IE 3311 Final Project

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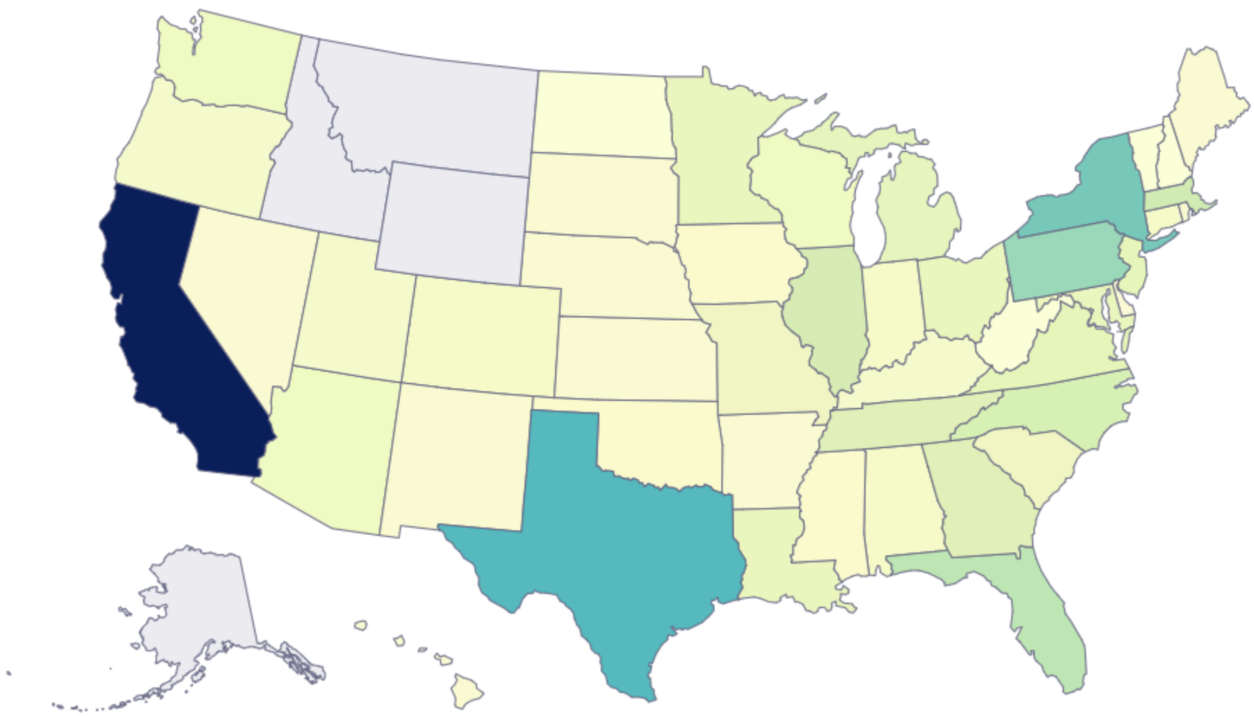
Introduction

Kidney disease is a major health concern in the United States, and for many individuals with end-stage renal disease (ESRD), a kidney transplant is the best option for life. However, the demand for donor kidneys exceeds the supply, leaving many patients waiting for years. Even if a patient has a willing donor, compatibility difficulties such as incompatible blood types or antibodies may preclude a direct transplant. Kidney Paired Donation (KPD) programs offer a remedy by allowing patients with incompatible donors to swap kidneys with other donor-recipient pairs experiencing the same issue. This procedure ensures that each patient receives a compatible kidney while the donors continue to play an important role in saving lives.



https://worldpopulationreview.com/state-rankings/kidney-transplant-waiting-list-by-state

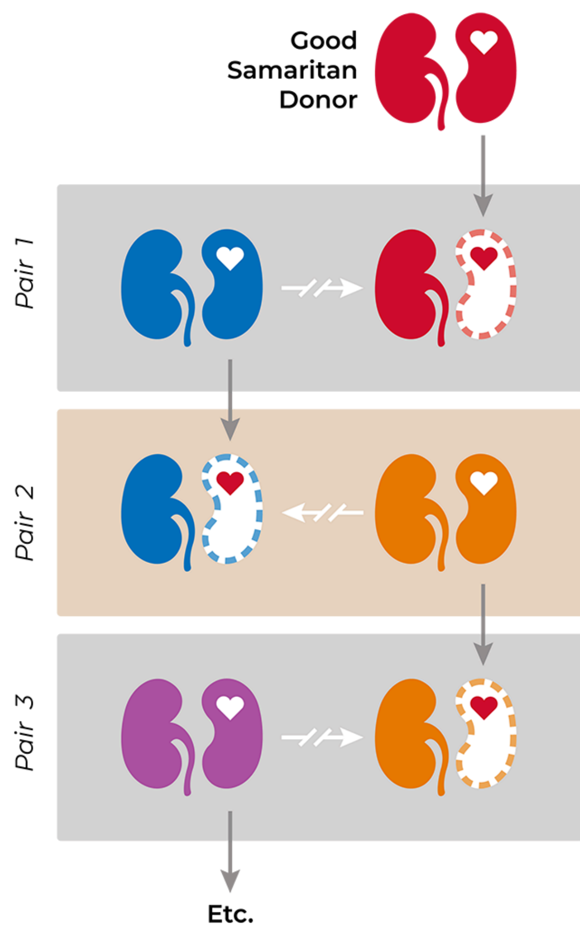
The graph above shows the waitlist candidates from each state; the darker the color, the more people are waiting for a transplant. As you can see, California and Texas are in need of the most at around 26000 people, and places like Idaho and Montana do not need as much

The Organ Procurement and Transplantation Network (OPTN) coordinates these exchanges through the KPD Pilot Program. The program's primary goal is to enhance the number of successful transplants by identifying the best possible match between donors and recipients. To do this, modern techniques such as optimization algorithms and data analysis are used to develop effective matching tactics. The procedure entails handling complex elements like donor compatibility, time limits, and logistical considerations, all with the goal of increasing the number of successful transplants and providing the best possible outcomes for patients.

This project focuses on creating a Kidney Paired Donation Plan that increases the number of successful transplants within a particular network. Using operations research methodologies, the goal is to improve the efficiency of the live donor procedure, allowing more patients to get life-saving transplants. Applying these tools has the potential to greatly enhance patient outcomes and the overall organ donation system, emphasizing the importance of data-driven decision-making in healthcare.

Kidney Transplant Criteria

Eligibility for a kidney transplant is based on several key factors, which include medical, psychological, and practical considerations. These factors are all important to ensure that patients receive the best possible outcomes from their transplant.



https://www.kidneyregistry.com/wp-content/uploads/2021/02/samaritan.png

The primary medical qualifying requirement is the necessity for a kidney transplant owing to end-stage renal disease (ESRD). This condition indicates that the kidneys no longer function adequately to keep the person healthy, necessitating dialysis. In addition to requiring a transplant, patients must be healthy enough to endure surgery and tolerate long-term immunosuppressive treatment. Some medical issues, like active cancer, severe heart or lung illness, or continuing infections, may preclude a person from receiving a transplant (OPTN, 2024).

In addition to physical concerns, psychological and social elements are taken into consideration. Kidney transplant candidates must have the mental and emotional capacity to follow medical instructions following the transplant, such as taking medications and attending frequent checkups. A robust support system, such as family or friends, is also essential to assist the patient during their rehabilitation and ensure that they continue to care for themselves in the long run (OPTN, 2024). This evaluation assures that patients are not only physically ready for the transplant but also mentally prepared for the obligations that would follow.

Another important aspect of eligibility is the patient's lifestyle. While a history of substance abuse doesn't automatically rule someone out, those who have been sober for a significant period and are actively in recovery may still be eligible for a transplant. The transplant team also looks at whether the patient has a stable home and financial situation, including insurance to cover the transplant and follow-up care (OPTN, 2024). Without these, it can be difficult for patients to get the ongoing care they need after the transplant.

Finally, compatibility is key to finding a suitable donor. The transplant team will test both the blood type and tissue compatibility between the patient and potential donors. If a patient has a donor who isn’t compatible, kidney-paired donation (KPD) might be an option. In this system, two or more patients with incompatible donors can swap kidneys, allowing both patients to receive a compatible organ. This increases the chances of finding a suitable match and can help save more lives (National Kidney Foundation, 2024).

Each transplant program may have specific criteria, so patients should always check with their medical team for detailed information. These requirements ensure that patients are physically and mentally prepared for the transplant and that they will receive the necessary support for a successful recovery.

Project Statement

The main goal of this project is to help as many patients as possible get a compatible kidney transplant by matching them with other pairs who also have incompatible donors. Using the provided dataset, the plan is to create a matching system that makes it easier to exchange kidneys between these pairs. This will help improve patient outcomes and make the live kidney donation process work more smoothly across the United States.

An OR Formulation

Objective Function

Minimize: $\sum_{j} yj$

Constraints

Recipient Requirement: each recipient must receive exactly one unit of blood

$$\sum_{j \in i} xij \ = \ 1 \ \forall i$$

Donor Utilization: A donor (j) can provide blood only if they are utilized

$$xij \ \leq \ yj \quad \forall i, j$$

Compatibility: Only compatible donor-recipient pairs can be considered for xij. If donor j is not compatible with recipient i, xij = 0

Binary Variables: All decision variables must be binary

$$xij, yj \ \in \ \{0, 1)$$

Example Problem Setup

Assume:

Recipients i = 1, 2, 3

Donors j = 1, 2, 3

Objective Function

$$\text{Minimize } \sum_{j=1}^{3} yj$$

Constraints

Recipient Requirement:

$$x_{11} + x_{12} = 1 \ (Recipient\ 1)$$

$$x_{22} + x_{23} = 1 \quad \text{(Recipient 2)}$$

$$x_{31} + x_{33} = 1 \quad \text{(Recipient 3)}$$

Donor Utilization:

$$x_{11} \leq y_1,\ x_{12} \leq y_2 \quad \text{(Recipient 1)}$$

$$x_{22} \leq y_2,\ x_{23} \leq y_3 \quad \text{(Recipient 2)}$$

$$x_{31} \leq y_1,\ x_{33} \leq y_3 \quad \text{(Recipient 3)}$$

Compatibility

$$x_{13} = 0,\ x_{21} = 0,\ x_{32} = 0$$

Binary Variables

$$x_{ij}, y_j \ \in \{0, 1\}$$

Python/Gurobi Code

https://github.com/Maximilian3a/3311-Final-Project/blob/ccb9927dfdef3cfb7f318f63129e42a0e64b8112/3311%20Kidney%20Transplant%20Final-checkpoint.ipynb

Experiment Discussion

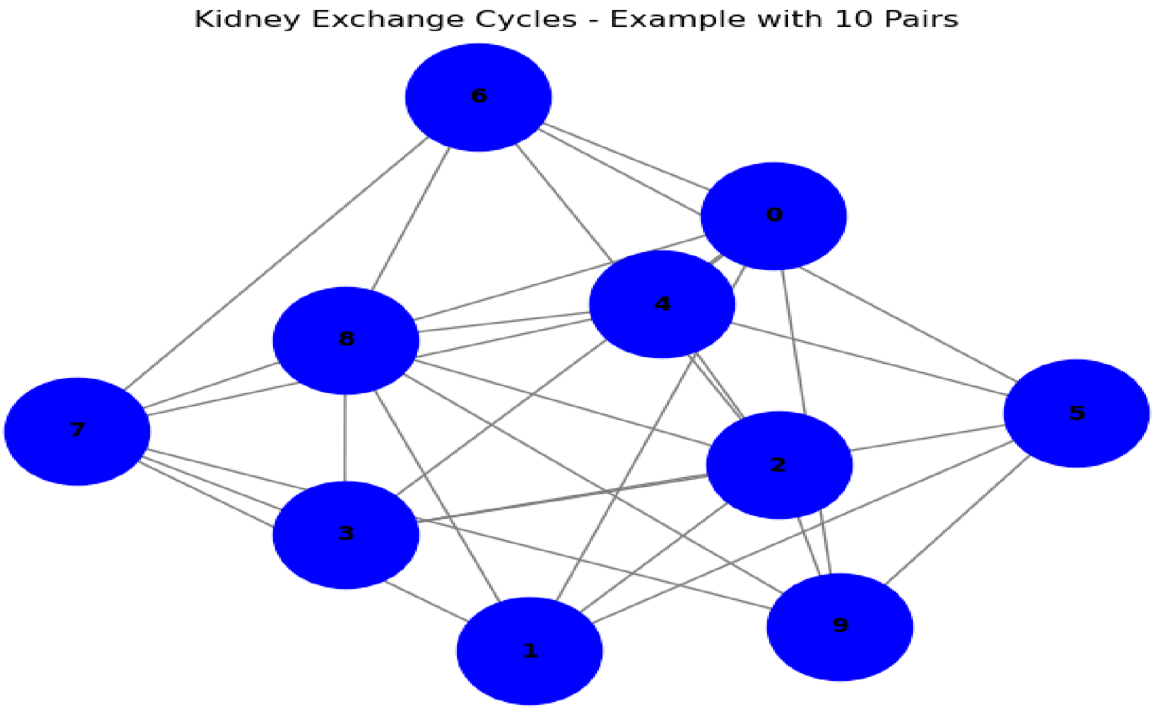
The optimization model was written using Gurobi Optimizer version 11.0.3 build V11.0.3rc0 (win64 - Windows 11.0 (22631.2)) in Jupiter Notebook using the coding language Python. A CPU model: Intel(R) Celeron(R) N4120 CPU @ 1.10GHz, instruction set [SSE2] was used to complete this code. It had a presolve time of .62 seconds.

An Optimal Plan & 10-Unit Sample Diagram

Based on the plan figured by the Gurobi optimization model, we come to the outcome of 2 pair models, which include:

[1, 12], [3, 8], [9, 15], [10, 19], [16, 18], [17, 37], [22, 33], [24, 35], [25, 43], [26, 61], [29, 42], [30, 31], [36, 51], [38, 53], [39, 54], [40, 44], [47, 68], [52, 67], [55, 93], [56, 73], [59, 62], [64,78], [65, 74], [66, 85], [71, 84], [76, 100], [87, 89], [88, 92], [94, 97], [96, 107], [99, 110], [104, 113], [105, 118], [108, 124], [111, 136], [117, 144], [119, 134], [121, 123], [122, 141], [126, 161], [127, 138], [132, 183], [139, 145], [142, 170], [149, 177], [150, 158], [155, 198], [156, 188], [159, 189], [165, 194], [169, 180], [171, 200], [172, 210], [174, 205], [176, 206], [181, 213], [184, 204], [190, 250], [193, 214], [195, 226], [203, 259], [207, 232], [211, 228], [212, 236], [220, 246], [231, 242], [233, 253], [240, 277], [243, 291], [248, 279], [249, 288], [251, 290], [252, 305], [257, 294], [260, 384], [263, 301], [264, 283], [265, 306], [270, 308], [273, 321], [275, 340], [287, 335], [295, 311], [296, 343], [297, 342], [304, 323], [313, 350], [317, 389], [319, 370], [322, 373], [325, 377], [329, 378], [330, 387], [332, 348], [337, 353], [349, 383], [352, 391], [359, 397], [361, 396], [362, 392], [366, 411], [371, 404], [376, 416], [380, 398], [381, 422], [382, 447], [385, 423], [388, 431], [393, 441], [395, 446], [400, 466], [402, 482], [403, 451], [406, 454], [410, 471], [413, 465], [418, 427], [419, 486], [424, 472], [426, 470], [428, 461], [433, 450], [435, 500], [439, 522], [443, 488], [448, 490], [452, 493], [456, 484], [457, 510], [462, 518], [468, 469], [476, 557], [478, 524], [479, 540], [489, 529], [492, 541], [498, 543], [499, 553], [506, 615], [507, 566], [509, 569], [513, 621], [514, 528], [515, 591], [519, 593], [525, 594], [526, 607], [527, 576], [532, 632], [534, 636], [537, 633], [538, 586], [546, 644], [550, 646], [554, 649], [556, 653], [559, 674], [560, 661], [563, 663], [571, 668], [572, 670], [574, 656], [575, 683], [577, 681], [578, 699], [580, 705], [587, 701], [589, 704], [600, 700], [602, 712], [604, 709], [605, 721], [609, 735], [612, 727], [617, 746], [619, 731], [622, 733], [627, 706], [628, 741], [630, 723].

You can then see a representation of what some of these look like based on blood type with the diagram below.



Evaluation of the Plan

The proposed plan would have:

- Tolerance of 1E-4
- Removes human error when choosing the optimal path for donors and recipients
- Produces results much quicker than if doctors had to make these decisions
- Allows for cost savings due to speed and efficiency
- Allows for doctors to analyze hundreds of donors and recipients within seconds
- Mitigation of risks
- Would only have 2 donor/recipient cycles

Please note that with this plan we cannot guarantee the following:

- Immediate results
- Complete removal of risks
- Full understanding based on the provided diagram, as this provides a snapshot of the plan, not a complete analysis
- Outside factors, including patient feelings, opinions, or preferences

Conclusions

While this plan shows a lot of potential, there are definitely some concerns that we have mainly the lack of 3 pair cycles within the optimization model. We believe this is mainly due to the solver's preference for 2-pair cycles, either due to more cycles being possible with 2 pairs or 2-pair cycles generally just being more present and optimal. We do believe though that while the consistency of the 2 pair cycles could be concerning, this could be a large benefit due to outside factors. As mentioned previously, there are numerous factors outside simply blood compatibility, and with 2 pair cycles, there is less of a chance for people's feelings or opinions about donating to complete strangers to be a factor, as with 6 people instead of 4 there is a 33% chance increase of these issues. This can be shown in a medical journal written by the [1]Seoul National University Hospital, which studied 1658 potential donors from 2010-2017 had 902 potential donors back out, and while a majority of 83.8% backed out due to medical factors, a sizable 16.2% backed out due to recipient-related factors. Due to consistent issues such as this, our model only producing 2 pair cycles may very well be a benefit in limiting these types of issues and would lead to more people receiving life-saving kidneys in the end.

[1] **Min, Kyungok, et al. *Barriers to the Donation of Living Kidneys for Kidney Transplantation*, U.S. National Library of Medicine, 14 Feb. 2022, pmc.ncbi.nlm.nih.gov/articles/PMC8844293/. Accessed 03 Dec. 2024.**