A Simulation-Optimization Framework To Improve The Organ Transplantation Offering System

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Abstract

We propose a simulation-optimization-based methodology to improve the way that organ transplant offers are made to potential recipients. Our policy can be applied to all types of organs, is implemented starting at the local level, is flexible with respect to simultaneous offers of an organ to multiple patients, and takes into account the quality of the organs under consideration. We describe our simulation-optimization procedure and how it uses data from the Organ Procurement and Transplantation Network (OPTN) and the Scientific Registry of Transplant Recipients (SRTR) to inform the decision-making process. In particular, the optimal batch size of offers is determined as a function of location and certain organ attributes. We present results of our kidney model, where we show that, under our policy recommendations, more organs are utilized and the required times to allocate the organs are reduced over the one-at-a-time offer policy that is currently in place.

Introduction

Organ transplants have allowed many transplant patients to extend and improve the quality of their lives by giving them the chance of receiving a functional organ. As of March 2022, there were more than 105,000 candidates on the national waiting list, with a new candidate being added every ten minutes.[1] Figure 1 shows us that even though the number of donations has increased over time, there is still a sizable gap between organ demand and organ supply, which is in part caused by a high discard rate for some organs.[2]

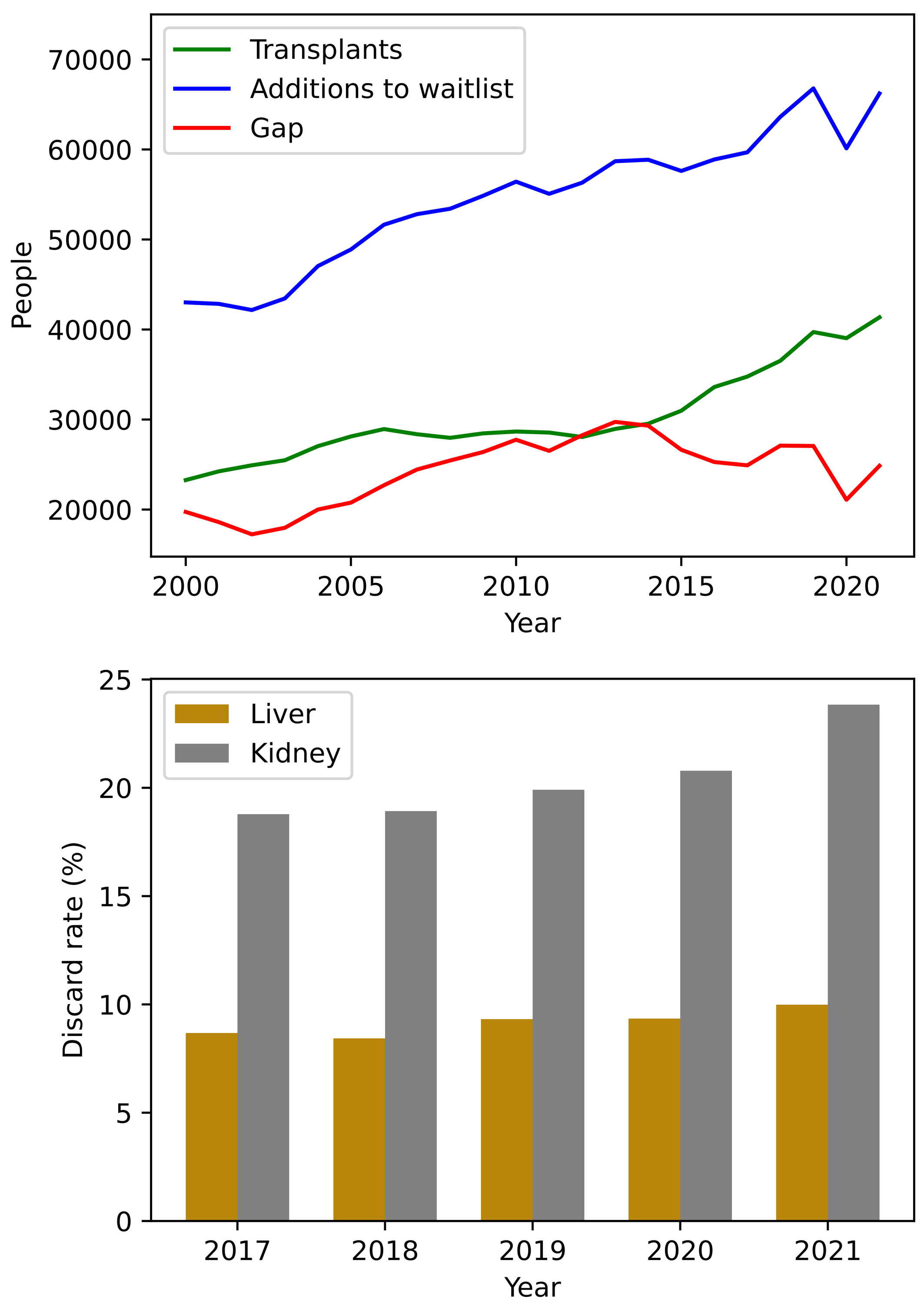

Figure 1. Donations, waitlist additions, and discard rates for kidneys and livers.

Currently, after an organ is procured, the steps are:

1. OPTN generates a prioritized list of patients, based on compatibility and health markers.
2. The organ is offered to the first patient on the priority list.
3. Step 2 keeps being repeated until a patient accepts or until the organ becomes inviable.

Offers expire one hour (thirty minutes under some special conditions) after the offer is made.[3] Because of a high percentage of rejections, many organs end up exceeding their maximum cold-ischemia time (CIT, i.e., the time between the chilling of an organ and the time it is warmed by having its blood supply restored), and are therefore discarded (discard rates for kidneys and livers on Figure 1).

Aim and Objectives

Our main goal is to improve the organ offering system without having to change the prioritization or matching rules. That is, given a particular prioritized list of organ transplant candidates, we will propose and study improvements to the process by which organs are actually offered to those patients. In particular, we seek to:

1. Propose a methodology that takes into account the positive effect of transplanting more organs (i.e., positive "gain"), while considering the costs involved in the offering process as well (i.e., negative "gain").
2. Return policies that optimize the "gain" of the transplantation system for any set of parameters.
3. Provide granular policies that provide recommendations at an organ and local level (versus just at the national level).
4. Evaluate the quality of the extra (versus current baseline) organs being donated.

Data

Both public and private data sources were used to compute all of the needed parameters for the simulation model. This includes:

- SRTR data from the 2018–2019 time period on all donor and wait-listed candidates.[2]
- The organs' arrival process, their distribution with respect to attributes, and the transplantation centers' historical behavior.
- The quality of organs was assessed by using private OPTN data involving the pool of organs donated and organs lost.
- Organ attributes such as being from "donor after cardiac death" or a "hepatitis C virus positive" donor were considered.
- The maximum CIT considered was 16 hours for livers and 40 hours for kidneys.[4,5]

Methodology — Simulation

We built a simulation model that incorporates all the information presented in the data section. We set as input the number, "x", of simultaneous offers for organs and simulate the transplantation system over a one-year period.

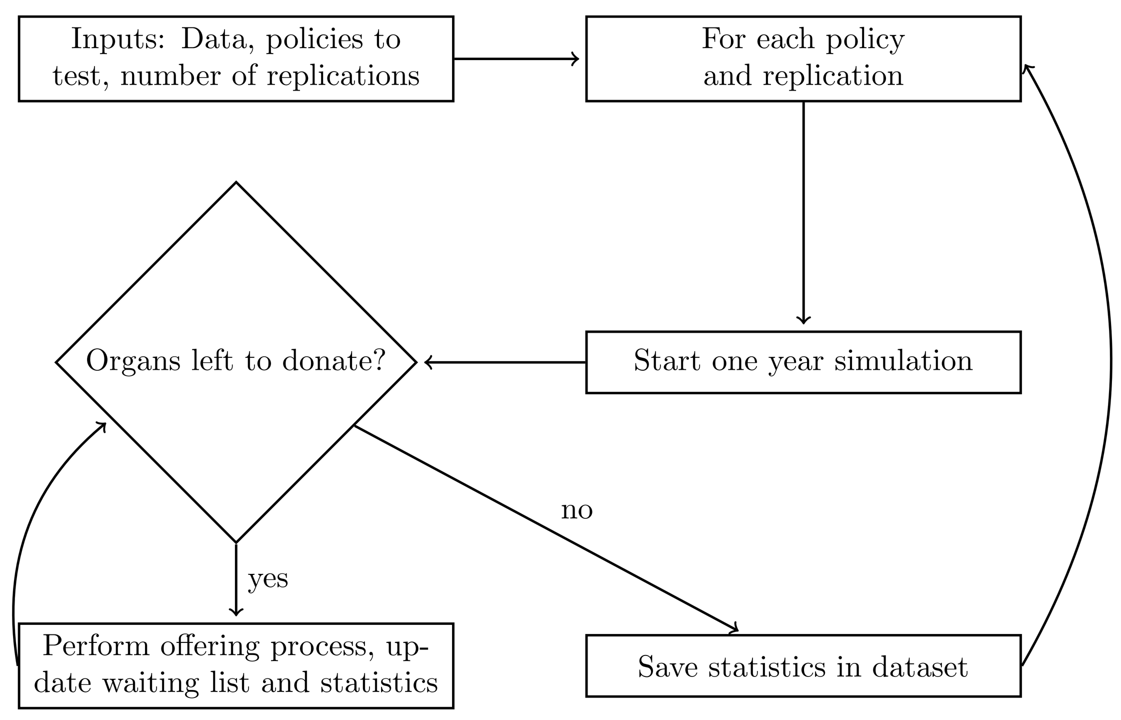

Figure 2. Simulation diagram.

Figure 2 shows a simplified version of the simulation process, and the offering process performed for each organ is summarized in Figure 3. The number of simultaneous offers (policy) is an input for the procedure, and all the other inputs come from real-world data.

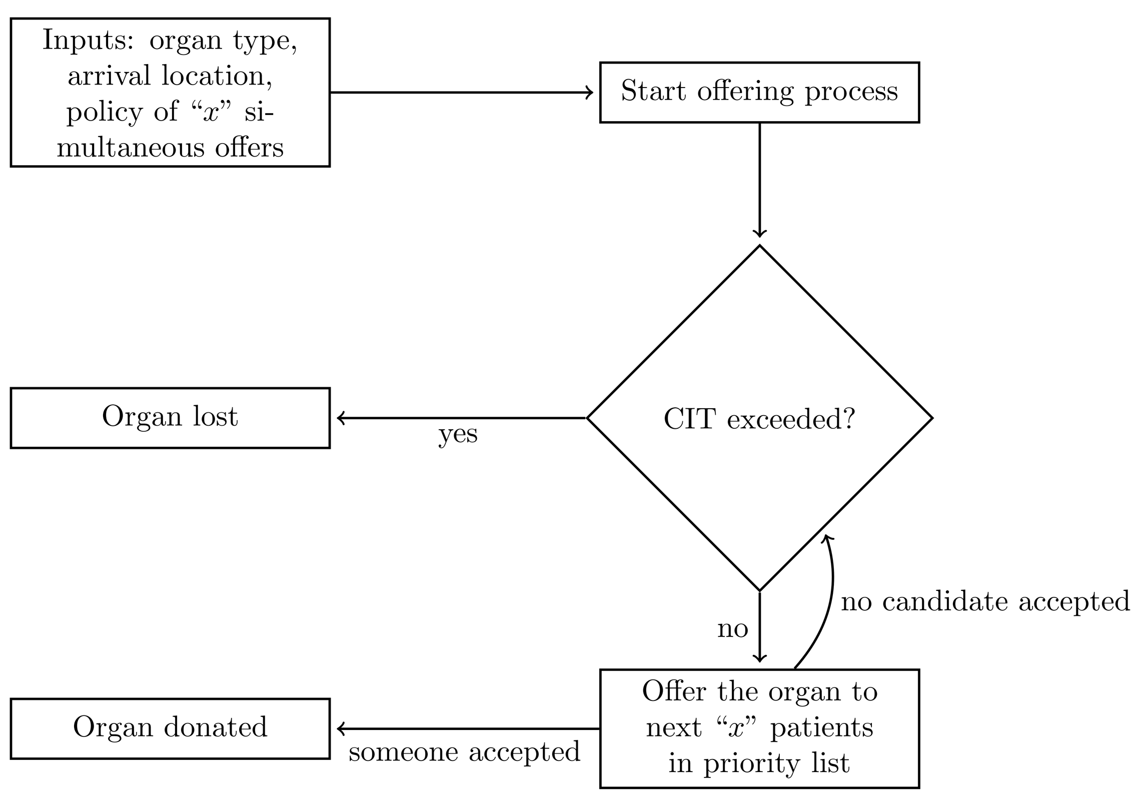

Figure 3. Procedure used to offer organs in the simulation.

Each time an organ is retrieved, then offered and either donated or discarded, we compute the "earnings" of the transplantation system obtained from that process. In particular:

- 1000 units are earned when an organ is transplanted.
- An offer costs 25 units (if it is the first time that organ is offered to one specific transplantation center), and 1 unit otherwise.
- The disappointment cost of a patient who accepted but did not receive an organ is 300.

These seemingly arbitrary earnings/costs reflect the extremely high value a successful transplant has, but also the negative consequences that a disappointed offer may have on the patients.

Methodology — Optimization

The following steps were used to derive a policy that maximizes the expected "gain" of the transplantation system:

1. Simulate many one-year period (replications) using different policies of "x" simultaneous offers.
2. For all replications, record the "gain" obtained for each organ (each organ is one sample in our training set).
3. Using the training set's data, compute the expected value of a policy for a particular (organ attributes, location) pair.
4. Return the policy with the highest expected value for all (organ attributes, location) pairs.

Experiment Results

Our main paper studied our policies' benefits for both the cases of kidney and liver. Figure 4 presents the results for kidney.

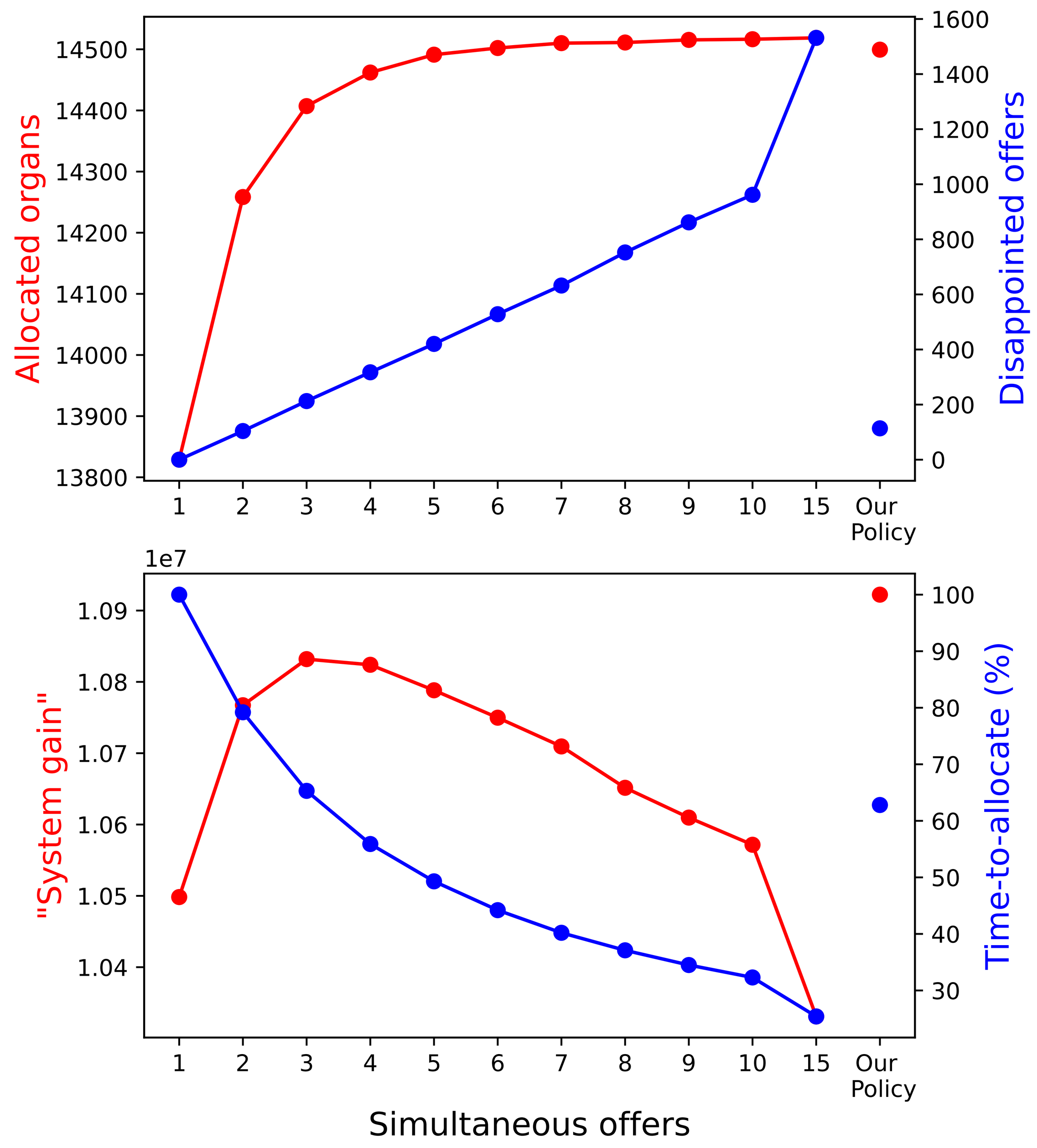

Figure 4. Results over test set for our proposed policy.

- Our policy outperforms the benchmark policy by around 650 allocated organs per year while also reducing the time needed to allocate the organs by 37.2%.
- Our policy induced fewer disappointed offers than most of the other fixed policies and allocated more organs than all of the policies with at most 5 simultaneous offers.

The average age of donors corresponding to discarded kidneys is larger than the average age of donors corresponding to accepted kidneys (53.1 years old versus 37.3); but other health markers are similar. Leading countries such as Spain routinely and successfully use organs donated from patients over 70 years old (+23%),[6] which suggests that a significant number of the discarded organs are of sufficient quality to provide good outcomes.

Conclusions

Our simulation-optimization procedure is able to replicate the behavior of the organ transplantation system in the U.S., and:

- Allows us to obtain a policy that maximizes the "gain" of the transplantation system.
- Provides policy recommendations depending on the attributes of the organ and its arrival location.
- Yields better organ utilization than the current system as well as faster times-to-allocate.

We would expect that more lives could be saved because of the ability to transplant more organs of good enough quality. In addition, as the time-to-transplant is reduced, better outcomes for the recipients can be expected.[7,8]

Future work includes creating a new "gain" function that better represents the trade-offs inherent in the transplantation system and also testing new allocation strategies.

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