Kidney Paired Donation Consultant Plan

Anderson Carter, Daniel Dealmeida, Harsh Patel

Advisor: Dr. Hamidreza Validi

Department of Industrial, Systems, and Manufacturing Engineering Texas Tech University

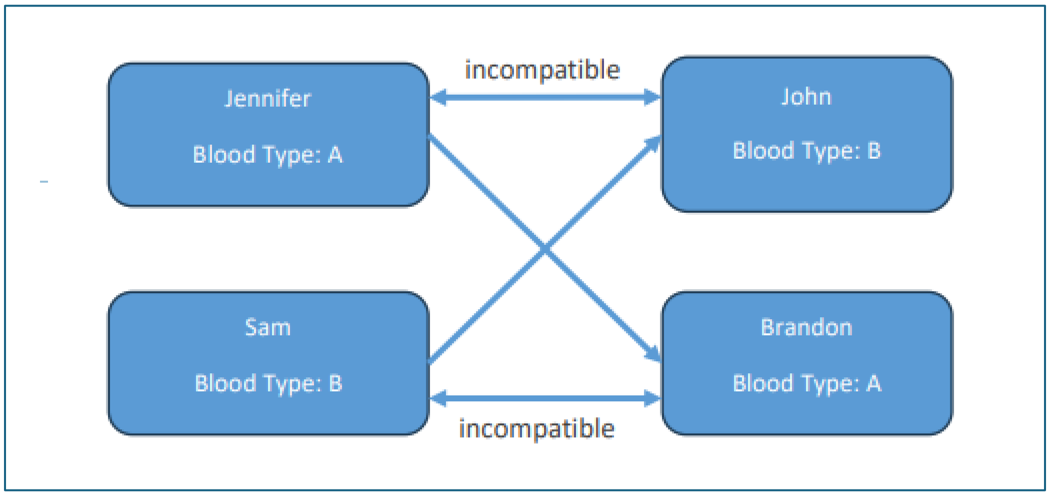
Table of Contents

Introduction

Organ Transplants in the US are needed to improve the lives of patients in need. This is what the Organ Procurement and Transplantation Network (OPTN) is here for. We are a group of Operations Researchers that specialize in Kidney Paired Donation (KDP) for the Kidney Pilot Program. We have been tasked with a pressing challenge in live kidney donation which entails the incompatibility of donors and their intended recipients. This project that we are working on will seek to develop a comprehensive KDP plan that maximizes the number of compatible kidney transplantations using OR techniques and optimization tools.

Kidney Paired Donation will allow patients with willing but incompatible donors to exchange kidneys with other patient-donor pairs in similar situations. By making a network of incompatible pairs, KDP increases the likelihood of finding compatible matches. This in turn expands the pool of available kidneys and improve the outcomes of transplantations.

For instance, take the diagram below that describes a certain situation in which Jennifer wants to donate her kidney to her brother John, and Sam who intends to donate to his colleague Brandon. Due to blood type incompatibilities, neither Jennifer nor Sam can donate to their respective pairs. However, through the KDP exchange process, Jennifer can donate to Brandon and Sam can donate to John, meaning both transplants can happen successfully.



Criteria

The Kidney Paired Donation program is designed to maximize the amount of kidney transplants between donors and recipients. One of the key issues around kidney donations is blood type compatibility. The donor's blood type must be compatible with the recipient for the kidney to be accepted by the body. For example, a recipient with a B blood type can receive a kidney from a B or an O-donor but not an A donor. This criterion is what the model we created is focused on

Another criterion required for kidney transplants is HLA typing focusing on finding matching antigens. They focus on 6 antigens, A, B, and DR antigens. For a better chance of success, the donor and recipient need fewer matching antigens. This is not covered in the model and would have to be considered before the transplant occurs.

Other criteria that need to be considered is the recipient's sensitivity. The more sensitive the recipient's body is the more likely it is to attack the foreign kidney. There are also other considerations like the location of the donor and recipient as that may cause issues for the process.

Problem Statement

The objective is to maximize the pairs of compatible kidney transplants between the incompatible donor and patient pairs. The pairings are based on blood type compatibility. The goal is to match the pairs up to where:

1. Donor from Pair A can donate to Patient from Pair B
2. Donor from Pair B can donate to Patient from Pair A.
3. Exchanges are limited to two-way or three-way cycles

OR Formulation

In this section, we would like to discuss our OR formulations and notations. The formulation seeks to optimize the matchings between pairs. This of course, considers 2 and 3 pair exchanges while adhering to compatibility constraints and ensuring feasibility of the exchange.

We would like to outline our optimization model with formulation and description of its contents. In our model, we will have nodes representing a donor-recipient pair. The edges will represent a direct edge from node *i* to node *j* if the donor *i* is compatible with the recipient *j*. This will of course, determined by our compatibility function that we have chosen to use.

Next, we will define the optimization problem. The goal is to matches the edges such that:

1. Each node can participate in at most one match (donating or receiving)
2. Maximize the total number of matches

After that we would like to incorporate the integer programming model with decisions variables, parameters, the objective function and constraints for our goal.

The Decision variables will only consist of one binary variable x_{ij}.

- x_{ij} = 1; if there is a directed edge (match) from node *i* to node *j*
- x_{ij} = 0; otherwise

The objective function will seek to maximize the number of selected pairs/matches. The formulation will look relatively as such:

- Maximize $\sum_{(i,j)\in G.edges} x_{ij}$

The constraint that is apart of our case is that each node must participate in at least match (either donor or recipient). The formulation for this constraint follows as such:

- $\sum_{j:(i,j)\in G.edges} x_{ij} \quad + \quad \sum_{j:(j,i)\in G.edges} x_{ji} \quad \leq \quad 1; \quad for\ all\ i\ \in G.nodes$
- $x_{ij}\ \in\ \{0,1\} \quad for\ all(i,j) \in G.nodes$

This formulation essentially counts all the matches where node *i* is donating (outgoing edges) and counts all the matches where the node *i* is receiving (incoming edges). Meaning that summing the two parts of the inequality together ensures that node *i* is involved in at least one match. The model will assume that the directed edge (i,j), only exists if donor *i* is compatible with recipient *j* and vice versa.

The binary variable ensures that a donor (i) is matched with a recipient (j). These constraints are important because it makes sure that no pair is involved in more than one transplant, preventing the scenario of mismatching recipients and an overcommitting donor. The binary variable also helps to ensure feasibility meaning the match either happens or it doesn't. So, every donor-recipient pair participates in 1 or no exchanges.

After all this is transferred into python code. We will seek to give an optimized solution matching one patient and their incompatible donor with another in the same situation. The code will be provided via the GitHub repository.

Python/Gurobi Code

The following GitHub repository provides our code used to solve the model.

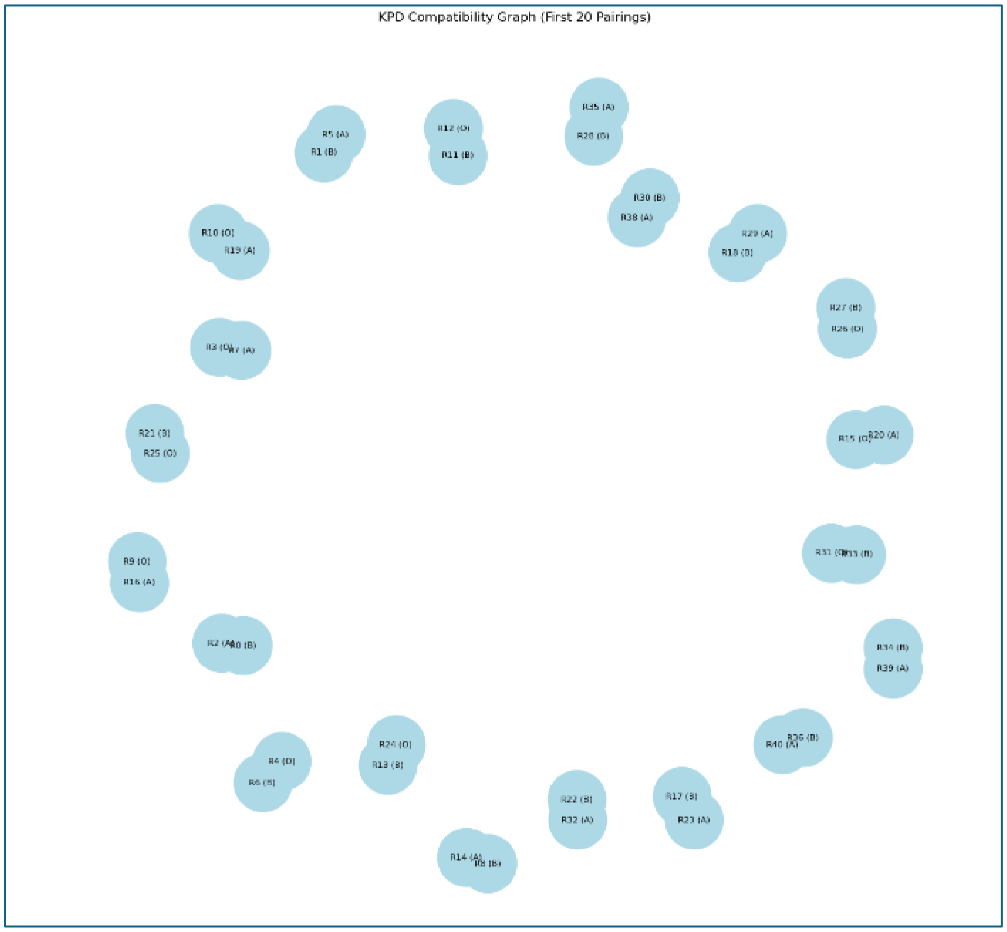
https://github.com/53rdAlchemist/Operations-Research

Experiment Discussion

The optimization model was written and solved using Gurobi version 11.0.3 on Jupyter Notebook using the python coding language. The model was run on an Acer Nitro 5 laptop with 16 GB of ram, 12th Gen Intel Core i5-12500 H @3.10 GHz CPU. The model was solved to the optimal solution in 1.17 seconds.

Plan

The proposed action is to switch the donors of each pairing to form new compatible pairs based on the optimization model created from the experiment. The results depend on the dataset provided to the code. Using our dataset, there were only switching of groups of 2, meaning each pair switched their donors with one pair and there were no chains. The graph shown is of the first 20 pairings of the solution. Using all pairings created a busy graph.



Evaluation of plan

Our proposed plan meets the criteria of blood type. The plan matches up each recipient with a blood compatible donor. Within our plan we thought to only use cycles of 2 meaning pairwise exchanges and not go more than that.

Our plans does not guarantee the other criteria, namely HLA compatibility test and recipient sensitivity. It also does not take into account any extra factors like distance between donor and recipient.

Conclusion

Our project has provided a way to pair up incompatible pairs with other pairs to ensure that each recipient has a compatible donor. It focuses only on blood compatibility to give a baseline availability for kidney transplant and would require the blood compatible pairs further testing before a kidney transplant could go through.

If we wanted to extend the model to include cycles of 3 or additional real-world complexities, we would need to have some sort of prioritization of weights. Meaning that we would need to give weights to certain matches which would mean adding another variable in the objective function. But for this task we went with baseline blood compatible pairs