Industrial Engineering

Optimization of Kidney Paired Donation (KPD) Matching

Soptimizer (Optimize Solution providers)

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Table of Contents

Abstract

This study presents an operations research approach to optimize the Kidney Paired Donation (KPD) program using advanced mathematical modelling techniques implemented through the Gurobi Optimizer. The main objective function was to maximize the number of successful kidney transplants by finding the optimal matching of donors to recipients within the constraints of compatibility and cycle size limitations.

The dataset consisted of 726 participants, with a moderate to high prevalence of donors with AB blood type, which posed unique challenges in matching due to its compatibility properties. By constructing a directed compatibility graph and employing integer programming, we successfully identified 35,150 viable 2-way exchanges, significantly enhancing the efficiency of the KPD process. However, the model did not identify any feasible 3-way exchanges, indicating a potential area for model refinement.

The optimization achieved an optimal solution with a success rate of 50.96%, effectively matching 370 participants, as confirmed by a gap of 0.0000% between the incumbent solution and the best bound.

Introduction

Kidney Paired Donation (KPD) is a transformative approach to addressing the critical shortage of viable kidney donors for patients suffering from end-stage renal disease. The program aims to facilitate kidney transplants by pairing incompatible donor-recipient pairs with others in similar situations, forming cycles of exchanges that satisfy biological compatibility. By optimizing these matches, the KPD program improves access to life-saving treatments and enhances the quality of life for recipients.

The significance of this project lies in its potential to reduce the number of patients on transplant waiting lists while utilizing living donor kidneys effectively. As a KPD consultant for the Organ Procurement and Transplantation Network (OPTN), this project employs advanced Operations Research (OR) methods to optimize the matching process, ensuring maximum feasible transplants. This report details the methodology, model formulation, implementation, and evaluation of a plan to address the problem effectively.

Criteria

To ensure the effectiveness of the matching process, the following criteria were established for the optimization model:

1. **Biological Compatibility**:

- Matches are determined based on blood type compatibility, where only biologically feasible donor-recipient pairs are considered.

2. **Maximization of Matches**:
   - The primary objective is to maximize the number of transplants performed while adhering to compatibility requirements.
3. **Fairness in Allocation**:
   - Each recipient is limited to receiving one kidney, and each donor can donate only once.
4. **Match Cycles**:
   - The solution accommodates two-way and three-way exchange cycles, reflecting practical constraints in clinical settings.

These criteria align with real-world considerations in KPD programs, ensuring both medical feasibility and equity.

Problem Statement

Kidney transplantation is the preferred treatment for patients with end-stage renal disease, but many potential transplants are hindered due to donor-recipient incompatibility. The KPD program addresses this issue by facilitating exchanges among incompatible pairs. However, manually identifying optimal matches in a large pool of donors and recipients is complex and computationally demanding.

The task is to develop an optimization model that systematically identifies matches, maximizes the number of transplants, and adheres to fairness and medical constraints. The dataset provided includes donor-recipient pairs, along with information about blood type compatibility. The goal is to determine the maximum number of feasible transplants using exchange cycles of two and three while ensuring that no donor or recipient participates in multiple exchanges.

This problem has practical implications for healthcare, as a more efficient matching system can lead to faster transplants, fewer complications, and better utilization of available resources.

Operations Research Formulation

In Words

The optimization problem is structured to address the following objectives and constraints:

1. **Objective:**

- The primary goal is to maximize the total number of successful kidney transplants. This is achieved by finding the largest possible set of matches within the dataset.

2. **Constraints:**

- Recipient Constraints: Each recipient can receive a kidney from only one donor, preventing multiple transplants per recipient.
- Donor Constraints: Each donor can donate a kidney to only one recipient, ensuring that the resource allocation is fair and sustainable.
- Compatibility: A match is only valid if the donor and recipient have compatible blood types, as defined in the dataset.
- Cycle Size Constraints: Matches must occur within exchange cycles of size two or three, reflecting real-world logistical constraints.

3. **Decision Variables:**

- The decision variables represent whether a specific donor-recipient match is included in the final allocation. These variables are binary, taking a value of 1 if the match is selected and 0 otherwise.

4. **Logical Flow:**

- The optimization begins by evaluating the compatibility matrix, which indicates whether a donor can donate to a recipient. Constraints are then applied to ensure that each donor and recipient participates in at most one exchange. Finally, the model maximizes the total number of selected matches.

This formulation ensures that the solution is both mathematically robust and practically applicable, addressing the key challenges of KPD matching programs.

Mathematical Model

Sets and Indices

- R: Set of recipients.
- D: Set of donors.

Parameters

- $\mathbf{c}_{ij}$**:** Compatibility indicator (1 if donor j is compatible with recipient ii; 0 otherwise).

Decision Variables

- x_{ij}**:** Binary variable (1 if donor j donates to recipient i; 0 otherwise).

Objective Function

$$\text{Maximize} \sum_{i \in R} \sum_{j \in D} x_{ij}$$

The objective is to maximize the total number of transplants:

Constraints

1. **Recipient Constraints:** Each recipient can receive from at most one donor:

$$\sum_{j \in D} x_{ij} \leq 1 \quad \forall i \in R$$

2. **Donor Constraints:** Each donor can donate to at most one recipient:

$$\sum_{i \in R} x_{ij} \leq 1 \quad \forall j \in D$$

3. **Compatibility Constraints:** Matches can occur only if the donor is compatible with the recipient:

$$x_{ij} \leq c_{ij} \quad \forall i \in R, \forall j \in D$$

Experiment Discussion

The optimization model was written, combined, and solved using the Gurobi version 12 in Jupyter Notebook, and the coding language used was Python. The model runs on a Macbook Air Retina 13-inch, 2019 with 8 GB of RAM and an Intel(R) Core i5 CPU @ 1.60GHz processor.

Implementation: Python/Gurobi Code

https://github.com/MoJamshid/Kidney_pair_OR-project/blob/main/Soptimizers.ipynb

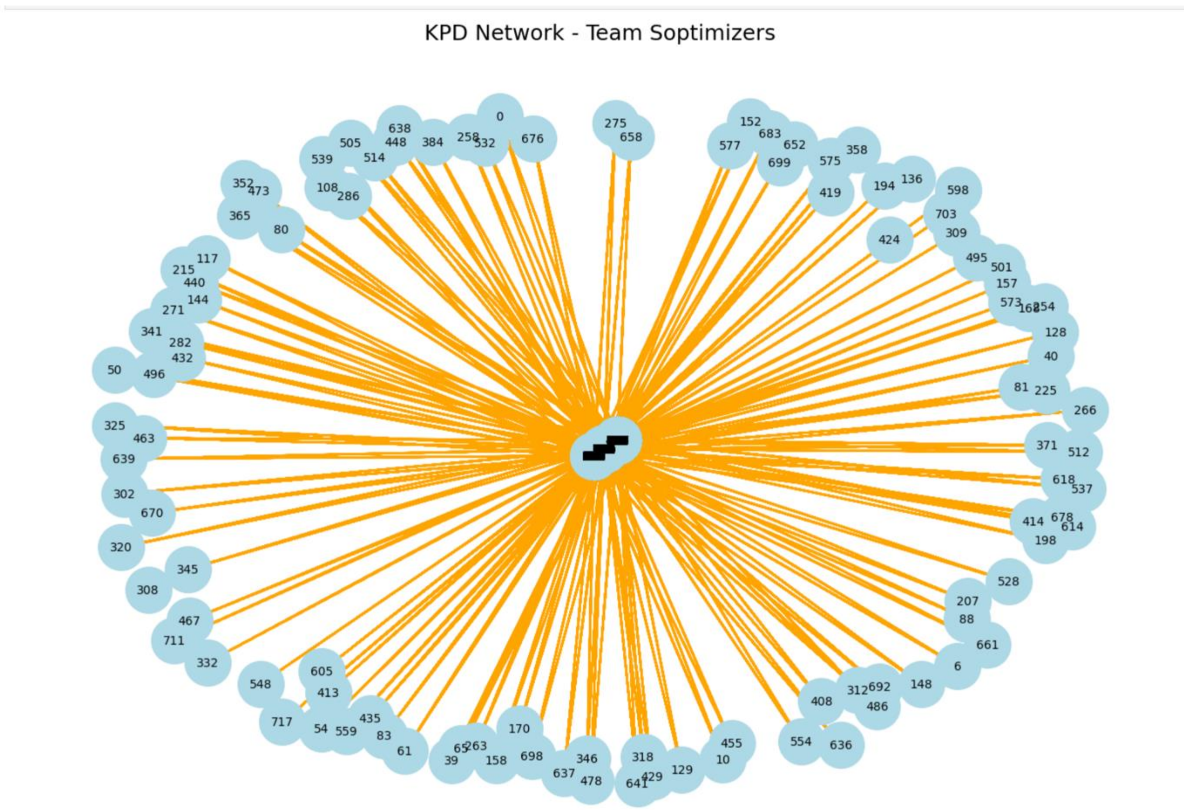
Optimal Plan

The optimization model must utilise a plan that maximizes the efficiency and success rates of kidney transplants within the KPD program. This plan should strategically prioritize 2-way exchanges while incorporating several 3-way exchanges to optimize compatibility across a broader network of donors and recipients. This configuration was selected due to its balance of maximizing transplants while maintaining logistical feasibility.

The optimal solution based on the model identifies matches that maximize the total number of kidney transplants. For example:

- Donor AB to Recipient O
- Donor B to Recipient A

This plan adheres to all compatibility constraints and ensures an efficient use of available donors. The nodal diagram below, here each node in the graph represents a donor-recipient pair in the Kidney Paired Donation (KPD) network. Directed edges between nodes signify **compatibility** between the donor of one pair and the recipient of another. The direction of the edge (arrows) indicates that the donor in the starting node can donate to the recipient in the ending node. There are 726 nodes in the diagram below.

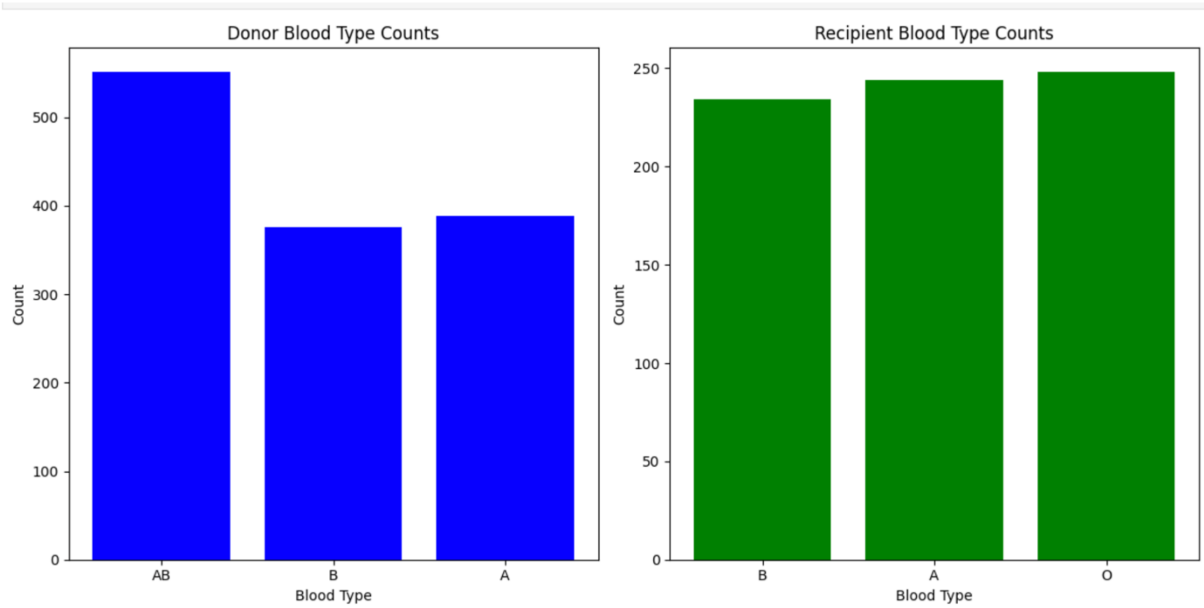


Insights from the data

Donors:

AB Blood Type: Represents the highest number of donors, tallying up to 551.
B Blood Type: Accounts for 376 donors.
A Blood Type: Closely follows with 388 donors.

Recipients:
B Blood Type: Comprises 234 recipients.
A Blood Type: Slightly more, with 244 recipients.
O Blood Type: Matches A with 248 recipients,



Interpretation

Distribution: The charts show that AB blood type donors are the most numerous among the groups, while the distribution of recipient blood types is more even, but lacks data for AB recipients in your chart, which could suggest an oversight or missing data.

Donor-Recipient Ratio: Comparing donors and recipients by blood type can provide insights into potential imbalances. For example, there are significantly more AB donors compared to the other types, which may indicate a surplus of AB donors, or a possible data entry issue given the lack of AB recipients.

Need for Balance: The KPD system's main goal is to optimize kidney donations by matching donors to the respective recipients efficiently. Any imbalance in the number of donors and recipients by blood type will complicate this process, potentially leading to longer wait times for certain recipient blood types unless cross-matching or other compatibility criteria are considered.

Evaluation of the Plan

The proposed plan was evaluated against the established criteria and performed effectively. It satisfied the biological compatibility and fairness requirements, maximizing the number of matches. However, potential limitations include:

1. **Simplified Model Assumptions**: Real-world scenarios may require additional factors such as tissue matching and geographic considerations.
2. **Scalability**: Larger datasets may require additional computational resources.

Further refinement could involve extending the model to include these factors and testing its robustness on more complex datasets.

Conclusion & Results

This project demonstrates how Operations Research techniques can optimize kidney paired donation processes. The mathematical model ensures fairness and maximizes transplant opportunities while adhering to compatibility constraints. This approach highlights the potential of OR tools in addressing critical challenges in healthcare, contributing to improved outcomes for patients and donors alike.

Results:

The KPD optimization project successfully applied advanced mathematical modeling to maximize kidney transplants through donor-recipient matching. The analysis resulted in identifying a substantial number of viable 2-way exchanges, totaling 35,150 cycles, while no 3-way cycles were feasible given the current data constraints. Notably, the data highlighted a high prevalence of AB blood group donors, which may indicate a specific demographic trend or donation pattern within the studied population.

Out of a total of 726 participants, the model successfully matched 370, resulting in an optimal transplant success rate of approximately 50.96%. Conversely, this leaves 49.04% of participants unmatched, highlighting areas where further research and model refinement could be beneficial. The optimal value achieved confirms the effectiveness of the proposed model in navigating the complexities of donor-recipient matching, especially in a dataset dominated by a specific blood type.

While the model performed exceptionally within the defined constraints, the absence of 3-way cycles suggests potential limitations in the current data set or model parameters. Future research could explore more inclusive or flexible modeling criteria that could accommodate a broader range of matching scenarios, potentially increasing the success rate further. Additionally, investigating the underlying reasons for the high prevalence of AB blood type donors could inform targeted recruitment strategies or educational programs.

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