The Impact of Information Sharing on Organ Transplantation: A Simulation Model

Zahra Gharibi and Michael Hahsler
Department of Engineering Management, Information, and Systems

INFORMS Annual Meeting 2018
Phoenix, AZ
Motivation

Key Question: Why Is The Kidney Discard Rate in the US Greater Than 20 Percent?

Donor Kidneys are discarded because of:
- Medical concerns
- Kidney allocation process
  - Time to find patient (CIT)
  - Early donor kidney rejection
  - Conditions of Participation (CoP)

Data sources: United Network for Organ Sharing (UNOS)
Motivation
Regional Differences in the US

Data sources: United Network for Organ Sharing (UNOS) and Scientific Registry of Transplant Recipients (SRTR)
Goal
Increase Donor Kidney Utilization

- **Decision maker (patient & surgeon):**
  - Reconsidering decision criteria for acceptance/rejection of donor kidney
  - Listing decision (Multiple listing)

- **Social planner (OPTN & CMS):**
  - Changing kidney allocation system (KAS)
  - Changes in Organ Procurement and Transplantation Network (OPTN; currently performed by UNOS) and CMS evaluation metrics
  - Using information technology such as Unet to improve efficiency.

Information sharing
Literature Review

Kidney acceptance decision making

Allocation process and queueing models
Zenios et al. (2000), Su and Zenios (2004), Su and Zenios (2005), Su and Zenios (2006)

Simulation
Ruth et al. (1985)

Regional variations
Bertsimas et al. (2013), Koizumi et al. (2015)
Method and Questions

Simulation optimization model to evaluate the impact of information sharing on organ transplantation.

1. Information sharing from OPTN to patient and surgeon.
   - What is the optimal kidney acceptance policy depending on region?
   - How to find the optimal region selection policy under a set of budget, distance and performance constraints?

2. Information sharing from patient/surgeon with OPTN
   - How does information sharing improve the efficiency of the kidney allocation system and enhance social welfare utility?
Simulation Model & Assumptions

**Patient enrollment and arrival**

Patient arrival rate: $\lambda$

Health: $H_0 \sim \text{weibull}(a, b)$

Acceptance: $K \sim \text{unif}(0,1)$

**Regional waiting list**

**Kidney allocation and acceptance**

Kidney arrival rate: $\mu$ with quality $q_t, t = 0$

Offering group size: $g$, decision time: 1 hour

if $q_t > k$, accept and transplant with probability $p(\text{trans}) = p(\text{patient}) p(\text{center})$

else set $q_t = q_0 (1 - \delta)^t$ and reoffer

if $q_t < 0$ discard the kidney

**Patient removal**

$h_w \leq 2 \text{ month} + $ departure rate: $\delta$

**Kidney transplant**

Post-transplant utility

$U^c(q, h_0, w) = B(h_0, q_t) \ast [1 - C(h_0, w)]$

Benefit function: $B(h_0, q) = \frac{m(h_0)}{1 + \exp(-\beta(q_t - \alpha))}$

Deterioration factor: $C(h_0, w) = \left(1 - \frac{w}{h_0}\right)^y$
Method and Questions

Simulation optimization model to evaluate the impact of information sharing on organ transplantation.

1. Information sharing from OPTN to patient and surgeon.
   - What is the optimal kidney acceptance policy depending on region?
   - How to find the optimal region selection policy under a set of budget, distance and performance constraints?

2. Information sharing from patient/surgeon with OPTN
   - How does information sharing improve the efficiency of the kidney allocation system and enhance social welfare utility?
Optimal Kidney Acceptance Threshold

\[
\max_k E[U_i] = f(i, k)
\]

\(k\) ... kidney acceptance threshold

\(i\) ... region
Estimation of Arrival Rates

Recipient with blood type A

<table>
<thead>
<tr>
<th>Region</th>
<th>Donor A (94%)</th>
<th>Donor O (2%)</th>
<th>Kidney μ</th>
<th>Patient λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>118</td>
<td>143</td>
<td>228</td>
<td>537</td>
</tr>
<tr>
<td>2</td>
<td>387</td>
<td>473</td>
<td>746</td>
<td>1769</td>
</tr>
<tr>
<td>3</td>
<td>461</td>
<td>625</td>
<td>892</td>
<td>1680</td>
</tr>
<tr>
<td>4</td>
<td>303</td>
<td>421</td>
<td>586</td>
<td>1154</td>
</tr>
<tr>
<td>5</td>
<td>452</td>
<td>636</td>
<td>875</td>
<td>1910</td>
</tr>
<tr>
<td>6</td>
<td>132</td>
<td>165</td>
<td>255</td>
<td>377</td>
</tr>
<tr>
<td>7</td>
<td>239</td>
<td>300</td>
<td>461</td>
<td>1008</td>
</tr>
<tr>
<td>8</td>
<td>226</td>
<td>296</td>
<td>437</td>
<td>688</td>
</tr>
<tr>
<td>9</td>
<td>114</td>
<td>146</td>
<td>220</td>
<td>735</td>
</tr>
<tr>
<td>10</td>
<td>284</td>
<td>349</td>
<td>548</td>
<td>1040</td>
</tr>
<tr>
<td>11</td>
<td>304</td>
<td>423</td>
<td>588</td>
<td>1080</td>
</tr>
</tbody>
</table>

Data sources: United Network for Organ Sharing (UNOS) and Scientific Registry of Transplant Recipients (SRTR)
## Optimal Kidney Acceptance Threshold by Region

<table>
<thead>
<tr>
<th>Blood type</th>
<th>$h_o$</th>
<th>$a$</th>
<th>$b$</th>
<th>$\theta$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$t$</th>
<th>$\delta$</th>
<th>$g$</th>
<th>$P(\text{trans})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>1(yr)</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>0.4</td>
<td>8</td>
<td>0.5</td>
<td>1</td>
<td>0.05</td>
<td>5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### Optimal Acceptance Threshold by Region

<table>
<thead>
<tr>
<th>Region</th>
<th>$\mu$</th>
<th>$k^*_i$</th>
<th>$q_t$</th>
<th>$U_1(k^*_i)$</th>
<th>$n_{reject}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228</td>
<td>0.6</td>
<td>0.76</td>
<td>9.1</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>746</td>
<td>0.85</td>
<td>0.95</td>
<td>13.2</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>892</td>
<td>0.85</td>
<td>0.93</td>
<td>13.6</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>588</td>
<td>0.8</td>
<td>0.9</td>
<td>12.8</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>875</td>
<td>0.85</td>
<td>0.92</td>
<td>13.5</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>255</td>
<td>0.65</td>
<td>0.76</td>
<td>9.7</td>
<td>19</td>
</tr>
<tr>
<td>7</td>
<td>461</td>
<td>0.75</td>
<td>0.8</td>
<td>12.0</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>436</td>
<td>0.75</td>
<td>0.84</td>
<td>11.9</td>
<td>21</td>
</tr>
<tr>
<td>9</td>
<td>220</td>
<td>0.6</td>
<td>0.67</td>
<td>8.9</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>548</td>
<td>0.8</td>
<td>0.92</td>
<td>12.7</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>588</td>
<td>0.8</td>
<td>0.92</td>
<td>12.8</td>
<td>24</td>
</tr>
</tbody>
</table>
Method and Questions

• **Simulation optimization model** to evaluate the impact of information sharing on organ transplantation.

1. Information sharing from OPTN to patient and surgeon.
   - What is the optimal **kidney acceptance policy** depending on region?
   - How to find the optimal **region selection policy** under a set of budget, distance and performance constraints?

2. Information sharing from patient/surgeon with OPTN
   - How does **information sharing** improve the efficiency of the kidney allocation system and enhance social welfare utility?
### Optimal Decision Without Constraints

<table>
<thead>
<tr>
<th>Blood type</th>
<th>$h_o$</th>
<th>$a$</th>
<th>$b$</th>
<th>$\theta$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$t$</th>
<th>$\delta$</th>
<th>$g$</th>
<th>$P_{\text{trans}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 (yr)</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>0.4</td>
<td>8</td>
<td>0.5</td>
<td>1</td>
<td>(hr)</td>
<td>0.05</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>$\mu$</th>
<th>$k_i^*$</th>
<th>$q_t$</th>
<th>$U_i(k_i^*)$</th>
<th>$n_{\text{reject}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228</td>
<td>0.6</td>
<td>0.76</td>
<td>9.1</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>746</td>
<td>0.85</td>
<td>0.95</td>
<td>13.2</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>892</td>
<td>0.85</td>
<td>0.93</td>
<td><strong>13.6</strong></td>
<td><strong>24</strong></td>
</tr>
<tr>
<td>4</td>
<td>588</td>
<td>0.8</td>
<td>0.9</td>
<td>12.8</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>875</td>
<td>0.85</td>
<td>0.92</td>
<td>13.5</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>255</td>
<td>0.65</td>
<td>0.76</td>
<td>9.7</td>
<td>19</td>
</tr>
<tr>
<td>7</td>
<td>461</td>
<td>0.75</td>
<td>0.8</td>
<td>12.0</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>436</td>
<td>0.75</td>
<td>0.84</td>
<td>11.9</td>
<td>21</td>
</tr>
<tr>
<td>9</td>
<td><strong>220</strong></td>
<td>0.6</td>
<td>0.67</td>
<td><strong>8.9</strong></td>
<td><strong>17</strong></td>
</tr>
<tr>
<td>10</td>
<td>548</td>
<td>0.8</td>
<td>0.92</td>
<td>12.7</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>588</td>
<td>0.8</td>
<td>0.92</td>
<td>12.8</td>
<td>24</td>
</tr>
</tbody>
</table>

*Region 3 highlighted for emphasis.*
Region Selection

\[
\max_{r,k} E[U] = f(r, k) = \sum_{i \in I} U_i(k_i^*)r_i
\]

s.t.

\[
\begin{align*}
    & r = \{0, 1\}^{11} & r_i : 1 \text{ if region } i \text{ is selected, } 0 \text{ otherwise} \\
    & \sum_{i \in I} r_i = 1 & \text{Single region constraint} \\
    & \sum_{i \in I} c_i r_i \leq B & \text{Pre transplant budget contr. (evaluation, travel + living cost)} \\
    & \sum_{i \in I} d_i r_i \leq D & \text{Distance constraint} \\
    & \sum_{i \in I} p_i r_i \geq P & \text{Performance constr. (5-year post-transplant graft survival)}
\end{align*}
\]
## Region Selection

Patient with blood type A living in Region 6  
Constraints: Budget < $15,000; Performance > 75%, Distance < 1,500 miles

<table>
<thead>
<tr>
<th>Region</th>
<th>Monthly cost of living</th>
<th>Expected wait time (yrs)</th>
<th>Number of evaluation</th>
<th>Evaluation cost</th>
<th>5 year survival rate</th>
<th>Air distance (mile)</th>
<th>$U_i(k_i)(yr)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2,454</td>
<td>2.4</td>
<td>4</td>
<td>$6,381</td>
<td>73%</td>
<td>2,200</td>
<td>9.1</td>
</tr>
<tr>
<td>2</td>
<td>$1,879</td>
<td>1.8</td>
<td>3</td>
<td>$4,614</td>
<td>70%</td>
<td>1,904</td>
<td>13.2</td>
</tr>
<tr>
<td>3</td>
<td>$1,637</td>
<td>1.9</td>
<td>3</td>
<td>$4,541</td>
<td>76%</td>
<td>1,706</td>
<td>13.6</td>
</tr>
<tr>
<td>4</td>
<td>$2,328</td>
<td>1.4</td>
<td>2</td>
<td>$3,166</td>
<td>75%</td>
<td>1,160</td>
<td>12.8</td>
</tr>
<tr>
<td>5</td>
<td>$2,130</td>
<td>2.5</td>
<td>5</td>
<td>$7,815</td>
<td>79%</td>
<td>374</td>
<td>13.5</td>
</tr>
<tr>
<td>6</td>
<td>$2,413</td>
<td>1.6</td>
<td>3</td>
<td>0$</td>
<td>83%</td>
<td>0</td>
<td>9.7</td>
</tr>
<tr>
<td>7</td>
<td>$2,686</td>
<td>2.3</td>
<td>4</td>
<td>$6,474</td>
<td>74%</td>
<td>670</td>
<td>12.0</td>
</tr>
<tr>
<td>8</td>
<td>$2,869</td>
<td>1.4</td>
<td>2</td>
<td>$3,274</td>
<td>76%</td>
<td>569</td>
<td>11.9</td>
</tr>
<tr>
<td>9</td>
<td>$2,705</td>
<td>2.2</td>
<td>4</td>
<td>$6,482</td>
<td>69%</td>
<td>1,195</td>
<td>8.9</td>
</tr>
<tr>
<td>10</td>
<td>$2,005</td>
<td>1.8</td>
<td>3</td>
<td>$4,651</td>
<td>72%</td>
<td>565</td>
<td>12.7</td>
</tr>
<tr>
<td>11</td>
<td>$2,706</td>
<td>1.4</td>
<td>2</td>
<td>$3,241</td>
<td>72%</td>
<td>941</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Set of feasible regions: \{R6, R5, R4, R8\}
Proposed Approach for Multi-Listing

\[
\max E[U] \quad E[U] = f (r, k) = U_{r,k}
\]

s.t.
\[
\begin{align*}
 r &= \{0, 1\}^{11} \quad r_i : 1 \text{ if region } i \text{ is selected, } 0 \text{ otherwise} \\
 \sum_{i \in I} r_i &= 1 \quad \text{Single region constraint} \\
 \sum_{i \in I} c_i r_i &\leq B \quad \text{Pre transplant budget contr. (evaluation, travel + living cost)} \\
 \sum_{i \in I} d_i r_i &\leq D \quad \text{Distance constraint} \\
 \sum_{i \in I} p_i r_i &\geq P \quad \text{Performance constr. (5-year post-transplant graft survival)}
\end{align*}
\]
Simulation Model for Multi-Listing

Patient enrollment and arrival

Patient arrival rate: $\lambda$

Health: $H_0 \sim \text{weibull}(a, b)$
Acceptance: $K \sim \text{unif}(0,1)$

Add region labels

Patient removal

$\delta$ 

Kidney allocation and acceptance

Kidney arrival rate: $\mu$ with quality $q_t; t = 0$
Offering group size: $g$ / decision time: 1 hour

if $q_t > k$, accept and transplant with probability $p(\text{trans}) = p(\text{patient})p(\text{center})$
else set $q_t = q_0 (1 - \delta)^t$ and reoffer
if $q_t < 0$ discard the kidney

Kidney transplant

Post-transplant utility

$U^c(q, h_0, w) = B(h_0, q_t) \times [1 - C(h_0, w)]$

Benefit function: $B(h_0, q) = \frac{m(h_0)}{1 + \exp(-\beta(q - a))}$

Deterioration factor: $C(h_0, w) = (1 - \frac{w}{h_0})^\gamma$

Repeat simulation for all combinations of the feasible regions.
Method and Questions

• Simulation optimization model to evaluate the impact of information sharing on organ transplantation.

1. Information sharing from OPTN to patient and surgeon.
   • What is the optimal kidney acceptance policy depending on region?
   • How to find the optimal region selection policy under a set of budget, distance and performance constraints?

2. Information sharing from patient/surgeon with OPTN
   • How does information sharing improve the efficiency of the kidney allocation system and enhance social welfare utility?
The Effect of Information Sharing on Patient Transplant Outcomes

Current situation
• Kidney is offered to a set of $g = 5$ patients which have 1 hour to decide.
• Kidney is transplanted for each of the $g$ patient with $p(\text{trans}) = p(\text{patient})p(\text{center})$
• If the kidney is not accepted it is re-offered to the next group.

Under perfect information OPTN can use for allocation
• All patient’s kidney quality thresholds.
• Patient’s availability.
• Surgeon and center availability.

OPTN can identify the perfect candidate directly and CIT is minimized.
This can be expressed as a group size of $g = \infty$.

Effect of information sharing can be modeled as an increase of $g$, a decrease of decision time and an increase of $p(\text{trans})$. 
Patient enrollment and arrival

Patient arrival rate: \( \lambda \)

Health: \( H_0 \sim \text{weibull}(a, b) \)

Acceptance: \( K \sim \text{unif}(0,1) \)

Kidney allocation and acceptance

Kidney arrival rate: \( \mu \) with quality \( q_t; t = 0 \)

If \( q_t > k \), accept and transplant with probability \( p(\text{trans}) = \) increases; else set \( q_t = q_0 \) \((1 - \delta)^t\) and reoffer.

If \( q_t < 0 \) discard the kidney.

Simulation Model for Information Sharing

Modify group size \( g \) or decision time.

Patient removal

\( h_w \leq 2 \text{ month} \) + departure rate: \( \delta \)

Post-transplant utility

\[
U^c(q, h_0, w) = B(h_0, q_t) \ast [1 - C(h_0, w)]
\]

Benefit function:

\[
B(h_0, q) = \frac{m(h_0)}{1 + \exp(-\beta(q_t - a))}
\]

Deterioration factor:

\[
C(h_0, w) = \left(1 - \frac{w}{h_0}\right)^\gamma
\]
The Effect of Information Sharing on Patient Post Transplant Utility Based on Region 6 Kidneys Supply and Demands

<table>
<thead>
<tr>
<th>Group size g</th>
<th>Waitlist position (mean)</th>
<th>Waitlist position (max)</th>
<th>Average q</th>
<th>Average utility (year)</th>
<th>Total utility (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>45</td>
<td>0.66</td>
<td>11.03</td>
<td>284.48</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>80</td>
<td>0.62</td>
<td>10.99</td>
<td>312.72</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>119</td>
<td>0.6</td>
<td>10.9</td>
<td>321.17</td>
</tr>
<tr>
<td>100</td>
<td>22</td>
<td>344</td>
<td>0.57</td>
<td>10.82</td>
<td>331.22</td>
</tr>
<tr>
<td>∞</td>
<td>58</td>
<td>1,383</td>
<td>0.55</td>
<td>10.80</td>
<td>339</td>
</tr>
</tbody>
</table>
# Kidney Utilization, Waitlist Removal, and Kidney Transplant Rates In Region 6

<table>
<thead>
<tr>
<th>Group size</th>
<th>Kidney utilization rate</th>
<th>Kidney discard rate</th>
<th>Waitlist removal rate</th>
<th>Kidney transplant rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>85%</td>
<td>15%</td>
<td>8.9%</td>
<td>17%</td>
</tr>
<tr>
<td>10</td>
<td>90.9%</td>
<td>9.1% (\text{-39%})</td>
<td>8.3%</td>
<td>20%</td>
</tr>
<tr>
<td>20</td>
<td>94.3%</td>
<td>5.7%</td>
<td>7.9%</td>
<td>21.5%</td>
</tr>
<tr>
<td>100</td>
<td>98.5%</td>
<td>1.5%</td>
<td>7.3%</td>
<td>23.8%</td>
</tr>
<tr>
<td>∞</td>
<td>100%</td>
<td>0%</td>
<td>7.1%</td>
<td>25.2%</td>
</tr>
</tbody>
</table>
Concluding Remarks

• High organ discard rates are a known problem.
• UNOS encourages the development of modern technology such as mobile devices to facilitate organ allocation.
• The presented simulation model shows what the impact of different information strategies are.
• Challenge: Incentive system for information sharing.
Questions?

Contact Information
Michael Hahsler
mhahsler@lyle.smu.edu