# Blood Transfusion Optimization using Linear Programming

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# Section 1: Introduction

Every day, millions of lives across the world rely on the blood donations of others. Still, an uncalculatable quantity of lives are lost everyday from blood shortages not being able to meet dire clinical demands. The purpose of this project is to develop a prescriptive analytics model that optimizes blood bank inventory management, ensuring efficient allocation and distribution of blood units to meet hospital demands while minimizing waste due to suboptimal blood type allocation. This project addresses the problem of determining blood type distribution to enhance operational efficiency.

# Section 2: Problem Definition

Real blood bank inventory management involves maintaining sufficient stock to meet unpredictable hospital demands while minimizing blood waste as much as possible. The problem is significant due to the critical role blood plays in nearly all critical medical procedures, and the high costs associated with blood collection, storage, and disposal. Everyday, real lives rely on optimal blood efficiency, as will be shown in depth throughout this paper.

This project only seeks to optimize blood type allocation efficiency through integer figures and AMPL solutions by assigning priorities to different “values” of blood types depending on their biological donation abilities. The key challenge of this is to ensure that all blood demand is met while using as little high value blood types as possible.

# Section 3: Literature Review

## I. *Towards 100% Voluntary Blood Donation: A Global Framework for Action*

Source: World Health Organization (2010) [1]

While not inherently scholarly, this healthcare framework written by the World Health Organization seeks to “provide information and guidance on the vital role of voluntary blood donors in assuring the availability of stable and sufficient supplies of safe blood for transfusion”. According to the framework, “many patients die or suffer unnecessary because they do have access to safe blood transfusion”. Many further examples are provided of preventable deaths under blood shortages due to diseases like Malaria, HIV and Sick-Cell Disease, though the most striking statistic revels that “Hemorrhage, for example, accounts for over 25% of the 530,000 maternal deaths each year … Access to safe blood could help to prevent up to one quarter of maternal deaths each year”. Overall, this framework displays the grave importance that effective blood management systems have on preventing global deaths.

## II. *Innovative blood transfusion strategies to address global blood deserts*

Source: The Lancet Global Health (2024) [2]

This scholarly article explains specifically why blood management can be so difficult for many parts of the world due to the extreme distances of patients from medical centers in blood deserts: “In rural settings worldwide, many people live in effective blood deserts without access to any blood transfusion. The traditional system of blood banking is logically complex and expensive for many resource-restricted settings and demands innovative and multidisciplinary solutions”. The article then further explains the dangers of blood deserts and mentions that “In many rural settings, hundreds of millions of people live without access to any blood; the only hospitals with stocked blood banks are hours away”.

## III. *Blood shortages and changes to massive transfusion protocols*

Source: Jeremy W. Jacobs, Garrett S. Booth (2022) [3]

This scholarly article from students at Yale University and Vanderbilt University highlights the dangers that blood shortages can cause in even highly developed countries like the United States under crisis like the recent COVID-19 pandemic. According to the article, “The COVID-19 Pandemic has resulted in severe ongoing blood shortages across the US, despite employment of numerous blood-conservation measures”. The article then goes on to mention that, during the pandemic, 43% of surveyed medical institutions resorted to altering their transfusion protocols to converse blood as much as possible. This reveals that the entire globe is vulnerable when supply chain issues limit blood supplies.

## IV. *Optimization of blood supply chain with shortened shelf lives and ABO compatibility*

Source: Qinglin Duan, T. Warren Liao (2014) [4]

This scholarly article investigates the limiting shelf life of blood as a constraint for optimization. According to the paper, “In clinical practice, red blood cells have a maximal shelf life of 42 days”. The article also explains the different interactions of donating each blood type and how “group O blood are needed more frequently to substitute for other compatible blood types”.

## V. *Blood platelet production: Optimization by dynamic programming and simulation*

Source: René Haijema, Jan van der Wal, Nico M. van Dijk (2007) [5]

Similarly to the last literature investigation, this scholarly article looks at blood perishability as a constraint, specifically focusing on blood platelets, which  are tiny fragments within blood that play a crucial role in blood clotting. According to the article, “Blood platelets are precious, as voluntarily supplied by donors, and are highly perishable, with limited lifetimes of 5-7 days. Demand is highly variable and uncertain. A practical production and inventory rule is striving for that minimizes shortage and spills”. This article reveals that blood platelets are even more scarce, perishable, and uncertain in demand than traditional liquid blood, and therefore management optimization of platelets is crucial.

## VI. *How much blood is needed?*

Source: International Journal of Transfusion Medicine (2010) [6]

The final scholarly source of this literature review attempts to predict blood demand using historical data. According to the article, “The World Health Organization (WHO) stated in 2009 that more than 81 million units of blood are collected globally per year and an estimated maximum of 80 million uses of RBC were transfused”. This gives a rough idea of supply versus demand of blood in highly developed countries. Knowing how much blood is demanded is crucial to being able to properly optimize blood use and donation rates.

# Section 4: Challenge Analysis

As was highlighted throughout the literature review, blood management optimization is a highly complex and, in many circumstances, a highly grave issue to look at. In modern developed countries, blood optimization systems generally only need to worry about blood type incompatibility and reducing waste as much as possible. However, in many blood deserts and underdeveloped countries, as well as during times of crisis, there is simply not enough blood to meet the extreme demands, meaning that those systems need to additionally consider not having enough supply to meet overall demand, and using as little blood as possible per procedure.

This model will examine purely the constraints of blood type compatibility. Therefore, the following challenge will need to be considered in the development of the model:

1. All blood type variants have limitations on what types of blood they can accept during procedures. Therefore, it is critical that less "useful" blood is used, when possible, to save the more "useful" blood like O-. Visualizations of blood type compatibility for each type of blood is presented below:

| | | Donor's blood type | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | O- | O+ | B- | B+ | A- | A+ | AB- | AB+ |
| Recipient's blood type | AB+ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | AB- | ✓ | | ✓ | | ✓ | | ✓ | |
| | A+ | ✓ | ✓ | | | ✓ | ✓ | | |
| | A- | ✓ | | | | ✓ | | | |
| | B+ | ✓ | ✓ | ✓ | ✓ | | | | |
| | B- | ✓ | | ✓ | | | | | |
| | O+ | ✓ | ✓ | | | | | | |
| | O- | ✓ | | | | | | | |

Figure provided by the Australian Academy of Science [7]

# Section 5: Methodology

To effectively optimize the allocation of blood types within respecting compatibility, I transformed the problem into a prescriptive integer programming formulation.

This formulation is highly simplified, as it only looks into optimizing blood compatibility without taking any other common problems into account. The formulation attempts to apply "value" to each form of blood type to ensure that blood types like O- are only used when necessary, since they are able to donate to any other blood types. As a result, costs for each blood type were allocated based on how many other blood types they can donate to. This model aims to minimize the "cost of usage" for each blood interaction.

## Mathematical Formulation

**Cost Table:** Costs reflect donation versatility (the number of others each blood type can donate to)

| Blood Type | Cost ($C_b$) |
|---|---|
| O+ | 4 |
| O- | 8 |
| A+ | 2 |
| A- | 4 |
| B+ | 2 |
| B- | 4 |
| AB+ | 1 |
| AB- | 2 |

| **Sets and Indices** | | |
|---|---|---|
| $B$ | Blood types | {O+, O-, A+, A-, B+, B-, AB+, AB-} |
| $b, b' \in B$ | Blood type index | $b$ for supply, $b'$ for usage |
| **Parameters** | | |
| $C_b$ | Usage cost of type $b$ | Cost Units |
| $M_{b,b'}$ | Compatibility matrix | 1 if $b$ is compatible with $b'$, 0 else |
| **Decision Variables** | | |
| $X_{b,b'}$ | Units of type $b$ used for type $b'$ | Non-negative integer |

**Objective:**

$$\text{Min} \sum_{b\in B} \sum_{b'\in B} C_b \cdot X_{b,b'} \qquad \text{(Minimize cost of blood usage, favoring less "useful" blood types.)} \tag{1}$$

**Subject to:**

$$X_{b,b'} \leq M_{b,b'} \cdot M \quad \forall b, b' \in B \qquad \text{(Only use blood type } b \text{ for } b' \text{ if compatible)} \tag{2}$$

$$X_{b,b'} \in Z_{\geq 0} \quad \forall b, b' \in B \qquad \text{(Blood units used must be non-negative integers)} \tag{3}$$

# Section 6: Data Description

It was very difficult to find useful data for my optimization. I attempted to search for accurate data of the percentage of blood donators assigned to each blood type and the percentage of patients that receive each blood type, the idea being that “higher value” blood donators, like O- donors, are more likely to donate. However, I was unable to find any data that suggested any blood type differences between blood donators and blood receivers.

Ultimately, the highest quality dataset that I was able to find was a Kaggle dataset by Kamile Novaes titled Global Blood Type Distribution. Using this blood type, I am at least able to gain an understanding of the distribution of each blood type across different countries.

One very interesting find when searching through the dataset was that typically underdeveloped countries also tend to have lower distributions of “valuable” blood types. For example, according to the dataset, the United States consists of 6.6% O- blood types while Sudan consists of only 3.5% O- blood types. This likely further contributes to the blood crisis that many underdeveloped countries are facing every day.

# Section 7: Computations and Solutions

After transforming the linear programming model into AMPL for computational solutions, I ran the optimization method using United States blood type distributions for both the supply and demand.

```
# Define blood types
blood_types = ["O_pos", "O_neg", "A_pos", "A_neg", "B_pos", "B_neg", "AB_pos", "AB_neg"]

# Define costs based on donation versatility
costs = {
    "O_pos": 4,
    "O_neg": 8,
    "A_pos": 2,
    "A_neg": 4,
    "B_pos": 2,
    "B_neg": 4,
    "AB_pos": 1,
    "AB_neg": 2
}

# Define demand based on U.S. blood type distribution (total 1000 units)
demands = {
    "O_pos": 374,  # 37.4%
    "O_neg": 66,   # 6.6%
    "A_pos": 357,  # 35.7%
    "A_neg": 63,   # 6.3%
    "B_pos": 85,   # 8.5%
    "B_neg": 15,   # 1.5%
    "AB_pos": 34,  # 3.4%
    "AB_neg": 6    # 0.6%
}

# Define supply based on U.S. blood type distribution (total 1000 units)
supply = {
    "O_pos": 374,  # 37.4%
    "O_neg": 66,   # 6.6%
    "A_pos": 357,  # 35.7%
    "A_neg": 63,   # 6.3%
    "B_pos": 85,   # 8.5%
    "B_neg": 15,   # 1.5%
    "AB_pos": 34,  # 3.4%
    "AB_neg": 6    # 0.6%
}
```

As expected, the results show that, since there would be an even number of supply and demand for each blood type, the allocation solutions would output equal integers:

```
Allocation (X[b,bp]):
X[O_pos,O_pos] = 374.0
X[O_neg,O_neg] = 66.0
X[A_pos,A_pos] = 357.0
X[A_neg,A_neg] = 63.0
X[B_pos,B_pos] = 85.0
X[B_neg,B_neg] = 15.0
X[AB_pos,AB_pos] = 34.0
X[AB_neg,AB_neg] = 6.0
```

I then attempted to input other countries, such as Sudan as the demand, the idea being that the U.S. would be able to keep up with Sudan's blood distribution demand because the U.S. blood distribution generally consists of higher quality blood types. However, there was simply not enough O+ donations available to be able to meet all of the Sudan results. I doing this method with a variety of different developing countries, though, unfortunately, none were ever able to find a feasible solution.

```
Status: Infeasible
No optimal solution found. Check model constraints for feasibility.
```

```
# Define demand based on Sudan blood type distribution (total 1000 units)
demands = {
    "O_pos": 480,  # 48.0%
    "O_neg": 277,  # 27.7%
    "A_pos": 152,  # 15.2%
    "A_neg": 28,   # 2.8%
    "B_pos": 35,   # 3.5%
    "B_neg": 18,   # 1.8%
    "AB_pos": 8,   # 0.8%
    "AB_neg": 2    # 0.2%
}

# Define supply based on U.S. blood type distribution (total 1000 units)
supply = {
    "O_pos": 374,  # 37.4%
    "O_neg": 66,   # 6.6%
    "A_pos": 357,  # 35.7%
    "A_neg": 63,   # 6.3%
    "B_pos": 85,   # 8.5%
    "B_neg": 15,   # 1.5%
    "AB_pos": 34,  # 3.4%
    "AB_neg": 6    # 0.6%
}
```

# Section 8: Results and Discussions

I am disappointed that the model was unable to find a feasible solution for developed countries to donate blood to underdeveloped countries due to underdeveloped countries typically having much greater percentage populations of O+ blood types, though I am proud that the model does theoretically work to optimize what patients should receive what types of blood to minimize “blood costs”, also known as minimizing usage of highly versatile blood types.

# Section 9: Conclusions

In conclusion, it was found that blood management optimization is critical in preventing the loss of lives. Developed countries like the United States generally do not see many issues with low blood supplies, but in the many undeveloped countries and blood deserts, millions of lives are lost every year as a result of blood supplies not meeting demands. The COVID-19 pandemic additionally revealed the vulnerability that even the most developed modern countries have to blood supplies under sudden supply chain disruptions. As a result, it is critical that blood banks and hospitals around the world optimize blood use as much as possible in cases of emergencies.

However, blood supply optimization is highly complicated given the fragile and finite nature of blood. Blood is expensive, perishes very quickly, and most blood types are not capable to donating to most other blood types. The model developed throughout this paper sets values to the most versatile blood donation types to ensure that they are used as sparingly as possible. The model efficiently works out which types of blood should be allocated given sets of supplies and demands of each blood type, though limitations in datasets prevents the model from having many useful applications. It would be very interesting to see this model work out solutions given accurate sets of modern blood donation and acceptance statistics.

For future work, I would love to see this model refined to also take into account issues like blood perishability and the different blood amounts needed for different patients. Under these circumstances, a model of blood platelets rather than traditional liquid blood would be interesting to view with how necessary they are to medicine and how quickly they perish.

# Section 10: References


[1] "Voluntary blood donation: Foundation of a safe and sufficient blood supply," Towards 100% Voluntary Blood Donation: A Global Framework for Action., https://www.ncbi.nlm.nih.gov/books/NBK305666/ (accessed May 7, 2025).

[2] Raykar, Nakul P et al., "Innovative blood transfusion strategies to address global blood deserts: a consensus statement from the Blood Delivery via Emerging Strategies for Emergency Remote Transfusion (Blood DESERT) Coalition," The Lancet Global Health, https://www.thelancet.com/journals/langlo/article/PIIS2214-109X(23)00564-8/fulltext?dm_i=7MI4,2B4A,D8SZT,8XBO,1 (accessed May 5, 2025).

[3] J. W. Jacobs and G. S. Booth, "Blood shortages and changes to massive transfusion protocols: Survey of hospital practices during the COVID-19 pandemic," Transfusion and Apheresis Science, https://www.sciencedirect.com/science/article/pii/S1473050221002974 (accessed May 7, 2025).

[4] Q. Duan and W. Liao, "Optimization of blood supply chain with shortened shelf lives and abo compatibility," International Journal of Production Economics, https://www.sciencedirect.com/science/article/pii/S0925527314000619 (accessed May 7, 2025).

[5] R. Haijema, jan van der Wal, and N. M. van Dijk, “Blood platelet production: Optimization by Dynamic Programming and Simulation,” Computers & Operations Research, https://www.sciencedirect.com/science/article/pii/S030505480500119X (accessed May 7, 2025).

[6] E. Seifried, “How much blood is needed?,” Vox Sanguinis, http://onlinelibrary.wiley.com/doi/10.1111/j.1423-0410.2010.01446.x/full (accessed May 8, 2025).

[7] E. Berthold, “Why are some blood types incompatible with others?,” Austrialian Academy of Science, http://www.science.org.au/curious/people-medicine/why-are-some-blood-types-incompatible-others (accessed May 7, 2025).