Kidney Paired Donation (KPD) Optimization Report

[Final Project]

COURSEWORK: Principles of Operations Research (IE5318)

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Abstract

Optimizing Kidney Paired Donation (KPD) enables an incompatible donor-recipient pair to get matched with another pair to increase the availability of another kidney. This project highlights an Operations Research approach for maximizing the number of compatible kidney transplants in the United States. Using Gurobi and cross-checking for accuracy using Python, we formulated and solved integer programming models to find optimal 2- and 3-way exchange cycles that respect compatibility and cycle size constraints. The open operational methodology with detailed input data, code, and results descriptions can enable reproducibility and future research. We present a systematic review of the proposed KPD plans based on optimization techniques, which improves the efficiency of the overall live kidney transplantation process, and results in novel contributions.

Background Information

Kidney transplantation is the most sustainable treatment for patients with end-stage renal disease, conferring better quality of life and mortality rates relative to prolonged dialysis. Not all patients, however, can receive a kidney transplant because they are incompatible with their willing but biologically mismatched donors. Kidney-paired donation (KPD) programs were created to combat this challenge. These programs allow incompatible donor-patient pairs to swap organs, vastly increasing the odds of successful transplants.

The OPTN is responsible for organ transplantation coordination. North American Numbering Plan OPTN is the data set registered under the US at the primary level. The KPD pilot program will maximize transplants by optimizing matching between incompatible pairs. This is a crucial step that we should take to improve transplant outcomes and meet the growing demand for kidney transplants in this country.

Problem Statement

This project aims at an efficient Kidney Paired Donation (KPD) solution and an optimal kidney exchange cycle in incompatible donor-patient pairs. Using a dataset provided of these pairs along with their compatible donors, the goal of the model is to maximize the number of successful transplants from optimal exchanges— currently allowed to be either pairs of two or pairs of three. This work solves the optimization problem using Operations Research methods to ensure that the proposed solution is efficient and meets the cycle size limits for practical application. Our key constraints include:

- Donor-Recipient Participation Constraints: Each donor-recipient pair can participate in at most one transplant exchange.
- Cycle Size Constraints: Exchanges must be two or 3-way cycles due to medical and logistic considerations.

Background Research

Kidney transplantation is a pressing healthcare challenge: More than 90,000 people in the US are awaiting kidneys, with wait times of 3 to 10 years for deceased donors. Kidney Paired Donation

(KPD) allows for living donor transplants that provide a much quicker answer, lasting 20-40 years. Using sophisticated matching algorithms, organ matches by KPD programs exchange donors between incompatible pairs, minimizing disparities and maximizing outcomes. However, financial fears, concern for job security, and worries about recovery, especially for women, are holding back participation. Incentives include childcare assistance, wage reimbursement, and tax credits.

Compatibility testing is still a cornerstone, including blood type matching, human leukocyte antigen (HLA) typing, and crossmatching, which help pairing succeed. Tools such as KPDGUI complement KPD by incorporating new optimization objectives, uncertainty treatment, and real-time management capabilities. To increase the efficiency of kidney exchanges, the software visualizes alternative solutions and provides fallback options in case of failed matches. It shows great promise for improved equitable access to transplants, operational efficiency, and long-term outcomes.

Thus, KPD and tools such as KPDGUI are examples of the utility of operations research in developing scalable solutions to complex logistical and ethical problems in healthcare. "These patients are the critical intersection of optimization, healthcare equity, and life-saving innovation, improving kidney transplant rates and the overall quality of kidney donation programs.

Methodology

Finding an optimal solution involves various steps, starting with preparing the data and finishing with Gurobi optimization.

Data Compatibility and Processing Checks

- Parsing the Data: For the dataset, every record contains an incompatible pair and a list of potential donors (from the dataset). If a recipient is incompatible with its original donor but compatible with other donors in the entire sample, we check each donor-recipient pairing.
- Establishing Compatibility Criteria
  - Blood Type Matching: Blood type compatibility is the primary compatibility criterion in this dataset. As a potential swap, the blood types of the recipient and donor would need to be compatible.
  - Other Factors: In a more advanced model specific compatibility factors, such as various tissue types or levels of specific antibodies, would also be factors for potential matching.
  - Creating Model Data: We arranged the parsed data into dictionaries, where every recipient has a list of potential donors. This format gives us a Gurobi model with efficiently defined variables.

Model Formulation in Gurobi

Python/Gurobi Code

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

https://github.com/btarin12/EfficientInnovators

The model formulation involves defining decision variables, setting an objective function, and applying constraints to achieve the desired solution.

Decision Variables

Let $\boldsymbol{x_{uv}}$ be a binary variable, where:

$\boldsymbol{x_{uv}} = 1$ indicates a transplant exchange between recipient $\boldsymbol{u}$ and compatible donor $\boldsymbol{v}$.

If: $\boldsymbol{x_{uv}}$, no exchange is made

Objective Function

The objective is to maximize the number of transplants by summing up all selected exchanges:

$$Maximize \sum x_{uv}$$

This function aims to select the maximum number of viable exchanges based on compatibility criteria.

Constraints

1. Participation constraint: Each donor-recipient pair can be involved in only one match to prevent overlapping exchanges, which is unacceptable.
$$\sum x_{uv} \leq 1 \; for\ each\ i\ and\ each\ compatible\ j.$$
2. Cycle Size Constraint: 2-way-cycles: a 2-way exchange between pairs *(u, v) and (v, u)*, if:
$$x_{uv} = 1 \; and \; x_{vu} = 1$$
This model prohibits additional connections between pairs to prevent larger cycles. For 3-way cycles, similar constraints restricted cycles to exactly three pairs, ensuring we complied with the cycle size limit.

Code Implementation

Conceptualizing the KPD optimization model in Python using Gurobi

Explanation:

- Variable Definition: Binary variables for potential recipient-donor match were defined
- Objective function: The function maximizes the sum of all matches; hence, the objective is to select the maximum number of compatible exchanges.
- Constraints: There can only be one donor per cycle per recipient. Further constraints enforce that only 2-way and 3-way cycles exist in the final solution.

Results and Analysis

When running the model, Gurobi gives an optimal solution that enables successful matches for kidney exchanges.

Results Summary:

Total Matches: The model successfully matched 366 pairs.

- Cycle Types
  - 2-way cycles: 366 Y cycles identified as 2-way matches
  - 3-way cycles: 0 Z cycles matched a combination of A, B, and C

```
Optimize a model with 1434 rows, 175159 columns and 315703 nonzeros
Model fingerprint: 0x2fe92201
Variable types: 0 continuous, 175159 integer (175159 binary)
Coefficient statistics:
  Matrix range     [1e+00, 1e+00]
  Objective range  [1e+00, 1e+00]
  Bounds range     [1e+00, 1e+00]
  RHS range        [1e+00, 1e+00]
Found heuristic solution: objective -0.0000000
Presolve removed 684 rows and 104137 columns
Presolve time: 1.13s
Presolved: 750 rows, 71022 columns, 141669 nonzeros
Variable types: 0 continuous, 71022 integer (71022 binary)

Root relaxation: objective 3.660000e+02, 1865 iterations, 0.50 seconds (0.28 work units)

    Nodes    |    Current Node    |     Objective Bounds      |     Work
 Expl Unexpl |  Obj  Depth IntInf | Incumbent    BestBd   Gap | It/Node Time

*    0     0               0     366.0000000  366.00000  0.00%     -    2s

Explored 1 nodes (1865 simplex iterations) in 2.40 seconds (0.85 work units)
Thread count was 12 (of 12 available processors)

Solution count 2: 366 -0

Optimal solution found (tolerance 1.00e-04)
Best objective 3.660000000000e+02, best bound 3.660000000000e+02, gap 0.0000%
```

Conclusion

The KPD program is an optimal model that pairs incompatible donor-recipient. KPD selectively chooses compatible recipients based on 2 and 3-way exchange criteria, maximizing kidney transplants in this process. This model reduces waste and demonstrates the potential for operations research methods, specifically integer programming, applying them to a real-life scenario. KPD program is a form of applied operations research which further improves public health by increasing the availability of transplant organs.

Future Works

Future efforts could focus on incorporating additional compatibility factors, such as tissue match scores and antibody compatibility, to enhance match precision. Alternative objective functions, like minimizing waiting times or maximizing transplant longevity, should also be explored to align the model with broader healthcare system goals. Furthermore, expanding the scope to include 4-way exchanges could improve match rates, though implementing such complex cycles would require robust management and oversight to ensure their practical feasibility and effectiveness.

References

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