

Optimization of Organ Transplantation Logistics from an Operations Research Linear Programming Perspective

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Abstract. Logistics is crucial in organ transplantation surgeries, focusing on maximizing donor-recipient matches within organ survival timeframes. This study explores the impact of clustering structures on organ matches, utilizing dynamic analysis and novel mathematical models to evaluate transportation modes and prioritize intra-regional organ transplantation while meeting time constraints. Initially concentrating on maximizing flow within a single timeframe, the study addresses disparate outcomes across organ types by developing an additional model for maximizing flow across multiple organ types. Computational analyses and diverse performance metrics underscore the potential for enhancing organ transplantation networks through re-clustering strategies.

Keywords: Organ Transplantation, Organ Transplantation Logistics, linear programming.

1. Introduction

Organ transplantation is a complex medical procedure involving donors and recipients, crucial for saving lives or improving quality of life. However, the persistent gap between organ supply and demand poses significant challenges, leading to long waitlists and preventable deaths. For instance, in the United States, 20 individuals perish daily due to organ unavailability, while over 110,000 patients await transplantation. Similarly, in Turkey, despite 4,500 organ transplantations in 2015, 25,500 individuals still await suitable organs. Addressing these challenges is crucial, given the intricate nature of the transplantation network, where patient and hospital locations, coupled with transportation times, play critical roles. Consequently, extensive research aims to optimize organ transplantation logistics, seeking to improve outcomes and save more lives.

This study aims to enhance organ transplantation logistics by constructing linear programming models that maximize potential donor-recipient pairings. These models focus on optimizing transportation times and maximizing potential flow of multiple organ types within a single time frame. By integrating optimization and simulation models, the study seeks to provide optimal solutions for strategic decisions, such as facility placement, while allowing for performance evaluation before implementation. This approach offers a comprehensive method to improve organ transplantation logistics and ultimately save more lives.

2. Organ transplantation process

In organ transplantation, the donor-recipient matching process follows a specific sequence. Initially, if an organ becomes available, urgent patients are prioritized within cold ischemia time constraints, bypassing hierarchical assignment. If no urgent patients are found, a hierarchical matching process begins, starting with the hospital introducing the organ. If no match is found, the search expands to other hospitals in the city, then to cities within the donor's Regional Coordination Center (RCC), and finally nationwide. After each successful transplantation, waiting lists undergo updates, with the city receiving the organ moving to the bottom, allowing the next city to move up in subsequent matches. This iterative process continuously refreshes waiting lists after each transplantation, ensuring dynamic allocation of organs.

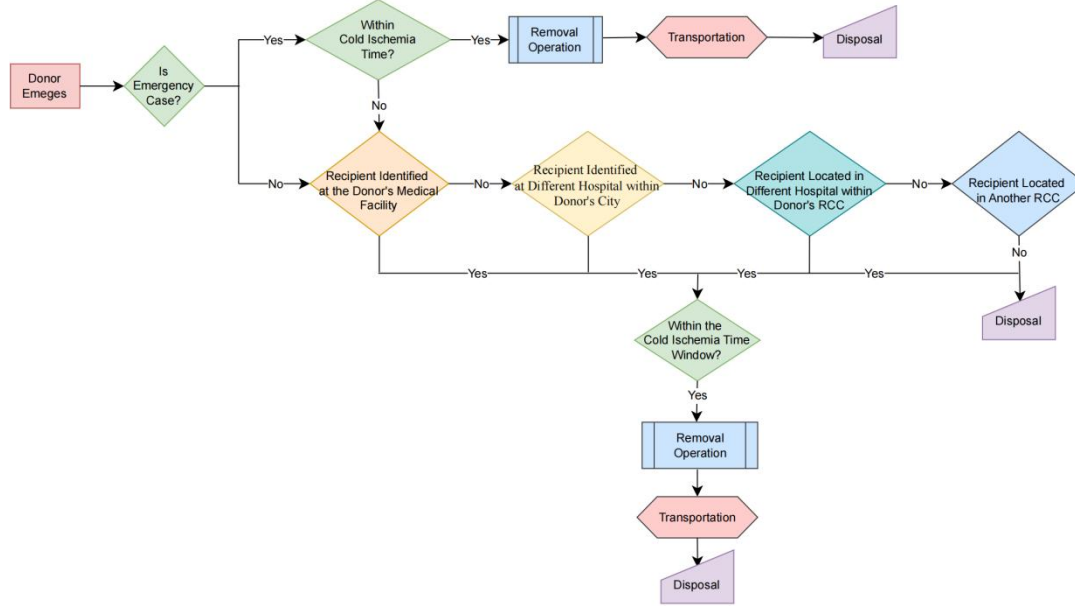


Fig. 1 Organ transplantation process abridged general view

2.1 Model 1: Shortest Transportation Time Optimization.

The ideal linear programming model for organ transplantation systems represents a multi-stage decision process. The mathematical formalization of the problem is as follows:

Define sets:

M: Set of potential donor cities.

N: Set of transplant hospital cities.

R: Set of potential Regional Coordination Center (RCC) locations.

Parameters:

D_i : Total donated organs in city , $i \in M$.

d_j : Total organ demand in city , $j \in N$.

b_{ij} : Land travel time between city , $i \in M$ and city $j \in N$.

p : Upper limit of RCCs to establish.

T : Maximum allowable travel time from donor city to transplantation center.

Decision Variables:

X_{ijk} : Binary variable representing if organs from city , $i \in M$ are transported to city , $j \in N$ through RCC , $k \in R$.

Z_k : Binary variable indicating the existence of RCC , $k \in R$.

y_{ijk} : Binary variable, where 1 signifies the travel route from city i to city j passes through RCC k .

Optimization Model:

$$\text{Minimize: } \sum_{i \in M} \sum_{j \in N} \sum_{k \in R} (D_i \cdot X_{ijk} \cdot b_{ij})$$

$$\text{subject to: } \sum_{i \in M} D_i \cdot X_{ijk} = d_j \quad \forall j \in N$$

$$\sum_{k \in R} Z_k \leq p$$

$$X_{ijk} \cdot b_{ij} \leq T \cdot y_{ijk} \quad \forall i \in M, j \in N, k \in R$$

$$Z_k \leq \sum_{j \in N} a_{kj} \quad \forall k \in R$$

$$X_{ijk}, Z_k, y_{ijk} \in \{0, 1\}$$

The objective of this linear programming model is to minimize the total travel time for organ transportation while ensuring sufficient organ distribution from potential donor cities to transplant hospitals through strategically placing RCCs, subject to specific constraints and logistical considerations.

2.2 Model 2: Maximizing Potential Flow of Multiple Organ Types.

When focusing on maximizing the potential flow of various organ types within the transplantation system, it necessitates a re-design of the linear programming model to account for the complexities arising from different organ types and to optimize the overall organ flow across multiple time frames. Below is the updated linear programming model:

Define sets and parameters as in the original model.

Introduce new decision variable:

W_{ijk} : Binary variable representing the transportation of organ type k from city i to city j .

Updated Optimization Model:

$$\begin{aligned} \text{Maximize: } & \sum_{i \in M} \sum_{j \in N} \sum_{k \in K} (W_{ijk}) \\ \text{subject to: } & \sum_{i \in M} W_{ijk} = d_j \quad \forall j \in N, k \in K \\ & \sum_{k \in K} \sum_{i \in M} W_{ijk} \cdot b_{ij} \leq T \quad \forall j \in N \\ & \sum_{j \in N} \sum_{i \in M} W_{ijk} \leq D_i \quad \forall i \in M \\ & W_{ijk} \in \{0, 1\} \quad \forall i \in M, j \in N, k \in K \end{aligned}$$

This updated linear programming model aims to maximize the efficiency of the entire organ transplantation system by optimizing the potential flow of various organ types. The model takes into consideration the distinct requirements of different organ types, ensuring adequate allocation for each organ type and optimizing the transport flow of organs across different time frames.

2.3 Model 3: Simulation model

The integration of simulation models with the proposed linear programming models (Model 1 and Model 2) offers a comprehensive approach to assessing their effectiveness in organ transplantation logistics. Simulation models provide a practical means to validate and evaluate these models in real-world scenarios by simulating complex dynamics such as organ allocation, transportation routes, and diverse organ types. This methodology complements the linear programming models by offering a more holistic perspective and allows for performance evaluation under varying conditions, including emergency cases and vehicle availability. By integrating simulation modeling, the study enhances understanding, validation, and application of optimized solutions for efficient organ transplantation logistics management, providing decision-makers with a robust framework to make informed choices in this critical healthcare domain.

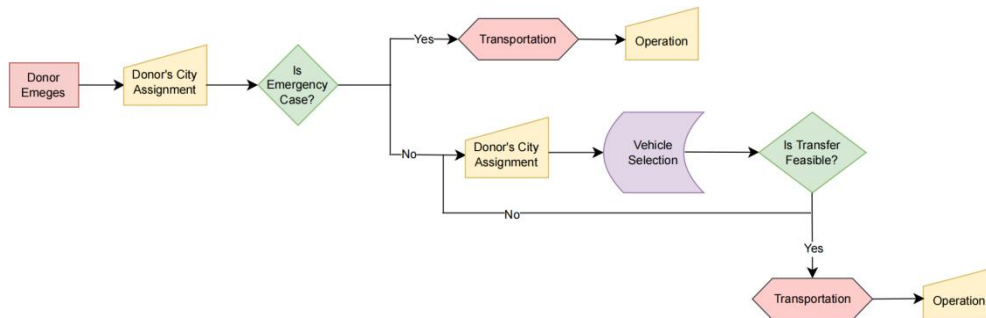


Fig. 2 High-level illustration of the simulation model

3. Conclusions

In the process of organ transplantation, the matching of donors with recipients operates as follows: Initially, upon the availability of an organ for transplantation, a nationwide search ensues to locate patients in urgent need of the organ. Should a patient meeting the urgent criteria be identified within the cold ischemia time constraints, the organ is promptly transported, whether by road or air, directly to the hospital where the patient is situated, without consideration of the hierarchical assignment within the Regional Coordination Centers (RCCs). If there are no suitable emergency patients, a hierarchical matching procedure commences, beginning with the waiting list of the hospital that introduces the donated organ into the system. Should no appropriate candidate be found, the search scope broadens. This study delved into the logistics of organ transportation within hierarchical systems and underscored the pivotal role played by clustering structures in the process of hierarchical matching. To address this, we proposed a linear programming model, incorporating diverse transportation options to pinpoint the most efficient means within the organ transplantation network while accommodating multifaceted influencing factors for precise outcomes. Furthermore, we employed a simulation model to analyze the deterministic model's outputs in an uncertain environment, simulating the authentic features of hierarchical systems. One of the significant contributions of this research was to highlight logistical challenges in organ transplantation and offer guidance for decision-makers in optimizing these systems. Not only did we identify the optimal clustering method within the hierarchical system, but we also evaluated the deterministic model's performance in an uncertain and more complex context using a discrete-event simulation model. Our approach aimed to enhance system performance by maximizing potential-weighted intra-regional flow and emphasized key cities defining average transportation time bounds within the clustering. Moreover, by reducing the transportation time from the donor city to the recipient city, we extended surgical operation time, indirectly enhancing surgical performance and thereby increasing the likelihood of successful transplantation.

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