollah, & Maghsudlu, 2016). The gathered and approximated data used in the research are represented in Appendix A.

First, to determine the efficiency of blood production and demand in Iran, an input-driven CCR model was used to evaluate the efficiency of the provinces. Figure 1 shows the efficiency of the provinces, that is, $\theta_{j0}, j = 1,2, \dots ,31$. In this figure, the provinces marked in green had an efficiency above 90%, orange 70- 90%, and red below 70%.

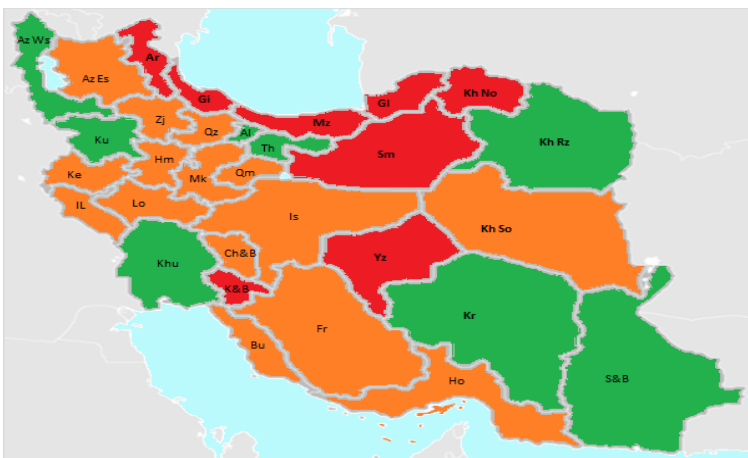

Figure 1. The efficiency level of blood transfusion in the current state (Source: Author)

According to Figure 1, only four provinces have 100% efficiency under the current conditions, and the rest have an efficiency of less than 1.

Now, it is supposed that due to the occurrence of some disruption, the demand for blood products increases by 10% in each step, that is, $y_k = y_{k-1} + \Delta y_{k-1}$, where $\Delta y_{k-1} = 0.1 y_{k-1}, k = 1,2, \dots ,10$.

Because reliable historical information on the probability of different disruption severities was not available, this study adopted a scenario-based stress-testing approach. Ten demand-growth scenarios, illustrating increases in blood demand from 10% to 100% in increments of 10%, were analyzed separately. In each run, the corresponding demand-growth scenario was assumed to occur with certainty ($p_s = 1$), while the probabilities of the remaining scenarios were set to zero. This approach allows for the assessment of the robustness of provincial resource requirements under different disruption severities without imposing potentially arbitrary probability distributions on uncertain events. The robust IDEA model was used to determine the amount of required increase in the inputs such that the efficiency of provinces remains at the same level as the current stage. Solving the model in Eq. (8), the amount of $\Delta x_{ik}, i = 1,2, \dots, 5$ for the kth scenario, $k = 1,2, \dots, 10$ is calculated. For instance, as the demand for output products is increased by 100%, the amount of increase in inputs is illustrated in Table 2 for different provinces. The detailed results for different scenarios can be found in Appendix B.

Table 2. Amount of required increase in inputs to maintain the efficiency level in the worst scenario, i.e., 100% increase in the demand

Province	Δx_1	Δx_2	Δx_3	Δx_4	Δx_5
Alborz	3	0.026	60776.000	61285.000	12880
Ardabil	-	-	40914.250	42101.690	-
Bushehr	-	-	29346.090	35599.780	-
Chaharmahal and Bakhtiari	-	-	30348.090	30911.120	430.448
East Azerbaijan	9	0.041	78192.650	81053.160	-
Gilan	-	0.039	98343.920	99735.930	8107.395
Golestan	-	0.022	77907.550	79102.380	4086.104
Hamadan	7	-	31234.120	30793.690	-
Hormozgan	2	0.015	55322.350	56372.180	10777.270
Ilam	1	-	16893.510	17174.600	742.761
Isfahan	11	0.066	101656.000	107273.300	-
Kerman	1	0.031	73336.610	68546.150	13959.470
Kermanshah	5	0.009	54433.910	53491.440	-
North Khorasan	-	-	28248.260	30276.750	3310.009
Razavi Khorasan	16	0.076	99945.060	106343.500	-
South Khorasan	-	-	23773.420	24271.630	517.494
Khuzestan	8	0.058	90911.350	90390.860	-
Kohgiluyeh and Boyer-Ahmad	3	-	25130.920	26083.920	-
Kurdistan	2	0.003	32570.590	34561.310	-
Lorestan	-	0.001	40412.430	46335.950	10761
Markazi	-	0.002	43998.340	44658.440	2482.543
Mazandaran	-	0.049	106050.300	126269.700	789.361
Fars	17	0.054	90488.650	115718.200	-
Qazvin	-	-	35587.860	40371.570	2375.278
Qom	2	-	38153.670	38832.330	6356.333
Semnan	-	-	26986.190	30015.330	4504.044
Sistan and Baluchestan	-	0.031	70448.950	71908.670	3647.831
Tehran	46	0.183	178729.900	169411.800	-
West Azerbaijan	1	0.037	77958.750	78853.140	-
Yazd	-	-	49753.660	50329.740	8165.829
Zanjan	-	-	28625.390	28994.460	349.111

Figure 2 illustrate the required increase in the first input for all provinces in a manner that maintains their current state efficiency. For this purpose, all scenarios of 10% to 100% increase for all five inputs in all provinces are shown in the aforementioned figures. (The remaining inputs adjustments are provided in Figures A.1-A.4 of the appendix A)

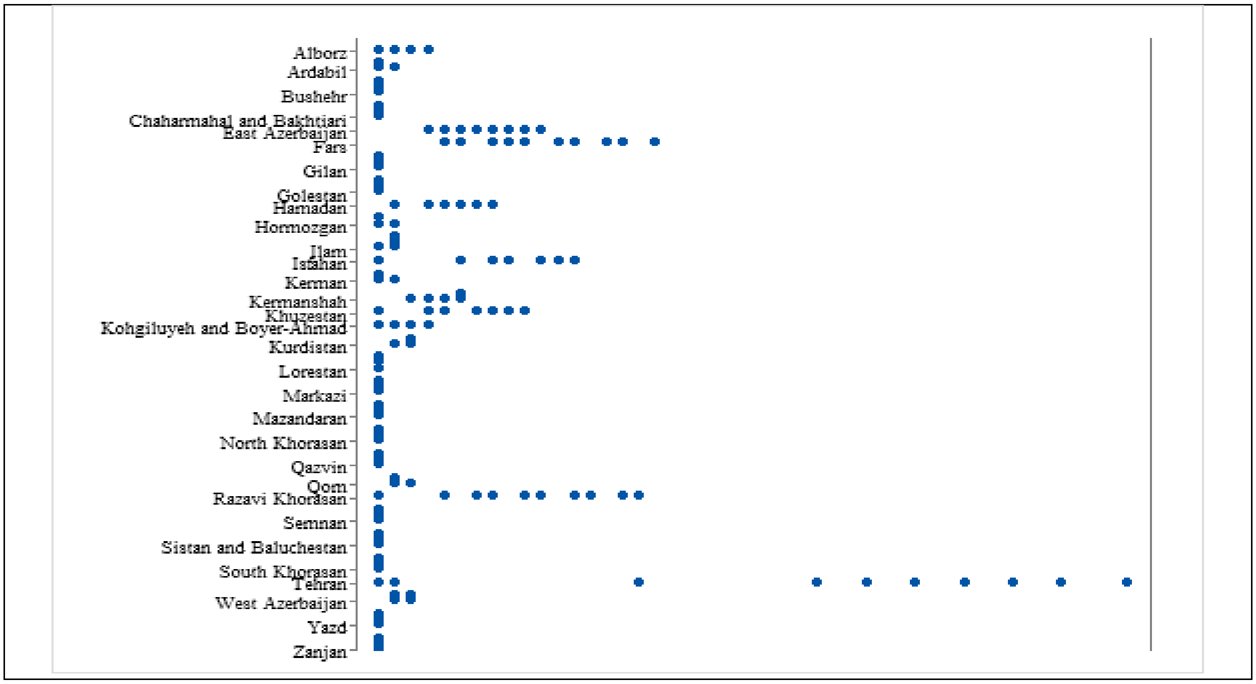

Figure 2. Required amount of increase in the number of blood transfusion centers in the provinces (Δx_{1j})

In Figure 2, and Figures A.1-A.4, each point illustrates the amount of input adjustment required under one of the demand growth scenarios. Therefore, multiple points related to a province indicate the resource needs under different levels of demand growth. According to Figure 2, it can be concluded that some provinces, such as Bushehr, Gilan, and Golestan, do not require any increase in x_{1j}, blood transfusion centers in each province in all scenarios. In contrast, some provinces, such as Fars and East Azerbaijan, require increasing the blood transfusion centers in all scenarios to maintain their efficiency in different scenarios.

As shown in Figure A.1(in appendix A), in some provinces, such as Hamadan and Ilam, no increase is required in the blood donor population to maintain their current efficiencies.

Figure A.2 (in appendix A) suggests that in almost all scenarios, most provinces require an increase in produced RBC.

The situation of the provinces in all the scenarios in Figure A.3 (in appendix A) is approximately similar to that in the previous input.

Figure A.4 (in appendix A) shows that the required increase in platelet production generally increases with the severity of the demand growth scenarios, although the amount of adjustment varies across provinces. For example, provinces such as Tehran require a significant increase in platelet production capacity in severe scenarios, whereas provinces such as Isfahan require no adjustment, indicating greater excess capacity.

Discussion

Blood is a fundamental component of the healthcare system, and the efficiency of the blood transfusion system is a critical concern for the stability of this system. Beyond the direct evaluation of blood transfusion efficiency as a crucial problem, the primary focus of the current study was to determine the level of resources required to maintain an acceptable level of blood transfusion efficiency in response to demand uncertainty. Research evidence shows that critical situations such as natural disasters, mass incidents, wars, and terrorist attacks are usually accompanied by a significant increase in the demand for blood and blood products. In such situations, an increase in the number of injured people, patients requiring emergency surgeries, and cases of severe bleeding causes a sudden increase in the need for red blood cells, platelets, and plasma. Studies on mass incidents have shown that most blood consumption occurs in the first hours after the crisis, and health facilities face pressure to meet blood transfusion needs. Therefore, an increase in blood demand is a well-known and confirmed consequence in the literature on crisis management and blood supply chains (Hick, Hanfling, Wynia, & Pavia, 2020).

To this end, an inverse robust scenario-based data envelopment analysis is developed in the current study. The inverse DEA logic determines the required change in inputs (outputs) when the number of expected outputs (or on-hand inputs) changes, so that a predefined efficiency level is maintained for decision-making units. The proposed model is an extension of inverse DEA to address increases in output (blood or its products) across different scenarios. Therefore, using Mulvey et al.'s (1995) approach, a scenario-based robust extension of the original IDEA approach is developed and tested for blood transfusion in Iranian provinces.

Considering an increase of 0.1k in each scenario, where $k = 1,2, \dots ,10$, the amount of the required adjustment to inputs is determined. As shown in Figure 2 and Figures A.1-A.5, the maximum amount of increase is required in the case of a 100% increase in demand. The proposed framework evaluates the inverse DEA model under a spectrum of disruption scenarios with increasing demand levels, instead of relying on a single expected demand realization. As a result, the model acts as a stress testing tool that assesses the stability of resource requirements under different disruption severities and provides managers with preparedness strategies for mild, moderate, and severe crisis conditions.

To provide a policy suggestion, the mean required adjustment for provinces in their corresponding inputs, in a way that they maintain their normal efficiency, is represented in Figure 3 (The remaining inputs are illustrated in Figures B.1-B.4 in Appendix B).

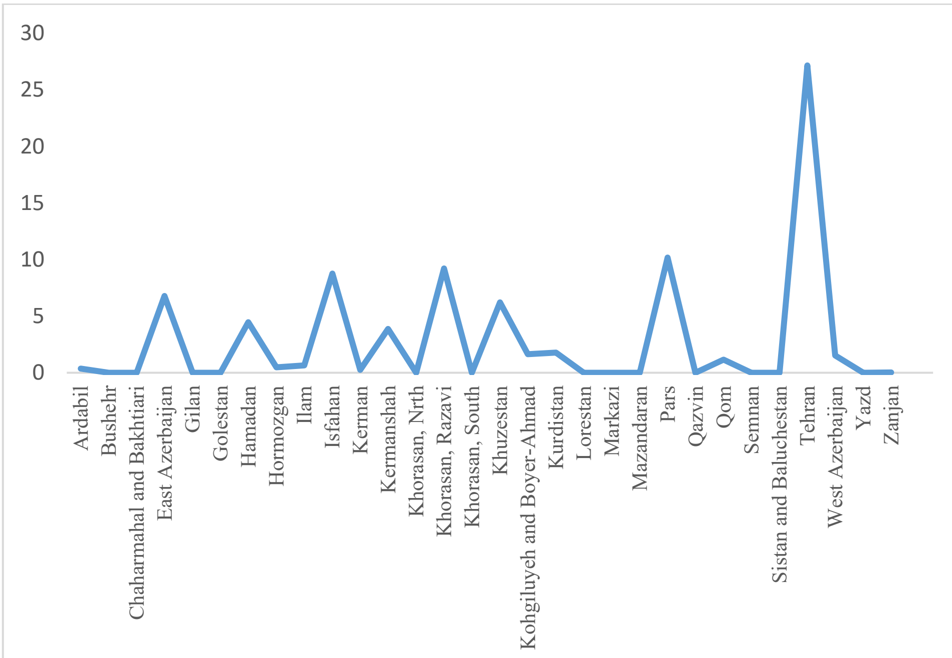

Figure 3. Mean amount of increase in the number of blood transfusion centers in the provinces (Δx_{1j}) to maintain the current efficiency when dealing with different scenarios

Unlike Figure 2 and Figures A.1-A.4, which illustrate scenario-specific adjustments, Figure 3 and Figures B.1-B.4 present the average amount of resource adjustment across all scenarios. Therefore, they provide an aggregated measure of provincial preparedness requirements and enable a comparison of the overall resilience capacity of provinces under uncertain demand conditions.

The present study is a generalization of classical IDEA models to a scenario-based steady state, in which, due to unforeseen environmental, social, or geopolitical stresses, the demand for blood products as the main output of the blood transfusion system increases, and the system must maintain its resilience to this fluctuation by adjusting its inputs. As a result, a steady-state form of the inverse model has been developed. In practical terms, the research findings can be used to prepare and anticipate decisions to prepare the system for unforeseen fluctuations. One of the first findings of this study was the estimation of additional blood donation infrastructure required across the provinces under demand disruptions. According to the results, the most severe scenario, corresponding to a 100% increase in demand, requires up to 46 additional blood donation centers in Tehran province. The average resource requirements across all scenarios are also presented in Figure 3 and Figures B.1-B.4 (Appendix B).

The results reveal considerable heterogeneity across provinces in terms of the degree of resource adjustment required. Tehran represents the most prominent case. This behavior can be caused by several structural characteristics. First, Tehran is the largest population center in the country and is considered to have the largest share of national blood donations and blood consumption. Second, the province includes a large number of tertiary hospitals and specialized medical centers that attract patients from all other provinces, resulting in an exceptionally high blood demand. Third, the existing blood collection infrastructure already operates at relatively high utilization levels, leaving limited spare capacity to manage the demand shocks. Consequently, although Tehran performs relatively efficiently under normal operating conditions, preserving this efficiency during severe disruptions requires disproportionately larger resource adjustments, including an approximately 18% increase in donor participation.

More generally, the findings suggest that provincial preparedness requirements are caused by population concentration, healthcare service scale, regional demand intensity, and the initial balance between the blood supply and demand. Therefore, resilience-oriented planning should be tailored to provincial characteristics rather than relying on uniform national policies. From a managerial perspective, these findings indicate that crisis preparedness strategies should account for substantial differences in provincial capacities and resource requirements, and therefore, resource allocation policies should be designed according to province-specific characteristics.

Another important managerial implication concerns increasing public participation in blood donation. Increasing the percentage of donors, in addition to implementing relevant campaigns, requires a comprehensive management approach to attract, retain, and build donor loyalty. Studies indicate that the most important motivation for people to donate blood is a sense of social responsibility and altruism. In this regard, the use of cultural, advertising, and educational campaigns emphasizing the impact of blood donation on donors and recipients is recommended. Using the narratives of patients and blood recipients can strengthen the sense of social responsibility among the public to donate more blood (Fergusen, 2015; Suárez-Artime, et al., 2026). In addition, many people avoid donating blood due to psychological barriers. Fear of needles, lack of information, fear of the treatment environment, and health concerns are among the most important of these factors. The use of educational-cultural and informational programs will reduce the psychological costs of blood donation (Carver, Chell, Davison, & Masser, 2018; Monteiro, Ferreira, Pontes Junior, Chocair, & Ferreira, 2024). In this regard, the use of social networks and digital marketing has been emphasized. The use of digital media helps in the formation of positive social norms (Sinha, Arun, Sravan Kumar, & Jain, 2026).

Retaining blood donors is a higher priority than attracting new donors. In general, attracting new donors will be more costly. In this regard, the quality of the blood donation experience will have a significant impact on repeat blood donation behavior (Piersma, Bekkers, Klinkenberg, de Kort, & Merz, 2017). Professional behavior of blood donation center staff, a suitable environment, instilling a sense of gratitude for the donor, and reducing waiting time are effective factors in the quality of the donor experience (Piersma, Bekkers, Klinkenberg, de Kort, & Merz, 2017; Monteiro, Ferreira, Pontes Junior, Chocair, & Ferreira, 2024). Another recommendation to increase the donor return rate is to develop a donor relationship management system. Using SMS systems, applications, and emails to appreciate and remind the donor of the allowed and best time to donate blood, as well as providing brief feedback on how the donated blood was used, will strengthen repeat donation behavior (Shehu, Veseli, & Winterich, 2024). In addition to psychological barriers, there are also physical barriers to blood donation. The most important physical barriers include the difficulty of accessing blood transfusion centers. The use of mobile blood donation systems and online appointment scheduling can greatly overcome physical barriers (Carver, Chell, Davison, & Masser, 2018; Monteiro, Ferreira, Pontes Junior, Chocair, & Ferreira, 2024).

Conclusion

The efficiency and resilience of blood transfusion systems are critical components of a resilient healthcare system, especially in situations where environmental, social, and geopolitical disruptions, such as natural disasters, large-scale accidents, military conflicts, and other emergencies, can lead to a sudden increase in the demand for blood and blood products. In such situations, maintaining system efficiency while meeting the increasing demand becomes one of the most important management challenges. In this study, to respond to this challenge, the proposed model combines the logic of inverse DEA with scenario-based robust optimization. This framework determines input adjustments required to accommodate different levels of demand growth while preserving the efficiency of decision-making units. From a methodological perspective, this study extends the conventional inverse DEA by incorporating scenario-based robust optimization, thereby extending the ability of inverse DEA to uncertain and scenario-driven environments. To evaluate the model, the blood transfusion system of the provinces of Iran was selected as a case study. To address the research objectives, the proposed model was first developed and then applied to estimate the input adjustments required under different demand scenarios. The results showed that provinces require different levels of resource adjustment under increasing demand conditions. The findings suggest that in some provinces, the number of blood donation centers should be increased by up to 46 centers, and in some cases, the donor-to-population ratio should increase by up to 18% to maintain efficiency. These results indicate that the readiness and capacity of provinces to respond to demand shocks are not the same, and resource planning should be done according to each province's conditions.

From a practical perspective, the results of this study can help blood transfusion organization managers design crisis preparedness strategies. Expanding fixed and mobile blood donation infrastructure based on existing capacities and projected provincial needs, implementing effective donor recruitment and retention programs, using digital tools to manage relationships with donors, and utilizing new technologies for demand forecasting and inventory management are among the measures that can increase the resilience of the blood transfusion system in the face of severe demand fluctuations.

Despite the contributions presented, this research also faces some limitations. First, demand growth is considered the sole source of uncertainty. Other disruptions, such as supply chain interruptions, donor shortages, financial constraints, and workforce limitations, are not incorporated into the model. Second, the demand-growth scenarios are defined based on predetermined levels, and their probability is assumed to be constant, whereas in reality the severity and probability of crises can change dynamically. Third, due to the lack of officially reported provincial demand statistics, the demand for RBCs, plasma, and platelets was estimated using per-capita consumption figures reported in the literature. Therefore, the efficiency scores and resource adjustment results should be interpreted with caution. Moreover, the proposed model is static in nature and does not capture temporal changes in capacities and demand in different periods. Accordingly, in future research, the developed model should be combined with other uncertainty management approaches such as stochastic programming, distributionally robust optimization, and fuzzy programming. In addition, developing dynamic and multi-period models to examine temporal changes in capacity and demand can provide more accurate insights into system resilience. Simultaneously examining supply and demand uncertainties, network modeling of the blood supply chain at different geographical levels, and integrating machine learning methods to predict demand and generate more realistic scenarios are other valuable avenues for future research. In addition, applying the proposed model to other health systems and comparing results across countries can enhance the generalizability of the findings and expand the resilience literature in health systems.

Data Availability Statement

The data are available in the appendices.

Ethical considerations

The ethical issues, including plagiarism, informed consent, misconduct, data fabrication, and/or falsification, double publication and/or submission, and redundancy, have been completely Witnessed by the authors.

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Conflict of interest

The authors declare no conflicts of interest.

References

Abdolazimi, O., Pishvaee, M., Shafiee, M., Shishebori, D., Ma, J., & Entezari, S. (2025). Blood supply chain configuration and optimization under the COVID-19 using benders decomposition based heuristic algorithm. *International Journal of Production Research, 63*(2), 571-593. https://doi.org/10.1080/00207543.2023.2263088

Abolghasemi, H., Amid, A., Zeinali, S., Radfar, M., Eshghi, P., Rahiminejad, M., . . . Hoorfar, H. (2007). Thalassemia in Iran Epidemiology, Prevention, and Management. *Journal of Pediatric Hematology/Oncology, 29*(4), 233-238. 10.1097/MPH.0b013e3180437e02.

Agac, G., Baki, B., & Atici, K. (2023). An evaluation of blood collection efficiency at the regional level: the case of Turkey Available. *International Journal of Health Governance, 28*(3), 299-310. https://doi.org/10.1108/IJHG-11-2022-0095.

Agac, G., Baki, B., & Murat Ar, I. (2024). Blood supply chain network design: a systematic review of literature and implications for future research. *Journal of Modelling in Management, 19*(1), 68-118. https://doi.org/10.1108/JM2-05-2022-0132.

Ahmadpour-Samani, P., Arman, M. H., & Foukerdi, A. (2022). Using Data Envelopment Analysis to Estimate Perceived Organizational Equity. *Industrial Management Journal*, *14*(3), 337–358. 10.22059/imj.2022.343989.1007950.

Arani, M., Momenitabar, M., Ebrahimi, Z., & Liu, X. (2021). A Two-Stage Stochastic Programming Model for Blood Supply Chain Management, Considering Facility Disruption and Service Level. *arXiv preprint arXiv:2111.02808*. https://doi.org/10.48550/arXiv.2111.02808

Carver, A., Chell, K., Davison, T., & Masser, B. (2018). What motivates men to donate blood? A systematic review of the evidence. *Vox Sanguinis, 113*(3), 205-219. https://doi.org/10.1111/vox.12625

Charnes, A., & Cooper, W. (1962). Programming with linear fractional functionals. *Naval Research Logistics Quarterly, 9*(3-4), 181-186. https://doi.org/10.1002/nav.3800090303.

Charnes, A., Cooper, W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research, 2*(6), 429-444. 10.1016/0377-2217(78)90138-8

Cheraghali, A. (2012). Overview of blood transfusion system of Iran: 2002–2011. *Iranian journal of public health, 41*(8), 89.

Chien, J., Yao, C., Chen, H., & Ho, T. (2025). Trends in blood transfusion and causes of blood wastage: a retrospective analysis in a teaching hospital. *BMC Health Services Research, 67*. doi:https://doi.org/10.1186/s12913-024-12170-x

Cook, W., & Seiford, L. (2009). Data envelopment analysis (DEA) – Thirty years on. *European Journal of Operational Research, 192*(1), 1-17. 10.1016/j.ejor.2008.01.032

Cooper, W., Seiford, L., & Zhu, J. (2011). Data Envelopment Analysis: History, Models, and Interpretations. In W. Cooper, L. Seiford, & J. Zhu, *Handbook on Data Envelopment Analysis* (pp. 1-39). Boston: Springer.

Emrouznejad, A., Amin, G., Ghiyasi, M., & Michali, M. (2023). A review of inverse data envelopment analysis: origins, development and future directions. *IMA Journal of Management Mathematics, 34*(3), 421-440. 10.1093/imaman/dpad006

Fariman, S., Danesh, K., Purtalebiyan, M., Fakhri, Z., Motallebi, A., & Fozooni, A. (2024). A robust optimization model for multi-objective blood supply chain network considering scenario analysis under uncertainty: a multi-objective approach. *Scientific Report, 14*, 9452. 10.1038/s41598-024-57521-0

Fergusen, E. (2015). Mechanism of altruism approach to blood donor recruitment and retention: a review and future directions. *Transfusion Medicine, 25*(4), 211-226. https://doi.org/10.1111/tme.12233

Ghahremani-Nahr, J., Kian, R., Sabet, E., & Akbari, V. (2022). A bi-objective blood supply chain model under uncertain donation, demand, capacity and cost: a robust possibilistic-necessity approach. *Operational research, 22*(5), 4685. https://doi.org/10.1007/s12351-022-00710-4

Hamisheh Bahar, M., Akhavan Niaki, S., & Khedmati, M. (2026). A Forward-Looking Approach to Blood Supply Chain Optimization: A Robust Dynamic Network Data Envelopment Analysis and Deep Learning Hybrid Model. *SSRN*, 1-56.

Hick, J., Hanfling, D., Wynia, M., & Pavia, A. (2020). Duty to plan: health care, crisis standards of care, and novel coronavirus SARS-CoV-2. *New Perspectives*, 10-31478. 10.31478/202003b.

Hollingsworth, B. (2008). The measurement of efficiency and productivity of health care delivery. *Health Economics, 17*(10), 1107-1128. 10.1002/hec.1391

Imamoglu, G., Ayyildiz, E., Aydin, N., & Topcu, Y. (2025). Bloodmobile location selection for resilient blood supply chain: a novel spherical fuzzy AHP-integrated spherical fuzzy COPRAS methodology. *Journal of Enterprise Information Management, 38*(4), 1407-1438. https://doi.org/10.1108/JEIM-07-2023-0379

Imamoglu, G., Topcu, Y., & Aydin, N. (2023). A systematic literature review of the blood supply chain through bibliometric analysis and taxonomy. *Systems, 11*(3), 124. https://doi.org/10.3390/systems11030124.

Jafarzadeh, A. H., Fathi, M. R., & KÖKSAL, C. D. (2026). Evaluating Financial Performance of Exchange-Listed Companies with Integrated DEA and Malmquist Index. *Industrial Management Journal*, *18*(2), 121–149. 10.22059/imj.2026.409783.1008283.

Kazemi Matin, R., Azadi, M., & Farzipoor Saen, R. (2022). Measuring the sustainability and resilience of blood supply chains. *Decision Support Systems, 161*, 113629. https://doi.org/10.1016/j.dss.2021.113629

Kohl, S., Schoenfelder, J., Fügener , A., & O. Brunner, J. (2019). The use of Data Envelopment Analysis (DEA) in healthcare with a focus on hospitals. *Health Care Management Science, 22*, 245-286. https://doi.org/10.1007/s10729-018-9436-8

Laspa, C., & Priporas, C. (2008). The productive efficiency of blood banks: Using data envelopment and simple ratio analyses to measure the performance of health services. *Journal of Management & Marketing in Healthcare, 1*(4), 412-428. https://doi.org/10.1179/mmh.2008.1.4.412

Mergoni, A., Emrouznejad, A., & De Witte, K. (2025). Fifty years of Data Envelopment Analysis. *European Journal of Operational Research, 326*(3), 389-412. 10.1016/j.ejor.2024.12.049

Monteiro, T., Ferreira, I., Pontes Junior, A., Chocair, H., & Ferreira, J. (2024). Barriers and motivations for blood donation: an integrative review. *Hematology, Transfusion and Cell Therapy, 46*, 283-288. https://doi.org/10.1016/j.htct.2023.09.2366

Moran, V., Suhrcke, M., & Nolte, E. (2023). Exploring the association between primary care efficiency and health system characteristics across European countries. *BMC Health Services Research, 23*. doi:https://doi.org/10.1186/s12913-023-10369-y

Moshtagh, M., Zhou, Y., & Verma, M. (2026). Coordinating a bi-level blood supply chain with interactions between supply-side and demand-side operational decisions. *International Transactions in Operational Research, 33*(3), 1971-2015. https://doi.org/10.1111/itor.13569

Moslemi, S., & Mirzazadeh, A. (2017). Performance evaluation of four-stage blood supply chain with feedback variables using NDEA cross-efficiency and entropy measures under IER uncertainty. *Numerical Algebra, Control and Optimization, 7*(4), 379-401. 10.3934/naco.2017024

Mulvey, J., Vanderbei, R., & Zenios, S. (1995). Robust Optimization of Large-Scale Systems. *Operations Research, 43*(2), 264-281. 10.1287/opre.43.2.264

Mykhailenko, D. (2018). Economic efficiency: definition, analysis of concepts. *Problemy Ekonomiky, 2*, 159-163.

National Blood Resource Education Program Expert Panel. (1990). The use of autologous blood. *263*(3), 414-417.

Nielsen, A., & Nielsen, N. (2016). Assessing productive efficiency and operating scale of community blood centers. *Transfusion, 56*(6), 1267-1273. https://doi.org/10.1111/trf.13493

Oliveira, E., & Reis, I. (2020). What are the perspectives for blood donations and blood component transfusion worldwide? A systematic review of time series studies. *Sao Paulo Medical Journal, 138*, 54-59. 10.1590/1516-3180.2019.0415.r1.06112019

Omidikhoda, A., Amini Kafi-Abad, S., Pourfatollah, A., & Maghsudlu, M. (2016). Blood collection, components preparation and distribution in Iran, 2008-2012 . *Transfusion and Apheresis Science*, 117-121. https://doi.org/10.1016/j.transci.2016.01.026

Osorio, A., Brailsford, S., & Smith, H. (2015). A structured review of quantitative models in the blood supply chain: A taxonomic framework for decision-making. *International Journal of Production Research, 53*(24), 7191–7212. 10.1080/00207543.2015.1005766

Ozcan, Y. (2008). *Health Care Benchmarking and Performance Evaluation: An Assessment using Data Envelopment Analysis (DEA).* Springer. https://doi.org/10.1007/978-0-387-75448-2.

Panwar, A., Olfati, M., Pant, M., & Snasel, V. (2022). A Review on the 40 Years of Existence of Data Envelopment Analysis Models: Historic Development and Current Trends. *Archives of Computational Methods in Engineering, 29*, 5397-5426. https://doi.org/10.1007/s11831-022-09770-3

Pereira, A. (2006). Economies of scale in blood banking: a study based on data envelopment. *Vox Sanguinis, 90*(4), 308-315. https://doi.org/10.1111/j.1423-0410.2006.00757.x.

Peykani, P., Mahmoodirad, A., & Amirteimoori, A. (2025). A novel adjustable intuitionistic fuzzy framework for two-stage data envelopment analysis: An application in the banking sector. *Information Sciences, 718*, 122372. https://doi.org/10.1016/j.ins.2025.122372.

Peykani, P., Seyed Esmaili, F., Pishvaee, M., Rostamy-Malkhalifeh, M., & Hosseinzadeh Lotfi, F. (2024). Matrix-based network data envelopment analysis: A common set of weights approach. *Socio-Economic Planning Sciences, 95*, 102044. https://doi.org/10.1016/j.seps.2024.102044

Piersma, T., Bekkers, R., Klinkenberg, E., de Kort, W., & Merz, E. (2017). Individual, contextual and network characteristics of blood donors and non-donors: a systematic review of recent literature. *Blood transfusion, 15*(5), 382–397. 10.2450/2017.0064-17

Pirabán, A., Guerrero, W., & Labadie, N. (2019). Survey on blood supply chain management: Models and methods. *Computers & Operations Research, 112*, 104756. https://doi.org/10.1016/j.cor.2019.07.014

Pirabán-Ramírez, A., Guerrero, W., Labadie, N., & Sotaquirá-Gutiérrez, R. (2026). A systemic model to assess shortage and wastage levels in demand-driven blood supply chains. *International Journal of Healthcare Management, 19*(2), 219-229. 10.1080/20479700.2024.2419280

Raykar, N., Makin, J., Khajanchi, M., Olayo, B., Valencia, A., Roy, N., . . . Rudd, K. (2021). Assessing the global burden of hemorrhage: The global blood supply, deficits, and potential solutions. *Sage Open Medicine, 9*, 1-11. 10.1177/20503121211054995

Razavi Hajiagha, S., Amoozad Mahdiraji, H., Behnam, M., Nekoughadirli, B., & Joshi, R. (2022). A scenario-based robust time–cost tradeoff model to handle the effect of COVID-19 on supply chains project management. *Operations Management Research, 15*, 357-377. https://doi.org/10.1007/s12063-021-00195-y

Samut, P. (2023). Efficiency determinants in healthcare: A systematic review of data envelopment analysis applications in health services. *Journal of Healthcare Management, 5*, 356-375. 10.1097/JHM-D-22-00086

Shehu, E., Veseli, B., & Winterich, K. (2024). Improving Blood Donor Retention and Donor Relationships with Past Donation Use Appeals. *Journal of Service Research, 27*(3), 346–363. https://doi.org/10.1177/10946705231202244

Sherman, H. (1984). Hospital Efficiency Measurement and Evaluation Empirical Test of a New Technique. *Medical Care, 22*(10), 922-938. 10.1097/00005650-198410000-00005

Shokouhifar, M., & Ranjbarimesan, M. (2022). Multivariate time-series blood donation/demand forecasting for resilient supply chain management during COVID-19 pandemic. *Cleaner Logistics and Supply Chain, 5*, 100078. https://doi.org/10.1016/j.clscn.2022.100078

Sinha, R., Arun , V., Sravan Kumar, R., & Jain, R. (2026). The role of social media, influencers, and online communities in blood donor recruitment and retention: A systematic scoping review. *Transfusion Clinique et Biologique, 33*(2), 113-122. 10.1016/j.tracli.2026.03.001

Soodejani, M., Haghdoost, A., Sedaghat, A., Baneshi, M., & Zolala, F. (2019). The increasing trend of blood donation in Iran. *Blood Research, 54*(4), 269-273. 10.5045/br.2019.54.4.269

Suárez-Artime, P., Rey-Brandariz, J., López García, M., Casal Acción, B., de Aguilar Pensado, A., & Varela-Lema, L. (2026). Motivations to donate blood and plasma: A scoping review of quantitative studies. *Transfusion, 66*(4), 853-870. 10.1111/trf.70137

Sun, M., Ye, Y., Zhang, G., Xue, Y., & Shang, X. (2023). Measuring the efficiency of public hospitals: A multistage data envelopment analysis in Fujian Province, China. *Frontiers in Public Health, 11*, 1091811. https://doi.org/10.3389/fpubh.2023.1091811

Tehran Times Straight Truth. (2024, April 29). *IBTO is WHO regional training authority: official*. Retrieved from Tehran Times: https://www.tehrantimes.com/news/497828/IBTO-is-WHO-regional-training-authority-official

Tehran Times Straight Truth. (2025, December 3). *Over 1.6 million people donate blood in 8 months*. Retrieved from Tehran Times: https://www.tehrantimes.com/news/521174/Over-1-6-million-people-donate-blood-in-8-months

Tsaples, G., & Papathansiou, J. (2021). Data envelopment analysis and the concept of sustainability: A review and analysis of the literature. *Renewable and Sustainable Energy Reviews, 138*, 110664. https://doi.org/10.1016/j.rser.2020.110664

Veihola, M., Aroviita, P., Kekomaki, R., & Sintonen, H. (2007). Discarded cellular components and the technical efficiency of component preparation. *The European Journal of Health Economics, 9*, 325-331. 10.1007/s10198-007-0079-9

Veihola, M., Aroviita, P., Kekomäki, R., Linna, M., & Sintonen, H. (2008). Discarded cellular components and the technical efficiency of component preparation. *The European Journal of Health Economics, 9*, 325-331. 10.1007/s10198-007-0079-9

Veihola, M., Aroviita, P., Linna, M., Sintonen, H., & Kekomäki, R. (2006). International comparison of the technical efficiency of component preparation. *Transfusion, 46*(12), 2109-2114. https://doi.org/10.1111/j.1537-2995.2006.01036.x

Veihola, M., Kekomaki, R., Linna, M., Sintonen, H., & Aroviita, P. (2008). Working hours and produced cellular components as variables to evaluate blood bank efficiency. *Transfusion Medicine, 18*, 241-249. 10.1111/j.1365-3148.2008.00875.x

Viennet, E., Dean, M., Kircher, J., Leder, K., Guo, Y., Jones, P., & Faddy, H. (2025). Blood under pressure: how climate change threatens blood safety and supply chains. *The Lancet Planetary Health, 9*(4), e304-e313. 10.1016/S2542-5196(25)00051-8

Wei, Q., Zhang, J., & Zhang, X. (2000). An inverse DEA model for inputs/outputs estimate. *European Journal of Operational Research, 121*(1), 151-163. 10.1016/S0377-2217(99)00007-7

WHO. (2025, May 30). *Blood safety and availability*. Retrieved from World Health Organization: https://www.who.int/en/news-room/fact-sheets/detail/blood-safety-and-availability?utm

World Health Organization. (2025, May 30). *Blood safety and availability*. Retrieved from World Health Organization: https://www.who.int/news-room/fact-sheets/detail/blood-safety-and-availability#:~:text=low%2Dincome%20countries.-,Blood%20supply,total%20of%20106%20million%20donations.

Xie, Q., Zhu, Y., Shang, H., & Li, Y. (2021). Variations on the theme of slacks-based measure of efficiency: Convex hull-based algorithms. *Computers & Industrial Engineering, 159*, 107474. https://doi.org/10.1016/j.cie.2021.107474

Zhou, J., Peng, R., Chang, Y., Liu, Z., Gao, S., Zhao, C., . . . Qin, X. (2023). Analyzing the efficiency of Chinese primary healthcare institutions using the Malmquist-DEA approach: Evidence from urban and rural areas. *Frontiers in Public Health, 11*. doi:https://doi.org/10.3389/fpubh.2023.1073552

Zubir, M., Noor, A., Mohd Rizal, A., Harith, A., Abas, M., Zakaria, Z., & Bakar, A. (2024). Approach in inputs & outputs selection of Data Envelopment Analysis (DEA) efficiency measurement in hospitals: A systematic review. *Plos One, 19*(8), e0293694. https://doi.org/10.1371/journal.pone.0293694