TEXAS TECH UNIVERSITY

Industrial Engineering™

Optimizing kidney paired donation using OR techniques

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1. Introduction:

End-stage renal disease affects a great deal of the worldwide population. Kidney transplantation, in comparison to dialysis, has a higher survival and quality of life for patients suffering from ESRD. However, because of high demand and a limited supply of cadaveric kidneys, long waiting lists have arisen. By December 2010, the OPTN reported that more than 87,000 kidney transplant candidates were awaiting a transplant on waiting lists in the U.S., against approximately 10,000 transplants from deceased donors performed in that year. This supply-demand imbalance underlines the urgency in exploring alternative strategies such as KPD to reduce reliance on deceased donor kidneys.

KPD has become an important strategy to increase the number of donor candidates. It allows those patients with willing but incompatible donors to exchange kidneys with other pairs who are similarly incompatible, so that matches can be facilitated, thereby avoiding the waitlist. Success in a KPD depends on effective pairing, which can be optimized through mathematical modeling along with sophisticated algorithms. This is further highlighted by the fact that nearly 55% of the population in the U.S. is medically ineligible to donate kidneys due to conditions such as hypertension, obesity, and diabetes. In addition, roughly 14% of adults in the United States suffer from chronic kidney diseases, which demands effective systems for matching of Kidney.

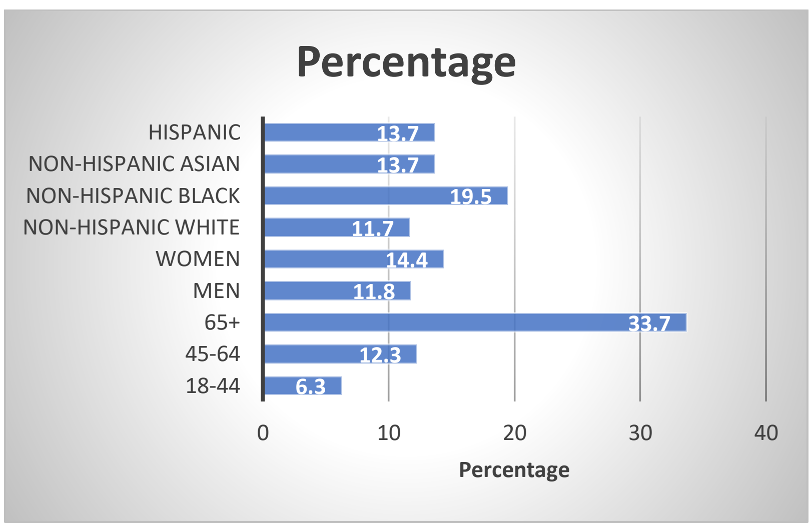

*Figure 1 Percentage of US Adults Aged 18 Years and Older with CKD, * by Age, Sex, and Race/Ethnicity.*

This proposed project meets that need by providing a system to match kidney donors and recipients on a national basis, using medical and blood type information for the best possible matches. For example, the following case could be considered: in Family 1, the grandfather with blood group AB needs a kidney, but his donor has blood group B, and thus cannot donate directly. At the same time, in Family 2, the son with blood group B needs a kidney, but his donor has blood group AB.

A KPD system might identify a two-way exchange in this case that would provide each patient with a compatible kidney because both pairs are individually incompatible.

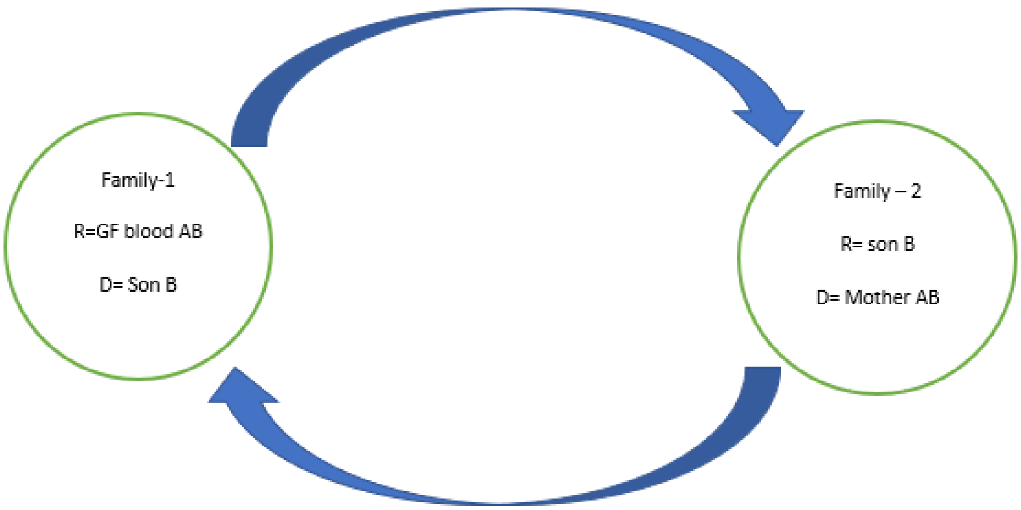

Figure 2 Cycle of 2 Donor Recipient.

Using data-driven algorithms, the project will find this kind of two-pair exchanges in a computationally efficient model the exchanges which then can provide an effective means for approaching the KPD, thereby enhancing transplant rates throughout the U.S.

2. Blood Type Compatibility:

It is very well known that matching kidneys has to do with blood type compatibility. It is all about understanding this blood type compatibility matrix, as shown in Table 1 below, to design an algorithm that will match pairs across blood types. Understanding the compatibility of blood types allows us to define specific model constraints and objectives in order to maximize the match rates within the KPD system.

Table 1: Blood Type Compatibility Matrix for Kidney Transplantation

Donor Blood Type	**Compatible Recipient Blood Types**
A	A, AB
B	B, AB
AB	AB
O	A, B, AB, O

3. Project Objectives and Methods:

This project considers the mathematical modeling of a linear program using operations research (OR) to optimize pairing in Kidney Pairing Donation, KPD. Such a model can save lives in kidney transplantation and reduce wait times for patients by giving maximum rates of successful matches. Using Gurobi as an optimizer and Python for data analysis, this model will check two- and three-pair exchanges and therefore have a strong and effective data-based method of approaching the KPD.

By including blood type compatibility in the model, this research will improve the results in KPD and provide the basis for further practical applications and further research in organ transplantation.

4. Operation Research model (in words and in math):

a. **Decision variables:**

A binary decision variable x_c defining whether cycle is selected or not.

$$x_C = \begin{cases} 1, & \text{if cycle is selected .} \\ 0, & \text{otherwise.} \end{cases}$$

b. **Objective:**

Maximize the total number of matches between donors and recipients.

$$Max \sum_{C} x_C \leq 1 \; for \; all \; C.$$

c. **Constraints:**

Each donor-recipient pair can participate in at most one cycle, Mathematically

$$\sum_{C} x_C \leq 1$$

The following figure gives an idea of our consideration of the cycles of transplants we considered. Essentially 2- or 3-ways cycles could be considered in the unidirectional way and in a periodic cyclic way.

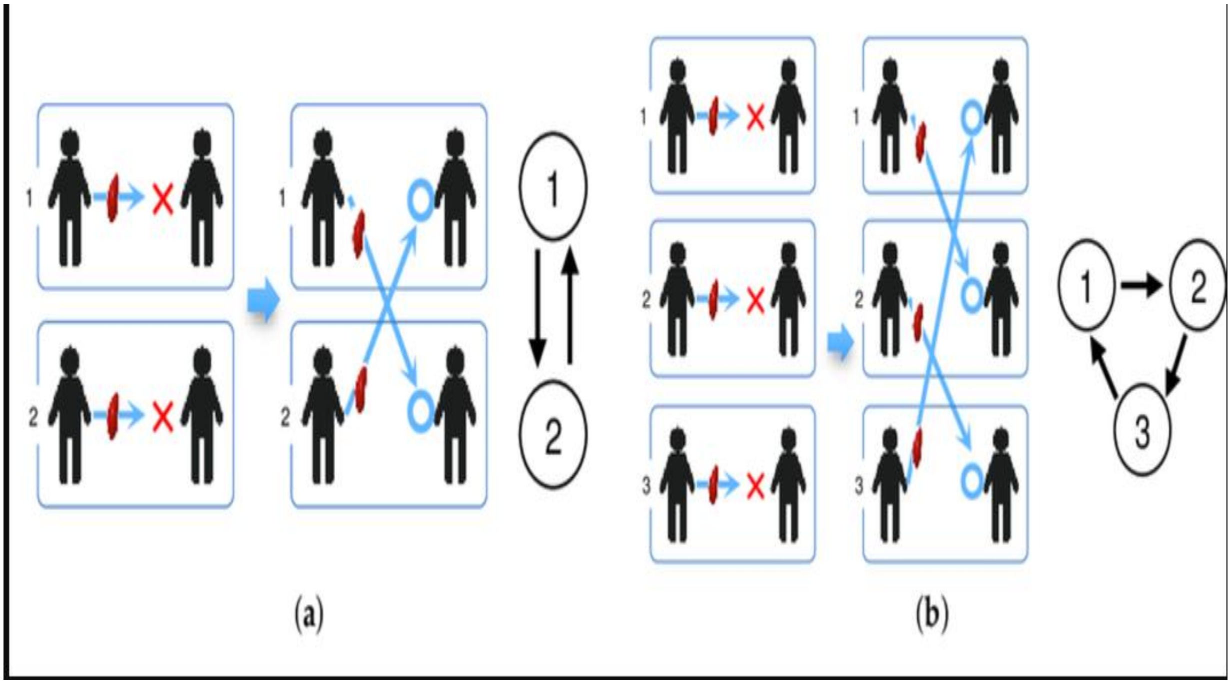

Figure 3 (a) Periodic cycle of size 2 (b) Periodic cycle of size 3.

I. Python/Gurobi Code

The following GitHub repository provides our Python/Gurobi code and data:

https://github.com/Raider9194/OR-Final-Report

5. Experiment discussion: We solved, optimized and wrote the model using Gurobi solver 10.0.3 and the coding language used was python. The model was on the system 11th Gen Intel(R) Core(TM) i7-1355U @ 2.80GHz 2.80 GHz with RAM 16.0 GB.

6. Results: Running the optimization model in Gurobi yields an optimal value of 326 matched transplants (163 each for type A and B). The fairness of this distribution of transplants for blood types are explained better by the following Fig. 4.

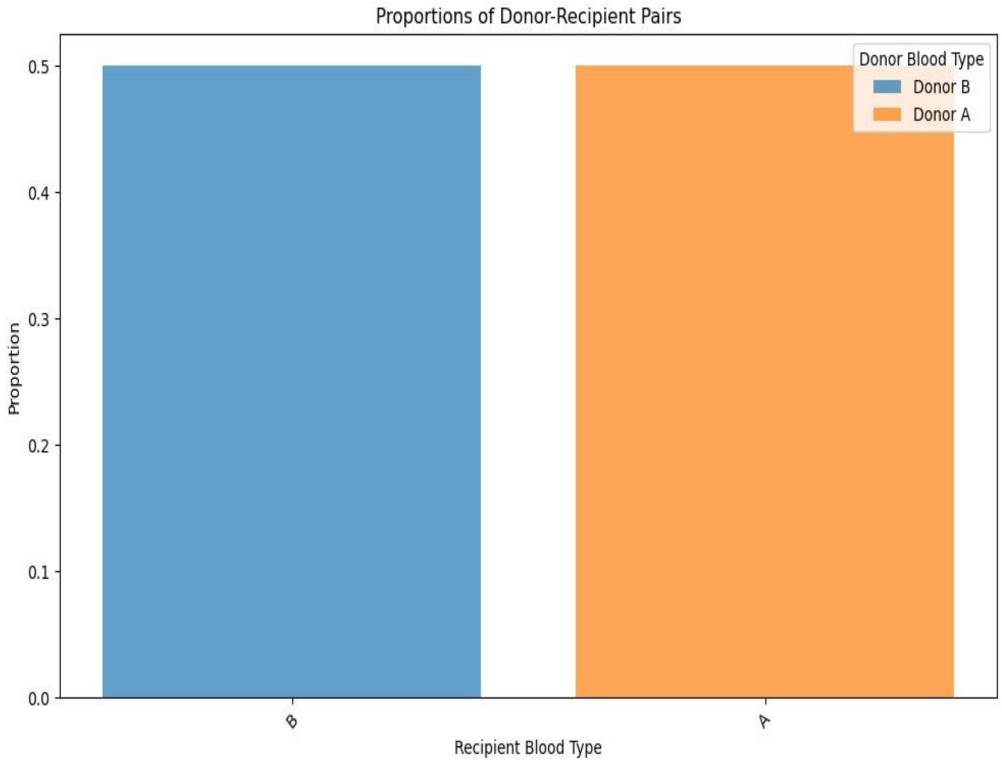

Figure 4 Proportion of successful transplants as per blood types.

In our model, no three-way cycles were found, which means that the data did not support such complex multi-pair exchanges. In the case of two-pair cyclic transplants, the data showed that no successful matches could be established involving blood groups AB and O, reflecting the inherent limitations in compatibility for these specific blood types within the dataset.

7. An optimal plan:

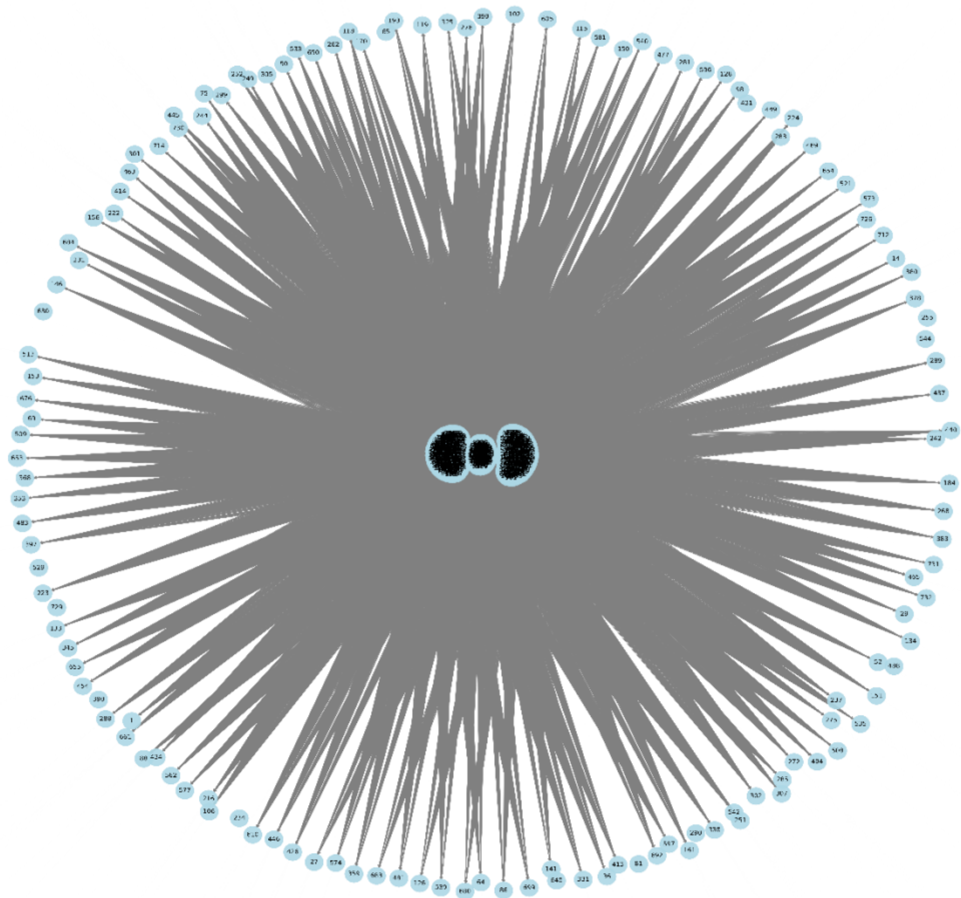

Figure 5 Network of successful kidney transplants, highlighting universal donors at the center connecting to multiple recipients.

Fig. 5 gives a better view of the successful transplants plan in the system. The middle cluster in the graph is constituted by donors with universal compatibility and forms the backbone of the matching since they connect to a wide variety of recipients. These universal donors greatly enhance the efficiency of the system by allowing matches that would otherwise be difficult to achieve. The radiating connections from the center going to the peripheral nodes illustrate how these universal donors facilitated transplants, thus having a higher overall success rate and a robust matching network. This visualization emphasizes the critical role of universal donors in achieving optimal results.

In the end, the model worked out an efficient and fair allocation through strategic cycle selections of the donor-recipient pairs that maximized the number of successful transplants. Optimization was set up with concern for the balance of matching each recipient effectively in a balanced system. This result underlines the strength of the approach in exploiting the compatibility of donors and recipients to their fullest potential and not leaving any opportunity for matches that could have been achieved. The methodology ensured that all the pairs were utilized optimally, leading to this maximum result.

8. Conclusion:

In conclusion, we used mathematical modeling and other OR techniques such as linear programming with Gurobi in python enhancing kidney paired donation (KPD) systems. Our main focus was on blood type compatibility and optimizing the donor to recipient pairings, achieving a maximum pairing of 326 through our modeling, we tried to significantly improve the transplant rates and decrease the wait times. Implementing the cycles of two- and three-way exchanges allowed a more effective way of matching and allocation of kidney and overall improvement of the kidney transplantation process.