Modeling of the US National Kidney Transplantation System as a Queueing Network and Discrete Event Simulation

Ashley E Davis[1, 2], Sanjay Mehrotra[1, 2, 3,*], John J Friedewald[2,5], Daniela P Ladner[2,4]

[1] Industrial Engineering and Management Sciences, Northwestern University, Evanston, IL 60208

[2] Transplant Outcomes Research Collaborative (NUTORC), Comprehensive Transplant Center, Northwestern University Feinberg School of Medicine, Chicago, IL 60611

[3] Center for Engineering and Health, Northwestern University Feinberg School of Medicine, Chicago, IL 60611

[4] Center for Healthcare Studies (CHS), Northwestern University Feinberg School of Medicine, Chicago, IL 60611

[5] Division of Nephrology, Department of Medicine, Feinberg School of Medicine, Chicago, IL 60611

***Corresponding Author:**
Sanjay Mehrotra, PhD
Professor of Industrial Engineering and Management Sciences
2145 Sheridan Road, Tech C246
Evanston, IL 60208
Phone: 847-491-3155
Fax: 847-491-8005
E-mail: mehrotra@iems.northwestern.edu

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Abbreviations: DSA: Donor Service Area, ESRD: End Stage Renal Disease, KDRI: Kidney Donor Risk Index, OPTN: Organ Procurement and Transplant Network, PRA: Panel Reactive Antibody, UNOS: United Network for Organ Sharing

Abstract

The United Network for Organ Sharing is planning to resolve the ever-growing geographic disparities in kidney transplantation. Currently used allocation simulation models are limited in their ability to integrate alternative kidney sharing strategies and analyze the impact of policy changes at the system level. This paper introduces a discrete event simulation of the kidney transplantation system, KSIM2. KSIM2 is designed to be easily adapted to test alternative geographic kidney allocation policies and provide transplant system outputs by DSA and patient demographic. Input analysis employing actual transplant system data was conducted to best represent patient and organ dynamic processes. KSIM2 was verified and validated against ten years of retrospective transplant system information.

1. Introduction

The United Network for Organ Sharing (UNOS) currently uses the Kidney-Pancreas Simulated Allocation Model (KPSAM) to test the impact of policy changes on the kidney transplantation system.[1] To date, KPSAM has been primarily used to investigate how changes in patient prioritization on the kidney transplant waitlist affect transplantation access and subsequent transplant outcomes for different patient subpopulations. KPSAM is limited however in its ability to characterize the impact of the policy change on macro-system outcomes. First, KPSAM requires complete patient and donor information to run. Second, KPSAM is only capable of simulating the transplant system for one year of kidney allocation, making it impossible to simulate the long-run impact of alternative policies. Third, transplant system geography is extensively hard-coded into KPSAM, making it difficult to examine different geographic allocation policies. Because of these limitations, UNOS will require a new simulation to aid the kidney allocation policy committee in their current charge to design new policies to reduce geographic disparities.[2]

Past simulation modeling efforts simulate the organ allocation process at patient-level precision. Kreke et al. (2002) developed a discrete event simulation of the national liver allocation system to best analyze the impact of liver allocation policy changes on patient outcomes.[3] Shechter et al (2005) use discrete-event simulation to model end stage liver disease and how it impacts the liver allocation process.[4] Zenios et al (1999) develop a Monte Carlo simulation model of the kidney transplantation system to compare the impact of different allocation policies on patient level access.[5] Pritsker et al (1995) and Taranto et al (2000) describe the large UNOS liver and kidney simulation models, respectively.[6,7]

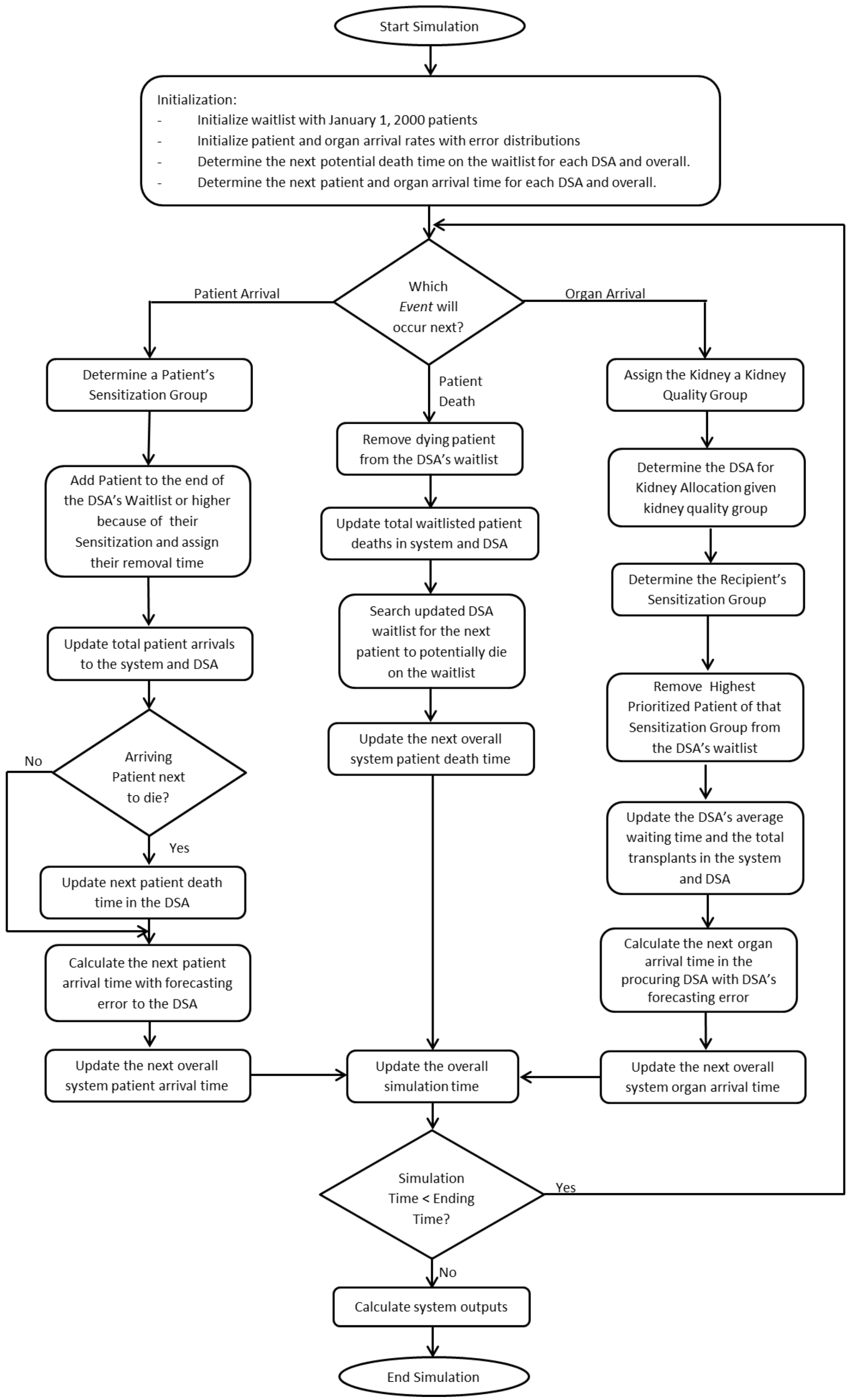
The discrete event simulation KSIM2 expands upon past modeling efforts (KSIM) to simulate the impact of alternative allocation policies at the system-level while incorporating differences in patient demographics, organ qualities, and transplant acceptance behaviors.[8] Transplant system outputs provided include each DSA’s (1) average waiting time to transplantation, (2) probability of being removed from the kidney waitlist with a kidney transplant, and (3) probability of being removed from the kidney waitlist without a kidney transplant. These DSA outputs can be provided by patient age, race, or sensitization level. KSIM2 additionally includes information about the quality of kidneys transplanted in each DSA, including the kidney donor risk index (KDRI) to inform the transplant community how their acceptance behaviors must change from the policy change to be impactful.[9] KSIM2 outputs are validated against retrospective Organ Procurement and Transplant Network (OPTN) kidney system outputs from 2000 through 2009.

The remainder of this paper is organized as follows. Section 2 provides a brief overview of KSIM2's design of the transplant system. Section 3 outlines the data sources and input analysis conducted for use in KSIM2. Section 4 concludes the technical appendix discussing the verification and validation of KSIM2 against 2000-2009 kidney transplant system outputs.

2. KSIM2 Design

KSIM2 is initialized with the listed kidney transplant population on January 1, 2000 and simulates ten years of the kidney simulation system given a specified allocation policy. The user must specify the demographic of interest for the run: total population, age (<18, 18-65, >65 years old), or race (Non-Hispanic White, Non-Hispanic Black, Hispanic, Asian, Other). After a KSIM2 simulation run, transplant system outputs provided include each DSA's (1) average waiting time to transplantation, (2) probability of being removed from the kidney waitlist with a kidney transplant, and (3) probability of being removed from the kidney waitlist without a kidney transplant. Figure 1 provides the general flowchart schematic of the simulation. This section will explain the flow of patients and kidney organs in the context of the actual kidney transplant system environment as well as a technical description of the flow of patients per DSA.

Figure 1: Flowchart of KSIM2



2.1. The Kidney Transplantation System

Geographically, UNOS divides the country in two ways. First, the country is divided into eleven regions of neighboring states. Each region is the further subdivided into Donor Service Areas (DSAs), with 58 total DSAs in the US. Each DSA has on Organ Procurement Organization (OPO) to facilitate local organ procurement and allocation services. Each DSA contains kidney transplant centers with 240 total kidney transplant centers in the US by 2009.[10] End Stage Renal Disease (ESRD) patients may seek transplantation at the transplant center of their choice.

ESRD prevalence and waitlisting rates historically have varied by patient demographic and DSA.[11] Upon listing for kidney transplantation in KSIM2 at a rate corresponding with retrospective listing behaviors, each patient is added to their DSA's kidney waitlist, specified a demographic, and are prioritized primarily on their waiting time in the system. Patients are also assigned a sensitization level upon entering KSIM2 according to their Panel Reactive Antibody (PRA) level (not sensitized (0-20% PRA), sensitized (20-80% PRA), and highly sensitized (80-100% PRA)). Additional prioritization points are given to patients who are sensitized. Sensitized patients have a difficult time finding a suitable kidney match for transplantation.[12] As a result, sensitized patients will not be eligible for as many organ offers as non-sensitized patients, and correspondingly will have a longer waiting time to transplantation. In KSIM2, highly sensitized patients are moved ahead of any currently listed patient with a waiting time on the list less than four years, mirroring current policy.

Organ procurement and acceptance vary greatly throughout the country.[13,14] When a kidney is donated in a specific DSA, OPO coordinators offer the kidney to patients by order of geographic prioritization; first to candidates in the DSA of procurement (local allocation), then in the UNOS region of procurement (regional allocation), and finally to the remaining patients in the nation as necessary (national allocation).[10] Acceptance behavior varies the most in the acceptance of poor quality kidney organs.[14] This unwillingness to accept poor quality kidneys occurs for numerous reasons. First, poorer quality kidneys are most affected by cold ischemic time (CIT).[15] By the time a kidney is shared beyond their DSA of procurement, the kidney has already sustained considerable CIT. Thus, distant DSAs will be less likely to accept the kidney for transplantation. Second, risk-averse behavior is further hindered by current accreditation standards that evaluate transplant centers according to non-risk-adjusted transplant recipient outcomes.[16] As a result, there is no incentive for transplant centers to take on the increased risk of transplanting a poorer quality kidney. Historically, only specific transplant centers scattered around the US traditionally transplant poorer quality kidneys.

With this knowledge, it is important to incorporate kidney quality into KSIM2. Kidney procurement and transplant acceptance KDRI probability distributions (0-1.0, 1.0-1.5, 1.5-2.0, 2.0-2.5, >2.5) were specified for each DSA based on their past kidney procurement and acceptance behavior, respectively. When a kidney is donated in KSIM2, the kidney is assigned a KDRI group based on the procuring DSA's past procurement KDRI probability distribution. Given this kidney quality, the kidney is allocated locally with a certain probability, determined by their kidney transplant acceptance KDRI probability distribution. If the kidney is not allocated locally, then the regional search begins with the regional DSA with the highest regionally prioritized patient. If that DSA does not accept the kidney based on their transplant acceptance KDRI distribution, then the search continues among the remaining DSAs in the region according to the remaining patient prioritization. Finally, if the kidney remains unallocated, their highest prioritized patient sorts the remaining national DSAs and an iterative search is completed for a recipient according to the DSA's transplant acceptance KDRI distribution. KSIM2 allows the user to turn off the KDRI transplant acceptance distribution process. This flexibility allows the user to test how alternative geographic kidney allocation policies will impact the transplant system given current acceptance behavior and ideal acceptance behavior (i.e. all kidneys will be accepted regardless of quality at all DSAs). This comparison will allow the user to understand the realistic and idealistic gains to be achieved by a policy change as well as the kidney acceptance behavior changes necessary to achieve idealistic gains.

Once a kidney is accepted for transplantation within a DSA, the search for a local recipient begins. A patient's demographic and sensitization level plays a key role in the allocation acceptance process. In KSIM2, a recipient sensitization level and demographic is assigned to the kidney begin allocated based on the DSA of transplantation's retrospective recipient characteristics. KSIM2 then searches for the highest prioritized patient on the DSA's waitlist with that corresponding demographic and sensitization.

<u>2.2. KSIM2 DSA Kidney Waitlist Dynamics</u>

For a single DSA i, patients of a specific blood type b arrive to kidney waitlist according to interarrival rate distribution $\lambda_{ib}(t)$ in year t. In KSIM2, patients are assumed to arrive to the simulation according to each DSA's interarrival rate distribution in the corresponding year. Once entering the waitlist, the patient is assigned a demographic d and sensitization level s and are prioritized on the list appropriately.

Patients are removed from their waitlist in KSIM2 for one of two main reasons. First, a patient may survive long enough on the waitlist to reach the highest prioritization and receive a suitable kidney match for transplantation. The rate at which patients are transplanted from the waitlist depends on the kidney allocation policy and the procurement rates in each DSA. Let $\delta_{ib}(t)$ represent the interarrival rate of kidneys of blood type b procured in DSA i in year t. In KSIM2, we assume that organs are donated for transplantation according to their DSA's organ interarrival rate and then are allocated appropriately as discussed in detail in the previous section.

Alternatively, a patient can become too sick to transplant and/or die on the waitlist. This is an unfortunate common occurrence because ESRD patients can only sustain their life on dialysis for a limited amount of time.[17] The individual patient mean abandonment time from DSA i's waitlist of blood type b waitlist in year t can be estimated by the mean time on dialysis among the entire ESRD population who never received a kidney transplantation, $\gamma_{ib}^{-1}(t)$. When a patient joins a DSA's waitlist in KSIM2, they are assigned a waitlist removal time according to their DSA's individual abandonment time distribution. If the patient is still on the waitlist at their removal time, they are removed from the waitlist without transplantation.

3. KSIM2 Input Analysis

Organ Procurement and Transplant Network (OPTN) data were used to characterize all of the necessary input parameters to run KSIM2 for the actual 2000-2009 kidney transplantation system. We will now define the data utilized for each input parameter separately.

3.1. Interarrival Rate Distributions

Interarrival rate distributions for patient arrivals and removals from the system as well as kidney procurements were estimated using OPTN DSA-specific kidney transplantation data from 2000-2009. We excluded patients seeking multi-organ or living donor kidney transplants as well as recipients and corresponding kidney organs involved in multi-organ, living donor, ABO-incompatible, and zero Human Leukocyte Antigen (HLA) mismatch kidney transplants. These exclusions were necessary since these recipients and corresponding kidney organs are not allocated according to the standard national kidney policy.[10] Thus including these patients would bias the interarrival distributions. In total, 116,004 patients and 93,653 organs were included in the distribution fitting using EasyFit 5.5 professional software.[18] Distributions were fit for each DSA, blood type, and year combination, resulting in a total of 4,640 distribution fits per parameter. The quality of each distribution fit was analyzed using the Kolmogorov-Smirnov (K-S) test. In Davis et al. (2013), it was determined that the exponential distribution was the overall best-fitting interarrival time distribution for each parameter of interest.[8] We will now discuss the specifics of each parameter over time.

Patient Interarrival Rates: Mean exponential patient interarrival times were calculated annually for each DSA and blood type combination from 2000 through 2009. Table 1 displays the annual blood type-specific patient interarrival rates per DSA for 2000. As shown, patient interarrival rates vary considerably across blood types and across DSAs. The rate of patient arrivals increased each year over the ten-year period from 2000 to 2009.

Kidney Interarrival Rates: Mean exponential kidney procurement interarrival times were calculated annually for each DSA and blood type combination from 2000 through 2009. Table 1 displays the annual blood type-specific kidney procurement rates per DSA for 2000. As shown, kidney procurement rates vary considerably across blood types and across DSAs. The rate of kidney procurement has not meaningfully increased each year over the ten-year period from 2000 to 2009.

Individual Waitlist Removal Rate: Mean exponential individual waitlist removal times were calculated annually for each DSA and blood type combination from 2000 through 2009. Table 1 displays the annual blood type individual waitlist removal times per DSA for 2000. As shown, individual removal times vary across blood types and DSAs, mainly due to differences in ESRD populations and dialysis quality around the country. The individual waitlist removal time has increased each year over the ten-year period from 2000 to 2009.

Table 1: KSIM2 DSA Mean Interarrival Time Parameterization in days by Blood Type in 2000

Blood Type:	A			AB			B			O		
Parameter [a]:	λ_{ib}^{-1}	δ_{ib}^{-1}	γ_{ib}^{-1}	λ_{ib}^{-1}	δ_{ib}^{-1}	γ_{ib}^{-1}	λ_{ib}^{-1}	δ_{ib}^{-1}	γ_{ib}^{-1}	λ_{ib}^{-1}	δ_{ib}^{-1}	γ_{ib}^{-1}
DSA	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
1	3.0	6.5	1368	24	41	1392	6	20	1629	2	6	1570
2	26.1	28.1	1116	361	335	1209	61	73	1626	14	30	1514
3	6.8	11.8	790	91	52	1810	24	52	1201	6	9	1051
4	1.4	3.8	1228	9	37	1249	3	13	1583	1	4	1453
5	9.9	11.8	1163	183	91	1363	46	73	1576	11	26	1060
6	1.3	3.4	1185	9	30	1277	3	9	1423	1	3	1324
7	5.0	15.9	1544	73	183	1358	17	61	1523	4	10	1475
8	6.6	10.4	1210	41	52	1373	16	37	1690	4	12	1784
9	11.8	19.2	1500	91	61	407	37	61	1289	8	15	1311
10	5.3	28.1	1457	37	122	1617	9	46	1698	3	10	1555
11	15.9	12.2	1083	52	46	1328	20	37	1646	7	7	1332
12	6.5	8.9	1184	73	33	1659	23	24	1221	5	11	1156
13	5.9	12.2	1204	33	52	1729	9	122	1539	4	17	1126
14	8.5	7.3	1534	122	46	1608	13	20	1772	4	5	1095
15	3.1	5.1	1463	16	41	1323	8	24	1380	2	4	1746
16	15.9	24.3	1565	183	73	1785	52	183	1603	12	23	1781
17	8.9	11.1	1332	73	91	552	23	37	1758	8	18	1251
18	1.7	2.7	1282	14	28	1621	4	10	1518	1	3	1508
19	7.0	8.7	1583	46	46	1450	14	33	1730	7	11	1263
20	7.4	12.2	1484	52	46	972	28	41	1727	6	9	1468
21	4.7	9.6	1477	30	37	1345	7	17	1721	3	6	1460
22	3.2	5.1	1248	18	37	1640	7	17	1339	2	5	1432
23	1.8	14.6	1267	14	61	1463	4	26	1426	1	17	1352
24	3.1	4.6	1301	21	26	956	8	11	1394	3	4	1264
25	3.3	4.9	1066	28	52	1196	9	14	1475	3	6	1145
26	5.5	7.6	1416	46	52	1676	15	37	1594	3	7	1560
27	45.6	16.6	1794	345	183	1304	73	52	1609	30	18	1513
28	7.6	5.2	1785	183	46	1759	18	26	1522	6	6	1432
29	33.2	20.3	1812	365	315	1721	73	122	1616	13	14	1603
30	4.7	6.4	1380	24	52	1533	7	28	1595	3	10	1510
31	16.6	21.5	1437	122	183	696	46	183	1706	11	41	1545
32	3.1	4.8	1153	18	41	1228	5	15	1449	2	5	1336
33	26.1	18.3	1525	325	340	626	91	61	1557	12	24	1787
34	16.6	30.4	1402	73	122	1407	30	91	1275	10	17	1519
35	10.4	22.8	1028	91	122	1363	28	41	1736	14	10	1265
36	8.7	20.3	1406	91	61	1222	17	183	1656	8	23	1320
37	1.6	6.4	1436	11	37	1575	3	15	1505	1	5	1560
38	17.4	28.1	900	183	183	811	52	26	1162	12	13	1096
39	6.6	13.5	1461	33	61	1595	19	61	1501	4	8	1434
40	9.9	18.3	1806	61	91	1128	26	73	1784	9	18	1384
41	7.8	14.6	1670	46	122	1442	28	33	1624	6	11	1306
42	17.4	13.5	1404	91	91	1806	37	61	1808	12	23	1705
43	9.4	13.0	1528	183	91	1189	33	73	1348	7	8	1248
44	12.2	7.6	1143	73	46	1082	52	41	1111	11	8	1187
45	1.4	3.7	1042	11	18	1412	3	11	1361	1	2	1039
46	3.9	7.3	1007	37	73	1019	11	13	1439	3	6	1377
47	10.7	20.3	1739	362	333	1720	37	46	1605	6	10	1759
48	4.9	8.7	1484	37	73	1487	10	30	1474	4	6	1497
49	5.1	8.9	1128	46	356	1639	14	15	1725	4	8	1550
50	15.2	52.1	1677	46	122	962	30	183	1761	7	28	1755
51	3.2	4.1	1160	41	37	1484	6	13	1596	2	3	1174
52	4.5	10.1	1046	33	52	1287	7	26	1394	2	6	1292
53	3.7	5.7	1249	61	91	1668	8	19	1144	3	5	1040
54	15.2	11.4	1351	122	73	645	61	73	1397	26	17	1358
55	6.3	17.4	1231	73	41	1663	15	52	1455	4	7	1245
56	5.1	4.6	1161	37	24	1543	20	19	1457	4	6	1696
57	8.3	16.6	1193	33	41	1233	14	41	1566	6	24	1191

58	7.0	7.6	1138	73	46	1622	24	46	1382	5	10	1538

[a]: λ_{ib}^{-1}: represents the mean number of days between two patients of blood type b joining DSA i's waitlist. δ_{ib}^{-1}: represents the mean number of days between two kidneys of blood type b being procured in DSA i. γ_{ib}^{-1} represents the mean number of days one patient can remain on the waitlist before becoming too sick to transplant or dying on the waitlist.
DSA: Donor Service Area

3.2. Accounting for Uncertainty in Patient and Kidney Interarrival Rates

The previous input distribution fitting assumes that the user of KSIM2 will have complete information about the arrival and removal patterns of patients and kidneys in the transplant system each year. More realistically, KSIM2 users will only be able to forecast parameterizations with some margin of error. Let $\epsilon_{ib}(t)$ and $\psi_{ib}(t)$ represent the error distribution of DSA i's blood type b patient and kidney procurement interarrival rates each year *t*, respectively.

Using OPTN data from 2000 through 2009, exponential smoothing with trend was used to forecast the value of $\lambda_{ib}(t)$ assuming knowledge of the true mean value of λ_{ib} for *n* years prior to year *t*, denoted $\hat{\lambda}_{ib}^{n}(t)$. Forecasts were calculated for *n=1,…,5* using smoothing parameters $\alpha = 0.2$ and $\beta = 0.3$. The error set for $\epsilon_{ib}(t)$ was then populated with $\hat{\lambda}_{ib}^{n}(t) - \lambda_{ib}(t)$ for each *n* forecast. Kidney procurement error distributions were populated in a similar manner using *n* year exponential smoothing with trend forecasts of mean kidney procurement rates in year *t*, $\hat{\delta}_{ib}^{n}(t)$ for *n=1,…,5*.

In KSIM2, the mean annual patient and kidney procurement interarrival rates (Table 1) are allowed to vary according to their annual error distributions. Table 2 displays the range in the error distributions per DSA and blood type for 2000.

Table 2: KSIM2 DSA Interarrival Time Error Range in Days Per DSA and Blood Type in 2000

Blood Type:	A		AB		B		O	
Parameter [a]:	ϵ_{ib}	ψ_{ib}	ϵ_{ib}	ψ_{ib}	ϵ_{ib}	ψ_{ib}	ϵ_{ib}	ψ_{ib}
DSA	Min-Max [b]	Min-Max	Min-Max	Min-Max	Min-Max	Min-Max	Min-Max	Min-Max
1	-0.52 - 1.05	-2.23 - 2.24	-3.36 - 32.02	-8.46 - 60.18	-1.64 - 5.07	-3.19 - 30.58	-0.58 - 0.4	-0.71 - 2.43
2	-14.38 - 15.12	-5.8 - 19.79	-36.39 - 9.32	-47.7 - 10.57	-14.86 - 38.26	-10.03 - 50.37	-7.25 - 12.48	-9.12 - 25.22
3	-0.83 - 1.58	-3.29 - 0.09	-22.59 - 86.1	-12.97 - 29.4	-5.62 - 10.68	-33.5 - 34.41	-2.52 - 3.77	-2.47 - 7.45
4	-0.26 - 1.07	-0.81 - 1.48	-0.47 - 4.05	-4.17 - 44.15	-0.43 - 0.81	-1.87 - 16.77	-0.18 - 1.01	-0.84 - 0.58
5	-1.4 - 0.88	-6.74 - 22.98	-15.15 - 8.5	-29.47 - 26.99	-6.14 - 14.98	-5.84 - 69.32	-0.38 - 5.03	-9.47 - 12.12
6	-0.27 - 1.24	-0.91 - 0.85	-0.35 - 6.54	-30.41 - 16.93	-0.45 - 1.73	-0.55 - 3.03	-0.27 - 0.42	-0.05 - 0.8
7	-0.44 - 0.65	-5.31 - 3.15	-0.12 - 27.67	-64.86 - 15.04	-7.06 - 8.35	-9.62 - 36.27	-0.45 - 0.7	-1.97 - 0.21
8	-4.71 - 0	-0.74 - 10.05	-6.29 - 32.68	-6.52 - 29.11	-4.09 - 0.71	-5.26 - 26.54	-0.01 - 1.92	-2.66 - 0.31
9	-8.47 - 17.09	-10.16 - 9.5	-10.74 - 31.98	-13.69 - 28.41	-3.66 - 33.31	-6.74 - 39.12	-1.73 - 5.47	-2.39 - 6.55
10	-0.24 - 1.1	-17.17 - 2.58	-26.64 - 3.84	-15.36 - 9.17	-0.54 - 4.54	-9.59 - 36.28	-0.66 - 0.41	-0.53 - 3.11
11	-6.59 - 8.71	-2.07 - 8.43	-6.22 - 21.44	-39.96 - 18.35	-4.56 - 69	-2.86 - 19.16	-0.86 - 10.85	-1.28 - 5.08
12	-1.23 - 10.72	-1.62 - 1.83	-35.64 - 21.47	-11.28 - 72.58	-7.12 - 15.52	-6.32 - 1.45	-2.53 - 1.2	-3.75 - 5.27
13	-3.66 - 0.16	-2.71 - 0.72	-14.12 - 17.95	-6.52 - 50.28	-4.64 - 2.79	-44.41 - 28.01	-0.84 - 0.89	-5.03 - 7.53
14	-7.12 - 0	-1.24 - 0.71	-7.15 - 10.35	-7.33 - 25.33	-5.78 - 8.7	-3.29 - 14.3	-2.01 - 3.11	-1.5 - 1.13
15	-1.22 - 6.23	-0.63 - 11.27	-8.76 - 30.43	-26.4 - 1.25	-3.74 - 9.28	-14.33 - 9.08	-0.7 - 3.13	-0.01 - 1.4
16	-5.11 - 36.79	-13.27 - 11.97	-7.68 - 19.66	-13.98 - 44.64	-10.91 - 18.09	-18.31 - 72.9	-2.9 - 22.89	-8.83 - 60.47
17	-2.93 - 7.05	-3.47 - 11.7	-10.96 - 19.36	-8.55 - 25.22	-4.77 - 46.15	-6.37 - 26.5	-1.71 - 2.8	-4.78 - 6.67
18	-0.71 - 1.06	-1.37 - 1.07	-2.35 - 0.67	-12.27 - 8.66	-0.96 - 1.54	-3.02 - 8.84	-0.55 - 0.66	0.08 - 1.29
19	-4.52 - 0.69	-2.22 - 5.58	-9 - 9.58	-9.82 - 25.56	-3.59 - 13.24	-5.57 - 17.74	-2.37 - 2.87	-3.04 - 6.84
20	-6 - 0.5	-5.91 - 6.35	-19.29 - 19.15	-5.64 - 59.64	-16.76 - 24.16	-8.21 - 28.46	-1.49 - 1.01	-2.7 - 8.71
21	-0.48 - 1.62	-1.87 - 0.69	-10.13 - 23.05	-8.34 - 49.11	-1.3 - 2	-2.93 - 43.56	-0.89 - 3.2	-0.91 - 4.62
22	-0.49 - 0.49	-1.22 - 3.12	-4.63 - 4.56	-13.19 - 5.31	-0.41 - 1.46	-11.21 - 2.24	-0.17 - 1.03	-1.64 - 0.08
23	-0.7 - 0	-2.1 - 1.34	-8.68 - 6.15	-10.18 - 57.71	-0.91 - 16.89	-8.54 - 11.32	-0.26 - 0.56	-3.33 - 8.52
24	-0.41 - 0.06	-1.45 - 2.23	-3.9 - 2.46	-3.76 - 10.29	-2.2 - 1.18	-1.59 - 10.82	-0.78 - 0.91	-0.38 - 2.92
25	-0.91 - 1.41	-0.25 - 0.49	-11.23 - 36.97	-12.99 - 43.07	-0.5 - 6.28	-2.77 - 22.66	0.55 - 1.54	-1.86 - 5.79
26	-2.15 - 0.01	-6.66 - 0	-17.67 - 30.88	-13.11 - 41.22	-4.23 - 10.22	-9.87 - 58.34	-0.34 - 2.08	-1.99 - 4.92
27	-7.07 - 19.37	-1.92 - 18.53	-23.13 - 33.65	-21.36 - 37.95	-14.3 - 50.77	-6.08 - 26.23	-6.92 - 29.69	-0.51 - 38.29
28	-4.89 - 6.56	-1.19 - 6.71	-17.97 - 24.02	-2.9 - 49.49	-4.42 - 27.69	-5.71 - 24.94	-1.66 - 0.02	-0.95 - 0.61
29	-29.55 - 0	-4.42 - 18.13	-9.16 - 37.6	-35.1 - 29	-22.44 - 62.31	-34.79 - 65.58	-3.83 - 8.56	-4.11 - 6.49
30	-1.36 - 1.26	-1.41 - 6.39	-7.25 - 44.71	-11.4 - 52.65	-0.54 - 2.37	-1.9 - 10	-1 - 0.12	-0.98 - 5.74
31	-10 - 4	-0.88 - 2.14	-6.55 - 35.01	-12.61 - 59.83	-8.92 - 3.01	-25.32 - 25.98	-2.18 - 4.13	-5.21 - 36.17
32	-0.78 - 0.47	-4.09 - 1.51	-8.88 - 25.38	-9.5 - 44.38	-4.73 - 0.48	-5.64 - 27.3	-0.47 - 0.55	-3.99 - 0.41
33	-11.05 - 1.13	-11.14 - 31.53	-23.68 - 8.89	-21.11 - 25.6	-6.84 - 50.77	-5.76 - 177.5	-2.58 - 6.41	-2.68 - 19.27
34	-5.46 - 0.99	-7.83 - 7.54	-26.95 - 45.46	-15.58 - 51.71	-15.63 - 41.47	-11.63 - 18.69	-0.47 - 6.46	-4.44 - 11.16
35	-0.8 - 5.1	-5.24 - 35.99	-6.56 - 34.71	-36.19 - 37.8	-8.61 - 58.17	-7.96 - 55.25	-2.6 - 2.6	-3.91 - 11.81
36	-1.95 - 1.45	-3.53 - 5.47	-5.25 - 31.12	-11.61 - 41.96	-4.05 - 28.47	-38.58 - 61.13	-1.83 - 1.99	-7.49 - 9.68
37	-0.01 - 0.23	-1.65 - 1.18	-9.13 - 0.28	-26.23 - 12.33	-0.16 - 1.69	-5.84 - 6.74	-0.19 - 0.15	-1.89 - 1.97
38	-0.59 - 20.57	-10.04 - 3.65	-33.59 - 40.24	-25.24 - 7.97	-11.71 - 37.41	-6.26 - 13.28	-5.89 - 26.93	-5.89 - 81.04
39	-1.54 - 2.65	-1.31 - 19.98	-6.76 - 22.05	-13.18 - 58.34	-5.61 - 14.37	-7.61 - 35.97	-0.98 - 2.64	-1.58 - 7.91
40	-0.42 - 7.53	-6.27 - 6.95	-17.9 - 29.21	-4.13 - 29.75	-9.13 - 9.15	-10 - 42.15	-2.53 - 5.42	-6.17 - 10.06
41	-0.86 - 0.44	-0.98 - 4.96	-18.13 - 67.22	-24.25 - 49.79	-2.66 - 0.87	-2.83 - 57.55	-0.16 - 2.51	-1.56 - 4.49

42	-8.12 - 12.98	0 - 5.02	-16.23 - 4.92	-10.48 - 25.3	-13.18 - 67.68	-7.02 - 34.35	-3.53 - 9.28	-4.7 - 12.25
43	-0.46 - 1.38	-3.12 - 5.83	-19.55 - 42.01	-2.68 - 44.32	-7.28 - 7.12	-10.5 - 45.57	-1.22 - 0.13	-3.76 - 7.23
44	-6.5 - 9.34	-0.91 - 2.46	-17.28 - 62.29	-13.28 - 30.43	-7.14 - 22.84	-9.73 - 27.26	-2.64 - 8.46	-2.86 - 4.05
45	-0.43 - 1.5	-1.43 - 1.31	-8.28 - 2.78	-5.78 - 9.16	-0.29 - 1.7	-3.84 - 4.38	-0.12 - 0.23	-0.17 - 0.2
46	-1.54 - 0.77	-3.6 - 5.08	-6.9 - 12.92	-17.61 - 16.58	-3.07 - 0.94	-4.32 - 9.28	-0.24 - 0.24	-0.69 - 0.29
47	-7.18 - 26.79	-4.61 - 61	-55.22 - 39.67	-51.38 - 66.07	-9.69 - 54.7	-6.32 - 33.43	-1.99 - 35.29	-2.73 - 83.47
48	-2.65 - 6.44	-1.49 - 4.67	-5.98 - 43.73	-9.28 - 41.88	-2.97 - 33.97	-5.03 - 62.33	-1.03 - 4.06	-2.13 - 12.69
49	-0.6 - 1.94	-0.34 - 1.98	-24.95 - 4.06	-32.2 - 33.14	-1.49 - 32.11	-5.79 - 62.39	-0.11 - 1.89	-0.43 - 1.75
50	-4.93 - 11.4	-4.82 - 13.64	-14.46 - 74.7	-17.5 - 69.08	-0.55 - 44.78	-5.67 - 20.8	-0.8 - 5.05	-6.45 - 7.83
51	-0.24 - 0.38	-3.09 - 0.23	-14.19 - 33.72	-10.79 - 24.64	-1.54 - 4.22	-5.76 - 10.09	-0.14 - 2.68	-1.05 - 2.52
52	-0.37 - 0.59	-1.43 - 1.6	-14.7 - 65.3	-5.75 - 20.93	-2.68 - 16.45	-1.23 - 45.9	-0.34 - 2.43	-0.87 - 9.22
53	-0.56 - 1.18	-2.27 - 2.39	-11 - 20.8	-20.93 - 40.21	-1.03 - 1.84	-4.91 - 29.45	-0.56 - 0.63	-0.76 - 0.67
54	-2.63 - 1.77	-1.46 - 6.5	-31.35 - 22.65	-14.04 - 61.57	-12.8 - 60.97	-9.86 - 68.03	-12.34 - 23.37	-8.84 - 28.38
55	-2.32 - 1.12	-7.75 - 0.9	-12.78 - 26.02	-7.94 - 35.53	-3.79 - 3.84	-12.24 - 44.78	-1.09 - 1.71	-0.2 - 7.76
56	-2.66 - 0.8	-2.53 - 9.59	-8.22 - 33.77	-14.44 - 55.74	-6.08 - 7.05	-6.46 - 37.5	-0.02 - 0.74	-2.53 - 6.35
57	-0.93 - 7	-8.77 - 8.05	-7.68 - 54.06	-11.11 - 18.52	-5.85 - 23.17	-2.33 - 29.49	-0.96 - 6.3	-7.65 - 11.9
58	-6.06 - 2.25	-1.57 - 1.54	-9.13 - 61.12	-9.89 - 48.52	-4.55 - 54.78	-12.29 - 117.71	-2.37 - 3.57	-2.75 - 8.25

[a]: ϵ_{ib} represents the patient interarrival time error distribution formed using exponential smoothing with trend. ψ_{ib} represents the kidney procurement interarrival time error distribution formed using exponential smoothing with trend.

[b]: Min-Max represents the minimum and maximum error term within sets ϵ_{ib} and ψ_{ib}, respectively.

DSA: Donor Service Area

3.3. DSA Parameterizations

In KSIM2, three main DSA-specific parameterizations are necessary. We will now discuss each of these parameterizations in detail.

Patient Demographics: Patient demographic-specific system outputs are provided by KSIM2 to show the impact of policy changes on specific patient subgroups. The user must specify the demographic of interest for the run: total population, age (<18, 18-65, >65 years old), or race (Non-Hispanic White, Non-Hispanic Black, Hispanic, Asian, Other). For the age and race demographic scenarios, OPTN data was used to specify the probability that arriving patients are within each demographic subgroup and the probability that a recipient is from a demographic subgroup. Table 3 and 4 show the probability distributions for age and race subgroup listed and recipient patient populations, respectively.

Patient Sensitization: As discussed, a patient's sensitization plays a large role in their ability to receive a suitable kidney match for transplantation.[12] KSIM2 incorporates patient sensitization levels by DSA according to the patient's PRA level (not sensitized (0-20% PRA), sensitized (20-80% PRA), and highly sensitized (80-100%). OPTN data was used to specify the probability that an arriving patient has a certain sensitization level as well as the probability that a transplant recipient has a specific sensitization level. Table 3 and 4 display the probability distributions for listing patient and transplant recipient sensitization levels, respectively.

KDRI Procurement and Acceptance: As discussed, procured kidneys are not of the same quality.[9,13,14] Furthermore, low quality kidneys are historically transplanted at only a few transplant centers across the country.[14] Therefore, KSIM2 must account for this behavior. A KDRI was calculated for each kidney procured and used for transplantation during 2000-2009 using OPTN data. The probability that a kidney procured in each KDRI range (0-1.0, 1.0-1.5, 1.5-2.0, 2.0-2.5, >2.5) was then determined for each DSA and blood group. A similar probability distribution was constructed for kidneys transplanted in each DSA for each blood group. Table 3 and 4 show the KDRI distributions for procured and transplanted kidneys, respectively.

Table 3: DSA Input Parameterization for Blood Type A Patients and Procured Kidneys in 2000

Parameter:	Listing Patient Age Demographics			Listing Patient Race Demographics					Sensitization Level (PRA)			KDRI Kidney Quality Procured				
Subgroup:	<18	18-65	>65	White	Black	Hisp.	Asian	Other	0-20%	20-80%	80-100%	0-1.0	1-1.5	1.5-2	2-2.5	>2.5
DSA	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1	32	62	7	63	36	0	0	0	82	11	7	45	39	13	3	0
2	34	59	8	68	29	2	0	0	85	10	5	44	33	17	4	0
3	23	64	13	59	6	25	2	8	85	8	7	48	34	15	3	0
4	28	59	13	49	10	22	17	3	84	11	6	32	47	16	5	0
5	22	66	12	65	7	16	9	2	79	11	10	37	41	19	2	0
6	32	59	8	38	11	39	10	2	87	9	5	38	38	18	5	1
7	25	61	14	45	8	34	9	4	89	7	4	30	52	14	4	0
8	27	60	13	74	5	17	2	2	75	13	11	49	36	12	2	1
9	27	61	12	70	15	13	2	0	81	11	8	41	46	12	2	1
10	27	65	9	42	44	7	6	1	80	12	8	32	39	21	6	2
11	23	61	16	55	27	15	3	1	84	9	6	45	38	13	4	0
12	22	64	14	45	20	31	1	2	89	7	5	36	41	17	3	2
13	22	59	19	65	27	6	1	1	86	9	5	40	38	16	5	2
14	23	56	21	70	15	12	3	0	76	17	7	43	37	16	3	1
15	28	61	10	56	39	2	2	0	77	12	11	35	42	17	5	2
16	19	71	10	7	1	1	60	32	90	5	4	27	49	18	5	1
17	18	67	15	84	8	6	1	1	84	10	7	37	48	12	3	1
18	29	62	8	54	28	13	4	1	81	9	10	31	40	21	6	2
19	24	64	12	78	18	2	1	0	81	14	4	45	41	11	3	1
20	26	64	11	84	14	1	0	1	79	17	4	39	40	18	3	0
21	26	65	9	47	49	3	1	0	74	14	13	41	41	14	3	0
22	25	64	11	77	12	7	2	1	87	8	5	37	44	14	5	1
23	22	62	16	60	34	2	3	1	83	11	7	31	42	18	6	3
24	27	64	10	70	25	3	1	0	78	12	10	39	43	14	4	0
25	23	64	13	87	4	2	3	5	77	14	9	37	39	19	4	1
26	25	62	13	79	17	1	2	0	88	9	3	45	37	13	4	1
27	35	63	3	26	72	1	0	1	88	8	4	38	38	16	7	2
28	26	64	11	76	17	4	1	1	82	10	8	46	40	11	3	0
29	35	56	8	55	42	1	1	1	81	11	7	41	41	10	7	1
30	26	64	10	57	38	2	1	1	77	14	9	34	42	15	8	1
31	20	67	13	84	8	5	2	1	88	7	4	37	45	15	2	1
32	26	62	12	59	24	12	4	1	78	12	10	27	45	18	7	3
33	27	62	10	23	4	39	0	34	85	9	6	52	32	13	2	2
34	26	67	6	54	19	15	6	6	85	8	7	49	32	14	4	0
35	28	61	11	88	8	2	2	1	89	10	1	31	44	16	7	2
36	26	65	9	84	10	4	2	0	89	8	4	32	46	15	5	1
37	26	59	15	42	30	20	7	2	89	8	3	27	41	21	9	2
38	27	61	13	66	26	5	1	2	81	9	9	24	44	26	4	3
39	24	67	9	75	21	2	2	0	75	15	10	22	44	26	7	1
40	20	66	14	74	20	5	1	0	76	14	10	43	40	14	3	1

41	27	63	9	79	19	1	2	0	83	11	6	34	51	11	4	0
42	17	67	16	73	26	1	0	0	76	13	11	35	45	14	5	1
43	24	63	14	74	15	4	1	7	86	8	5	44	40	11	5	0
44	18	64	18	81	7	6	5	1	93	4	3	41	41	14	4	0
45	22	62	15	68	24	4	2	1	84	10	7	31	42	17	7	3
46	22	60	18	89	10	1	1	0	86	10	4	35	43	17	4	0
47	30	62	8	1	1	95	0	4	78	16	6	39	33	22	5	0
48	27	60	13	50	49	0	0	0	77	14	9	40	34	19	4	3
49	27	63	10	78	19	2	0	0	75	14	11	53	33	11	3	0
50	31	63	6	37	60	1	2	0	80	11	9	38	40	13	8	1
51	29	62	10	53	21	21	4	0	78	13	9	42	38	15	4	1
52	26	65	9	31	8	59	1	1	77	9	13	50	32	14	3	0
53	30	63	7	49	21	26	3	0	83	10	8	38	43	14	5	0
54	28	61	11	86	2	8	3	2	73	13	14	52	38	8	2	0
55	27	66	7	54	43	1	1	0	72	14	14	37	39	20	4	0
56	22	64	14	76	6	5	8	6	76	12	12	49	37	12	2	0
57	21	65	14	69	21	7	2	1	74	14	11	35	43	19	3	1
58	21	69	10	85	8	3	3	1	85	10	5	32	42	20	4	1

DSA: Donor Service Area, Hisp: Hispanic, KDRI: Kidney Donor Risk Index, PRA: Panel Reactive Antibody

Table 4: DSA Input Parameterization for Blood Type A Recipients and Transplanted Kidneys in 2000

Parameter:	Recipient Age Demographics			Recipient Race Demographics					Sensitization Level (PRA)			KDRI Kidney Quality Transplanted				
Subgroup:	<18	18-65	>65	White	Black	Hisp.	Asian	Other	0-20%	20-80%	80-100%	0-1.0	1-1.5	1.5-2	2-2.5	>2.5
DSA	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1	36	60	4	62	38	0	0	0	87	11	3	44	37	15	3	0
2	35	59	6	69	29	1	0	0	89	9	2	50	34	13	2	0
3	28	61	11	63	5	22	2	7	88	7	5	50	32	15	4	0
4	35	56	8	51	10	20	15	3	87	9	3	36	48	13	3	0
5	26	62	12	66	9	15	9	2	84	9	7	37	42	19	2	0
6	35	59	7	44	11	34	9	2	88	8	4	34	41	19	5	1
7	31	58	11	50	10	28	8	4	89	7	4	24	51	21	4	1
8	31	59	10	75	5	16	2	2	78	13	10	56	32	9	2	0
9	31	61	8	73	16	10	1	0	83	11	6	43	48	6	2	1
10	31	62	6	45	43	6	5	1	84	11	5	39	39	17	4	1
11	29	59	12	61	22	14	2	1	87	9	4	51	37	9	3	0
12	27	62	11	45	18	33	2	2	95	4	1	38	43	16	2	1
13	27	58	16	67	26	5	1	1	90	7	2	36	40	19	3	2
14	28	55	17	73	15	10	2	1	80	15	6	50	36	13	1	0
15	33	60	7	58	38	2	2	0	82	11	7	39	43	14	3	0
16	28	66	6	10	2	1	57	31	95	4	1	33	45	18	3	1
17	27	63	10	88	7	4	1	1	88	8	4	34	51	12	2	1
18	35	59	6	57	27	12	3	1	85	8	6	30	40	22	6	2
19	33	59	8	83	14	1	1	0	84	13	3	48	42	8	2	0
20	31	61	8	85	14	1	0	0	82	17	1	43	40	15	2	0
21	31	62	7	50	46	3	1	0	81	10	9	41	43	14	2	1
22	30	61	8	81	10	6	2	1	90	7	4	36	43	15	5	1
23	26	62	12	61	35	2	2	1	86	10	4	19	39	24	14	4
24	35	58	7	73	23	2	1	0	83	10	6	41	43	12	3	1
25	27	61	12	88	4	1	2	5	80	12	8	37	39	19	3	1
26	29	61	10	76	20	1	2	1	95	4	1	54	35	10	1	0
27	39	59	2	30	69	0	0	1	93	6	2	49	40	9	2	0
28	35	58	7	82	13	3	1	1	84	10	7	55	37	7	1	0
29	40	53	7	62	35	1	1	1	84	11	4	46	45	8	2	0
30	31	61	8	58	39	1	1	1	80	13	7	31	41	18	9	2
31	28	63	9	86	7	4	1	1	94	4	2	40	45	13	2	1
32	31	60	9	59	25	11	4	1	84	10	5	26	45	18	8	3
33	32	61	7	37	2	35	0	25	86	9	5	52	32	11	2	2
34	28	66	7	62	16	13	5	4	90	6	3	64	32	4	0	1
35	36	58	6	89	6	2	1	1	92	8	0	34	43	15	7	1
36	33	61	6	83	11	4	2	1	92	6	2	36	46	15	3	1
37	31	58	11	46	28	19	6	1	90	8	3	20	39	26	13	2
38	33	58	9	71	23	4	1	2	84	9	7	23	45	24	5	4
39	33	61	7	75	22	2	2	0	84	11	5	25	43	26	6	0
40	26	64	9	77	18	4	0	0	80	14	6	45	39	13	3	0

41	29	62	9	79	19	1	1	0	89	9	1	36	50	11	3	0
42	31	61	8	73	26	0	1	0	84	12	4	40	45	13	1	1
43	31	60	9	76	13	4	1	6	89	8	3	52	35	9	3	0
44	28	60	12	85	5	5	4	1	93	5	3	41	40	14	5	0
45	27	61	12	71	23	4	2	1	88	8	5	32	42	17	6	2
46	30	57	13	89	9	1	1	0	89	8	3	34	44	17	4	0
47	36	59	5	2	0	95	0	3	81	15	4	45	33	17	4	1
48	31	59	9	48	50	1	0	1	84	11	5	50	33	14	1	1
49	33	60	7	79	19	1	1	0	77	15	7	58	32	9	2	0
50	37	60	4	43	55	1	1	0	85	10	5	38	40	15	6	0
51	31	61	8	57	19	20	4	0	82	12	6	46	38	14	2	0
52	31	62	7	36	9	52	1	1	80	8	12	45	34	17	3	0
53	33	61	6	53	21	23	3	0	85	9	6	38	43	14	5	0
54	32	58	9	89	1	6	2	2	74	14	12	69	28	3	0	0
55	30	63	7	57	41	1	1	0	70	14	16	35	40	20	4	1
56	30	61	9	79	6	4	7	5	79	11	10	51	36	11	2	0
57	24	64	12	73	20	4	2	1	85	10	5	36	43	16	3	2
58	24	68	8	88	6	2	2	1	88	8	4	31	44	19	5	1

DSA: Donor Service Area, Hisp: Hispanic, KDRI: Kidney Donor Risk Index, PRA: Panel Reactive Antibody

4. KSIM2 Verification and Validation

KSIM2 was implemented using C++ for each patient blood type separately. KSIM2 was replicated 100 times per blood type to best estimate KSIM2 system outputs. One complete run of KSIM2 requires 31.3 second of CPU time, and 100 runs of KSIM2 requires 52 minutes 11.8 seconds of CPU time. To ensure the accuracy of KSIM2's system outputs when testing alternative allocation policies, KSIM2 was verified and validated against actual OPTN kidney transplantation system data.

Verification was completed using (1) code debugging, (2) model reviewing, and (3) comparing generated system inputs and outputs against actual transplant system data. Post-verification, we concluded that KSIM2 provided a suitable translation of kidney transplantation system dynamics.

KSIM2 was completed for each system output using a similar methodology to that for KSIM (Davis et all, 2013). This validation process included using t-tests to explain the goodness of fit and 95% confidence interval on the relative error between simulated and actual system outputs for each DSA, blood type, and year combination per system output. Table 5 provides a summary of the 95% confidence interval on the relative error between simulated and actual system outputs for each DSA and system output for blood type A in year 2000. The maximum 95% confidence interval upper bound never exceeded 11.3% relative error.

Table 5: 95% Percent Relative Error Confidence Interval for DSA System Outputs in 2000

Blood Type:	A			AB			B			O		
Parameter [a]:	Waiting Time	Transplant Probability	Removal Probability	Waiting Time	Transplant Probability	Removal Probability	Waiting Time	Transplant Probability	Removal Probability	Waiting Time	Transplant Probability	Removal Probability
DSA	95% CI for Percent Relative Error			95% CI for Percent Relative Error			95% CI for Percent Relative Error			95% CI for Percent Relative Error		
1	0.35 - 2.03	0.35 - 1.33	4.42 - 6.1	0.35 - 2.03	0.35 - 1.33	4.42 - 6.1	9.13 - 10.92	6.8 - 9.59	2.21 - 3.58	9.13 - 10.92	6.8 - 9.59	2.21 - 3.58
2	5.81 - 9.46	1.77 - 1.88	6.16 - 9.8	5.81 - 9.46	1.77 - 1.88	6.16 - 9.8	1.95 - 3.81	1.49 - 3.36	2.66 - 4.52	1.95 - 3.81	1.49 - 3.36	2.66 - 4.52
3	6.48 - 9	0.05 - 2.47	1.89 - 4.4	6.48 - 9	0.05 - 2.47	1.89 - 4.4	8.85 - 10.16	3.29 - 7.6	8.73 - 10.04	8.85 - 10.16	3.29 - 7.6	8.73 - 10.04
4	1.75 - 3.03	1.4 - 2.68	0.17 - 1.11	1.75 - 3.03	1.4 - 2.68	0.17 - 1.11	5.48 - 8.08	0.85 - 1.75	1.2 - 1.4	5.48 - 8.08	0.85 - 1.75	1.2 - 1.4
5	1.82 - 11.87	1.83 - 11.86	3.95 - 5.64	1.82 - 11.87	1.83 - 11.86	3.95 - 5.64	1.36 - 3.73	1.76 - 6.85	1.14 - 3.95	1.36 - 3.73	1.76 - 6.85	1.14 - 3.95
6	2 - 11.05	4.08 - 4.97	3.45 - 5.61	2 - 11.05	4.08 - 4.97	3.45 - 5.61	1.13 - 5.04	0.1 - 4.01	5.99 - 9.9	1.13 - 5.04	0.1 - 4.01	5.99 - 9.9
7	5.08 - 6.57	3.43 - 8.21	5.55 - 6.09	5.08 - 6.57	3.43 - 8.21	5.55 - 6.09	1.46 - 2.38	1.63 - 2.21	0.41 - 3.43	1.46 - 2.38	1.63 - 2.21	0.41 - 3.43
8	3.04 - 5.59	3.33 - 5.88	5.76 - 8.31	3.04 - 5.59	3.33 - 5.88	5.76 - 8.31	4.07 - 6.63	5.69 - 8.24	9.8 - 10.36	4.07 - 6.63	5.69 - 8.24	9.8 - 10.36
9	2.09 - 7.64	1.82 - 7.38	6.42 - 11.98	2.09 - 7.64	1.82 - 7.38	6.42 - 11.98	3.67 - 9.45	1.64 - 6.42	1.64 - 7.41	3.67 - 9.45	1.64 - 6.42	1.64 - 7.41
10	5.72 - 8.16	5.68 - 8.12	1.42 - 3.87	5.72 - 8.16	5.68 - 8.12	1.42 - 3.87	8.97 - 12.94	0.38 - 3.59	1.09 - 2.88	8.97 - 12.94	0.38 - 3.59	1.09 - 2.88
11	2.1 - 9.28	4.04 - 11.21	1.57 - 5.74	2.1 - 9.28	4.04 - 11.21	1.57 - 5.74	0.89 - 4.05	2.89 - 7.84	3.73 - 8.68	0.89 - 4.05	2.89 - 7.84	3.73 - 8.68
12	1.78 - 4.7	1.02 - 3.94	0.1 - 2.82	1.78 - 4.7	1.02 - 3.94	0.1 - 2.82	4.74 - 8.32	7.14 - 10.72	5.66 - 9.24	4.74 - 8.32	7.14 - 10.72	5.66 - 9.24
13	1.31 - 7.87	5.49 - 11.05	6.49 - 9.04	1.31 - 7.87	5.49 - 11.05	6.49 - 9.04	2.59 - 4.63	4.79 - 6.83	0.97 - 3.01	2.59 - 4.63	4.79 - 6.83	0.97 - 3.01
14	1.85 - 14.95	3.76 - 4.85	1.8 - 4.9	1.85 - 14.95	3.76 - 4.85	1.8 - 4.9	3.68 - 4.21	7.81 - 10.69	3.85 - 4.04	3.68 - 4.21	7.81 - 10.69	3.85 - 4.04
15	2.95 - 11.24	8.54 - 10.83	8.53 - 10.82	2.95 - 11.24	8.54 - 10.83	8.53 - 10.82	1.69 - 3.62	2.16 - 4.09	4.32 - 6.24	1.69 - 3.62	2.16 - 4.09	4.32 - 6.24
16	0.97 - 1.58	1.46 - 4.01	0.43 - 2.99	0.97 - 1.58	1.46 - 4.01	0.43 - 2.99	2.76 - 5.31	0.05 - 2.5	0.28 - 2.84	2.76 - 5.31	0.05 - 2.5	0.28 - 2.84
17	0.59 - 9.29	0.97 - 7.73	7.34 - 9.04	0.59 - 9.29	0.97 - 7.73	7.34 - 9.04	1.54 - 2.73	13.84 - 21.02	5.13 - 9.31	1.54 - 2.73	13.84 - 21.02	5.13 - 9.31
18	8.94 - 12.67	0.32 - 3.41	0.03 - 3.71	8.94 - 12.67	0.32 - 3.41	0.03 - 3.71	4.65 - 8.72	1.42 - 2.65	2.34 - 6.41	4.65 - 8.72	1.42 - 2.65	2.34 - 6.41
19	0.44 - 1.56	6.34 - 9.47	1.49 - 2.61	0.44 - 1.56	6.34 - 9.47	1.49 - 2.61	0.95 - 4.6	5.69 - 9.34	3.66 - 7.31	0.95 - 4.6	5.69 - 9.34	3.66 - 7.31
20	1.28 - 5.67	2.96 - 3.98	4.67 - 9.61	1.28 - 5.67	2.96 - 3.98	4.67 - 9.61	3.81 - 5.54	1 - 1.36	2.62 - 6.74	3.81 - 5.54	1 - 1.36	2.62 - 6.74
21	0.03 - 3.07	1.47 - 4.58	0.81 - 2.29	0.03 - 3.07	1.47 - 4.58	0.81 - 2.29	1.03 - 5.99	5.06 - 10.02	2.18 - 7.14	1.03 - 5.99	5.06 - 10.02	2.18 - 7.14
22	1.14 - 4.47	3.07 - 6.39	8.6 - 11.92	1.14 - 4.47	3.07 - 6.39	8.6 - 11.92	3.33 - 6.73	0.99 - 2.4	0.6 - 4	3.33 - 6.73	0.99 - 2.4	0.6 - 4
23	0.84 - 7.1	5.88 - 9.14	0.73 - 6.99	0.84 - 7.1	5.88 - 9.14	0.73 - 6.99	3.22 - 5.55	3.84 - 6.18	4.73 - 7.06	3.22 - 5.55	3.84 - 6.18	4.73 - 7.06
24	3.52 - 6.08	1.78 - 4.33	5.27 - 7.83	3.52 - 6.08	1.78 - 4.33	5.27 - 7.83	1.51 - 4.06	1.52 - 4.07	7.35 - 9.9	1.51 - 4.06	1.52 - 4.07	7.35 - 9.9
25	5.65 - 8.99	4.65 - 10.99	1.1 - 5.24	5.65 - 8.99	4.65 - 10.99	1.1 - 5.24	1.95 - 3.45	2.51 - 2.88	4.06 - 9.46	1.95 - 3.45	2.51 - 2.88	4.06 - 9.46
26	8.67 - 10.48	3.23 - 7.04	1.76 - 5.05	8.67 - 10.48	3.23 - 7.04	1.76 - 5.05	2.51 - 2.83	7.42 - 10.75	7.67 - 10	2.51 - 2.83	7.42 - 10.75	7.67 - 10
27	0.55 - 6.15	1.37 - 6.97	0.03 - 5.57	0.55 - 6.15	1.37 - 6.97	0.03 - 5.57	0.56 - 4.72	5.12 - 10.4	2.71 - 7.99	0.56 - 4.72	5.12 - 10.4	2.71 - 7.99
28	3.7 - 7.83	3.08 - 7.2	2.3 - 9.42	3.7 - 7.83	3.08 - 7.2	2.3 - 9.42	0.58 - 7.91	1.29 - 7.62	0.67 - 8	0.58 - 7.91	1.29 - 7.62	0.67 - 8
29	0.7 - 2.47	1.11 - 10.66	4.01 - 5.78	0.7 - 2.47	1.11 - 10.66	4.01 - 5.78	0.14 - 2.82	0.92 - 1.75	1.94 - 4.62	0.14 - 2.82	0.92 - 1.75	1.94 - 4.62
30	3.77 - 6.55	0.7 - 3.48	1.12 - 3.89	3.77 - 6.55	0.7 - 3.48	1.12 - 3.89	0.19 - 3.04	5.86 - 8.71	1.09 - 1.76	0.19 - 3.04	5.86 - 8.71	1.09 - 1.76
31	8.19 - 10.06	2.02 - 5.88	0.2 - 4.07	8.19 - 10.06	2.02 - 5.88	0.2 - 4.07	0.44 - 2.85	3.57 - 5.98	1.01 - 3.42	0.44 - 2.85	3.57 - 5.98	1.01 - 3.42
32	3.53 - 6.09	0.7 - 1.85	5.69 - 8.24	3.53 - 6.09	0.7 - 1.85	5.69 - 8.24	1.25 - 3.81	3.59 - 6.14	1.41 - 3.97	1.25 - 3.81	3.59 - 6.14	1.41 - 3.97
33	1.64 - 3.04	0.28 - 4.39	4.72 - 9.39	1.64 - 3.04	0.28 - 4.39	4.72 - 9.39	0.58 - 5.03	1.89 - 2.55	9.84 - 10.29	0.58 - 5.03	1.89 - 2.55	9.84 - 10.29
34	2.58 - 6.02	0.09 - 3.34	2.14 - 5.57	2.58 - 6.02	0.09 - 3.34	2.14 - 5.57	0.23 - 4.08	6.06 - 9.91	6.47 - 10.32	0.23 - 4.08	6.06 - 9.91	6.47 - 10.32
35	4.03 - 10.11	0.61 - 5.47	2.16 - 3.92	4.03 - 10.11	0.61 - 5.47	2.16 - 3.92	1.5 - 5.38	4.03 - 7.91	1.49 - 2.39	1.5 - 5.38	4.03 - 7.91	1.49 - 2.39
36	1.2 - 4.56	1.95 - 5.31	7.43 - 10.78	1.2 - 4.56	1.95 - 5.31	7.43 - 10.78	1.18 - 5.43	1.19 - 3.06	6.02 - 10.27	1.18 - 5.43	1.19 - 3.06	6.02 - 10.27
37	0.92 - 4.31	1.79 - 3.44	1.67 - 3.56	0.92 - 4.31	1.79 - 3.44	1.67 - 3.56	0.55 - 1.16	0.77 - 0.94	0.12 - 1.59	0.55 - 1.16	0.77 - 0.94	0.12 - 1.59
38	4.25 - 5.78	5.19 - 6.34	6.2 - 7.73	4.25 - 5.78	5.19 - 6.34	6.2 - 7.73	0.27 - 3.57	0.74 - 4.57	0.55 - 4.39	0.27 - 3.57	0.74 - 4.57	0.55 - 4.39
39	1.73 - 5.22	9.24 - 10.73	4.22 - 7.71	1.73 - 5.22	9.24 - 10.73	4.22 - 7.71	0.92 - 2.75	3.87 - 7.53	0.94 - 2.72	0.92 - 2.75	3.87 - 7.53	0.94 - 2.72
40	8.12 - 10.68	3.29 - 5.84	7.19 - 9.74	8.12 - 10.68	3.29 - 5.84	7.19 - 9.74	7.04 - 9.59	0.64 - 3.19	2.69 - 5.24	7.04 - 9.59	0.64 - 3.19	2.69 - 5.24
41	1.88 - 3.12	1.09 - 6.08	7.65 - 10.64	1.88 - 3.12	1.09 - 6.08	7.65 - 12.64	2.28 - 5.08	1.03 - 1.77	6.26 - 9.06	2.28 - 5.08	1.03 - 1.77	6.26 - 9.06
42	0.73 - 1.03	2.44 - 3.19	1.4 - 2.15	0.73 - 1.03	2.44 - 3.19	1.4 - 2.15	1.12 - 4.62	2.86 - 7.35	7.31 - 9.81	1.12 - 4.62	2.86 - 7.35	7.31 - 9.81
43	2.22 - 7.4	2.62 - 7.79	0.89 - 6.06	2.22 - 7.4	2.62 - 7.79	0.89 - 6.06	0.79 - 1.03	2.34 - 4.16	0.24 - 2.06	0.79 - 1.03	2.34 - 4.16	0.24 - 2.06
44	5.43 - 7.88	3.4 - 5.85	0.98 - 3.43	5.43 - 7.88	3.4 - 5.85	0.98 - 3.43	1.02 - 6.09	1.27 - 6.33	1.1 - 3.96	1.02 - 6.09	1.27 - 6.33	1.1 - 3.96
45	0.99 - 3.47	1.6 - 4.09	0.56 - 3.05	0.99 - 3.47	1.6 - 4.09	0.56 - 3.05	5.51 - 9.68	1.3 - 2.87	8.61 - 10.78	5.51 - 9.68	1.3 - 2.87	8.61 - 10.78

46	4.21 - 5.03	7.78 - 9.61	5.15 - 5.68	4.21 - 5.03	7.78 - 9.61	5.15 - 5.68	9.01 - 10.67	1.31 - 5.97	1.09 - 5.76	9.01 - 10.67	1.31 - 5.97	1.09 - 5.76
47	1.69 - 2.18	1.81 - 2.07	4 - 7.88	1.69 - 2.18	1.81 - 2.07	4 - 7.88	2.65 - 4.28	0.27 - 1.9	3.09 - 4.72	2.65 - 4.28	0.27 - 1.9	3.09 - 4.72
48	2.17 - 2.72	0.58 - 1.98	0.86 - 1.69	2.17 - 2.72	0.58 - 1.98	0.86 - 1.69	6.35 - 8.9	0.77 - 1.78	3.68 - 6.23	6.35 - 8.9	0.77 - 1.78	3.68 - 6.23
49	0.91 - 7.64	0.05 - 6.77	1.39 - 8.12	0.91 - 7.64	0.05 - 6.77	1.39 - 8.12	2.08 - 7.48	9.77 - 11.18	4.5 - 9.9	2.08 - 7.48	9.77 - 11.18	4.5 - 9.9
50	4.04 - 9.17	1.71 - 3.43	1.41 - 3.72	4.04 - 9.17	1.71 - 3.43	1.41 - 3.72	0.68 - 4.4	6.35 - 9.07	5.27 - 9	0.68 - 4.4	6.35 - 9.07	5.27 - 9
51	7.53 - 10.9	6.87 - 9.24	0.63 - 5	7.53 - 10.9	6.87 - 9.24	0.63 - 5	2.33 - 2.52	0.31 - 4.55	5.8 - 10.66	2.33 - 2.52	0.31 - 4.55	5.8 - 10.66
52	0.56 - 2.41	2.57 - 5.54	3.37 - 6.34	0.56 - 2.41	2.57 - 5.54	3.37 - 6.34	4.57 - 8.87	0.7 - 4.99	9.44 - 10.74	4.57 - 8.87	0.7 - 4.99	9.44 - 10.74
53	1.49 - 4.4	5.32 - 10.2	5.87 - 8.76	1.49 - 4.4	5.32 - 10.2	5.87 - 8.76	3.45 - 6.34	5.57 - 8.45	0.29 - 3.18	3.45 - 6.34	5.57 - 8.45	0.29 - 3.18
54	1.78 - 2.79	8.26 - 10.27	1.78 - 6.23	1.78 - 2.79	8.26 - 10.27	1.78 - 6.23	6.4 - 10.2	5.9 - 9.7	3.47 - 6.33	6.4 - 10.2	5.9 - 9.7	3.47 - 6.33
55	3.42 - 6.33	0.99 - 1.92	6.77 - 9.68	3.42 - 6.33	0.99 - 1.92	6.77 - 9.68	1.01 - 4.26	0.03 - 3.21	0.25 - 3.49	1.01 - 4.26	0.03 - 3.21	0.25 - 3.49
56	0.07 - 2.49	5.29 - 7.85	2.88 - 5.43	0.07 - 2.49	5.29 - 7.85	2.88 - 5.43	1.12 - 3.67	6.27 - 8.82	1.16 - 1.39	1.12 - 3.67	6.27 - 8.82	1.16 - 1.39
57	3.17 - 6.5	4.7 - 8.03	0.49 - 2.84	3.17 - 6.5	4.7 - 8.03	0.49 - 2.84	3.25 - 9.48	3.11 - 3.13	6.23 - 10.47	3.25 - 9.48	3.11 - 3.13	6.23 - 10.47
58	1.22 - 6.12	0.58 - 4.32	1.76 - 6.65	1.22 - 6.12	0.58 - 4.32	1.76 - 6.65	1.14 - 4.64	7.97 - 11.46	3.76 - 7.25	1.14 - 4.64	7.97 - 11.46	3.76 - 7.25

[a]: Waiting time represents the years to transplantation within a DSA. Transplant probability represents the proportion of listing patients that will at some point receive a kidney transplant. Removal probability represents the proportion of listing patients who will be removed from the waitlist without receiving a kidney transplant.

[b]: 95% CI for % Rel. Error: 95% confidence interval on the relative error between simulated and actual system outputs.

DSA: Donor Service Area

5. Conclusions

In this paper, we have introduced a discrete event simulation, KSIM2, which extends a previous simulation model of the kidney transplantation system at the DSA level (KSIM). KSIM2 classifies patients and donated kidney organs more realistically. Patients are distinguished in KSIM2 by demographic and sensitization level, and donated kidney organs are distinguished by KDRI. The simulation was verified and validated using actual OPTN transplantation data from 2000 through 2009 to ensure KSIM2 is ready for use in the transplant community to test alternative geographic organ allocation strategies.

Parallel research aims to design alternative organ allocation strategies in collaboration with transplant system stakeholders.[19] KSIM2 fills a pertinent gap in the current kidney allocation policy development process by allowing for the quick testing of the impact of different geographic organ allocation strategies. This simulation is not intended to replace UNOS's current allocation simulation model, KPSAM, which investigates the impact of policies at the patient level given complex patient factors.[1] Instead, it was our intent for KSIM2 to be used by UNOS to simulate the impact of various proposed policies to iteratively refine alternative geographic allocation strategies at a high, system level. In completing this work in collaboration with transplant system stakeholders, it is our hope that KSIM2 will prove beneficial in the struggle to reduce geographic disparities in kidney transplantation.

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