DEPARTMENT OF INDUSTRIAL, MANUFACTURING & SYSTEMS ENGINEERING

TEXAS TECH
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Kidney Pair Donation Optimization: Utilization of Operations Research for Kidney Transplantation

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Introduction

Across the United States, there is a surging demand for kidney transplantations. On average, there are 35,000 patients added to the kidney transplant list every year making it the most requested organ. From that list, 4,500 people die due to not being able to find a compatible donor in time. With variables such as blood type, kidney size, kidney availability, and waitlisting, the odds of finding a match jump to 1 in 100,00 people.

The Kidney Paired Donation (KPD) Program is designed to reduce the number of patients waiting for kidney transplants by matching pairs of incompatible donors and recipients with other pairs in a similar situation. Through this system, patients have a significantly shorter wait time and a higher likelihood of receiving a kidney from a living donor rather than relying on a deceased donor.

Established in 1986, the KPD Program has become a standard practice in transplant medicine. To date, it has facilitated over 2,000 kidney transplants. As of October 6, 2024, only 23 hospitals in the United States participate in kidney paired donation programs, with Texas leading the nation by hosting five of these facilities.

Kidney Transplantation Criteria

When a donor organ is put into a patient, it is vital to ensure the blood types of the pair are compatible. If this is not carefully taken into consideration the patient's body will reject the donor organ.

The following blood types are compatible:

- Donors with blood type A... can donate to recipients with blood types A and AB
- Donors with blood type B... can donate to recipients with blood types B and AB
- Donors with blood type AB... can donate to recipients with blood type AB only
- Donors with blood type O... can donate to recipients with blood types A, B, AB and O *(O is the universal donor: donors with O blood are compatible with any other blood type)*

So,

- Recipients with blood type O... can receive a kidney from blood type O only
- Recipients with blood type A... can receive a kidney from blood types A and O
- Recipients with blood type B... can receive a kidney from blood types B and O
- Recipients with blood type AB... can receive a kidney from blood types A, B, AB and O *(AB is the universal recipient: recipients with AB blood are compatible with any other blood type)*

In 1984, the United States Congress passed the National Organ Transplant Act (NOTA). This act sets multiple rules and regulations regarding organ donation such as prohibiting the sale of organs, mandating the Organ Procurement and Transplantation Network (OPTN), funding and granting donation programs, and ensuring equitable organ donation programs based on geography and medical need.

Problem Statement

This project proposes a development to maximize the number of possible and compatible kidney transplantations. As stated previously, utilization of a KPD plan is key to optimizing the number of successful transplantations possible. Operations Research tools and techniques will be implemented into our plan. Our plan will respect typical KPD techniques, but will also obey:

- Biological compatibility within donating blood types.

-Constraining donation group sizes to cycles of 2 and 3 only.

An OR Model (in words and in math)

Our Mixed Integer Programming (MIP) model is a representation of the donor-recipient blood type compatibility problem.

Sets and Parameters

From this we can recognize the sets and parameters necessary to evaluate our model

- N represents the set of nodes (donors and recipients)
- E represents all the possible directed edges, E is a subset of the cartesian product of N x N, ($E \subseteq N \times N$)
- D_n represents the donor blood types of node n, where $n \in N$
- R_n represents the recipient blood type of node n, where $n \in N$
- C(d) represents the set of compatible recipient blood types with donor blood types d, where $d \in D_n$

Decision Variables

In our model we define our decision variable as $y_{ij} \in \{0,1\}$, where x is a binary variable that acknowledges the existence of a node from i to j.

$$y_{ij} \in \{0, 1\}$$

Objective Function

We aim to maximize the number of compatible recipient-donor matches. From this we derived our objective function.

Maximize: $\sum_{(i,\, j)\, \in E} y_{ij}$

Constraints

An edge (i, j) is compatible if the donor (i) can provide a suitable organ for the recipient (j). In the case of our model, we developed an indicator function $\mathbb{1}(R_j \in C(d))$ which evaluates to 1 if R_j is within the compatibility set of d (C(d)), and 0 otherwise.

$y_{ij} \leq \sum_{d \in D_i}^{\mathbb{1}} \left(R_j \,\in\, C(d)\right),\ \forall (i,j) \in E$

Bloody type Compatibility :

$$C(O) = \{O,\ A,\ B,\ AB\}$$

$$C(A) = \{A,\ AB\}$$

$$C(B) = \{B,\ AB\}$$

$$C(AB) = \{AB\}$$

Incorporated into the indicator function, $R_j \,\in\, C(d)$, as shown previously.

No Self-Loops (One cannot donate to themselves)

$$y_{ii} = 0,\ \forall i \,\in\, N$$

Binary Variable Constraint (1 if compatible, 0 otherwise)

$$y_{ij} \,\in\, (0,1)\ \forall (i,j) \,\in\, E$$

Python/ Gurobi Code

The Github repository includes our project Python/Gurobi code & data.
https://github.com/lkaigler/Deterministic-Operations-Research-Project

Experiment Discussion

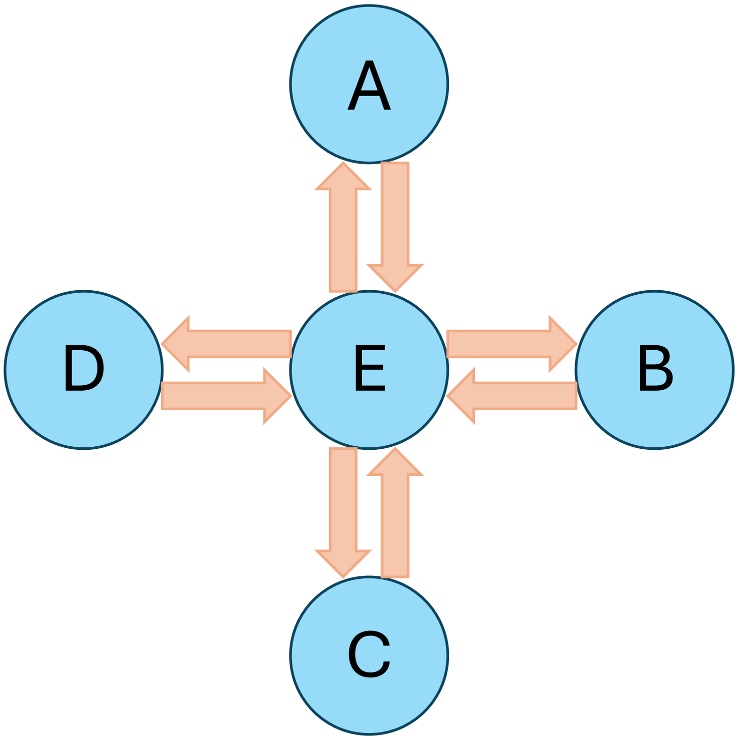
Our optimization model was produced using Python 3.12.4 and Gurobi 11.0. Our scripts were written in Jupyter Notebook and ran on a Macbook Pro with 16 GB RAM and 2.2 GHz 6-Core Intel Core i7 processor. The MIP formulation is solved to optimality with the objective value of 620 cycles of 2 in .17 seconds.

Optimal Plan

In our Mixed Integer Programing model, the first cycle shows every possible solution for donor and recipient combination which is more than the original data set because it includes a donor in multiple possible solutions. That original list, however, does not represent an effective list of the best combinations. For example, O can match with every other type, but AB can only match with itself. When we apply our constraints to the model, it shows the best optimal solution for the donor and recipient combinations. From that combination list, our code can find the most effective amount possible of donor & recipient combinations which is 620 from the original large sample size.

Evaluation of the Plan

Our proposed plan has met all constraints and compatibility rules related to blood type. Every donation pair is compatible with each other, and our model found the maximum number of pairs. Patients with a larger network of people have a higher chance of finding a donor. The same idea is applied to those in need who have blood type O. They can accept from all blood types and have a higher chance of success. Patients that know who their donor will have a significantly greater chance of success than someone trying to find a donor via donor programs, hospitals, etc.



As stated, the diagram above depicts how “E” will have many more transplantation options than those around him. E’s network consists of all involved and has a 100% chance of finding a partner. The rest only have a 25% chance of finding a partner.

Conclusion

This project aims to create the maximum amount of transplantation cycles possible for a given population. The mixed integer program model has determined 620 donor & recipient combinations. By evaluating the data provided, a plan of cycle size 2 has been optimized to find who can pair with who, and how many will be possible.

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