Proceedings of the 2013 Winter Simulation Conference
R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, eds

CHARACTERISTICS OF A SIMULATION MODEL OF THE NATIONAL KIDNEY TRANSPLANTATION SYSTEM

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ABSTRACT

The United Network for Organ Sharing is planning to resolve the ever-growing geographic disparities in kidney transplantation. Currently available simulation techniques are limited in their ability to analyze the impact of policy changes at the system level. This paper discusses the development of a discrete event simulation of the kidney transplantation system, KSIM. KSIM design is discussed and can easily be adapted to test alternative geographic organ allocation policies. Input analysis employing actual transplantation system data was conducted to best represent patient and organ arrival processes. After discussing our model, we briefly describe how KSIM was verified and validated against twenty years of actual transplantation system information. We also describe the potential usability of KSIM in organ allocation policy development.

1 INTRODUCTION

End Stage Renal Disease (ESRD) affects over 700,000 patients in the United States (US), with increasing disease incidence rates each year (United States Renal Data System 2010). Compared to dialysis, kidney transplantation provides improved patient survival (Port et al. 1993) and quality of life while also being more cost-effective (Laupacis et al. 1996). Kidney transplantation, however, is hindered by great organ donation shortage. While over 95,000 patients are currently listed for kidney transplantation, less than 17,000 patients received a kidney transplant in 2012 (Organ Procurement and Transplant Network 2013). As a result, transplant patients must wait an exorbitant amount of time to receive a kidney transplantation, and thousands of patients die awaiting transplantation each year (United States Renal Data System 2010).

The United Network for Organ Sharing (UNOS) develops all organ allocation policies to direct how donated organs are distributed to patients around the country. Unfortunately, where a patient seeks transplantation around the US affects their transplant experience. In 2009, waiting times to transplantation varied from 0.5 years to 5.22 years and kidney transplantation rates varied from 3% to 30% across the country. These geographic disparities have increasingly grown since the 1990s (Davis et al. 2013). In 1998, the Department of Health and Human Services affirmed that organ allocation should not discriminate between patients based on geography (Department of Health and Human Services 1998). Since then, no changes to kidney allocation have been implemented to reduce geographic disparities. By June 2013 however, UNOS officials have mandated that each organ-specific allocation policy committee develop geographic metrics to be corrected in organ allocation. Then, they have prioritized their agenda to develop alternative sharing strategies to reduce geographic disparities in organ transplantation (Organ Procurement and Transplant Network 2012).

UNOS currently uses the Kidney-Pancreas Simulated Allocation Model (KPSAM) to test potential allocation policy changes (Scientific Registry of Transplant Recipients 2008). Historically, KPSAM has been used to investigate how changes to patient prioritization on the kidney transplant waitlist affects transplantation access and subsequent transplant outcomes for different segments of the patient population. KPSAM is limited however in its ability to characterize the impact of an allocation policy change on macro-level system outcomes. First, KPSAM requires complete patient and donor information to function. As a result, only retrospective studies can be completed. Second, KPSAM is only capable of simulating one year of organ allocation at a time. Therefore, testing the long run impact of a policy change is not possible. Third, transplant system geography is extensively hard-coded into KPSAM making it difficult to examine alternative organ allocation strategies. Because of these limitations, UNOS will require a new kidney transplantation system simulation to aid allocation policy committees in their task to develop alternative allocation strategies to reduce geographic disparities.

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. Shechter et al. (2005) use discrete-event simulation to model end stage liver disease and how it impacts the liver allocation process. 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. Pritsker et al. (1995) and Taranto et al. (2000) describe the large UNOS liver and kidney simulation models, respectively.

The contribution of our work is to study input data characteristics, design of a kidney transplantation system simulation framework, and some output analysis that can be used to study the impact of allocation polies at the system-level to investigate geographic disparities. This simulation is used in a follow-up paper (Davis et al. 2013) to test the impact of alternative kidney allocation strategies. Our discrete event simulation, KSIM, allows for retrospective and prospective studies of how changes in geographic allocation policy will impact geographic access to transplantation services at the Donor Service Area (DSA) level. Best-fitting distributions of patient and organ arrival processes were determined for each DSA from retrospective Organ Procurement and Transplant Network (OPTN) data to simulate patient and organ dynamics. System outputs from KSIM include each DSA's average time to kidney transplantation, the probability of a patient being removed from the transplant waitlist without transplantation, and the probability a patient will be removed from the transplant waitlist with a kidney transplant. KSIM outputs are validated against actual OPTN system outputs from 1990 through 2009.

The remainder of this paper is organized as follows. Section 2 provides a brief overview of the kidney transplantation system. Section 3 outlines KSIM's approach to simulating the kidney transplantation system and the input analysis conducted to best represent patient and organ dynamics in KSIM. Section 4 discusses the verification and validation of KSIM against actual 1990 through 2009 OPTN kidney transplantation system data. Section 5 concludes the paper with our final thoughts and areas for further study

2 THE KIDNEY TRANSPLANT SYSTEM

Geographically, UNOS divides the country in two ways. First, the country is divided into 11 regions of neighboring states. Second, each region is further subdivided into DSAs, with 58 total DSAs in the US. Each DSA has one Organ Procurement Organization (OPO) to facilitate local organ procurement and allocation services. Each DSA also contains kidney transplant centers, with 240 centers in total in the US.

ESRD patients may seek transplantation at the transplant center of their choice. Upon listing, they are added to the corresponding DSA waitlist where they are prioritized primarily based on their waiting time in the system. Patients are removed from any DSA waitlist if they receive a kidney transplant or become too sick to transplant. Since ESRD prevalence varies considerably around the country (Ashby et al. 2007), DSA waitlist sizes vary widely.

When a kidney is donated within a DSA, OPO coordinators offer the kidney first to patients in the same DSA of procurement (local allocation), then to patients in the same region (regional allocation), and ultimately nationally as necessary (national allocation) (Organ Procurement and Transplant Network 2010). Organ allocation varies greatly throughout the country as each DSA differs in their acceptance of locally, regionally, and nationally allocated organs. Since organ donation varies considerably around the country, the number of kidney transplants in each DSA very widely (Ashby 2007).

3 KSIM DESIGN

3.1 Patients

Patients arrive seeking transplantation according to a DSA-specific interarrival time distribution. For each DSA, blood type, and year combination, we characterize the interarrival time distribution. The overwhelming best-fitting distribution to describe patient interarrival times is the Exponential distribution (4410 (95%) of distribution fittings). The next best-fitting distribution was the Gamma distribution (186 (4%) of distribution fittings) and the third best-fitting distribution was the Lognormal distribution (46 (1%) of distribution fittings). The mean interarrival rate varied considerably across DSAs for each blood type. While the best-fitting distribution shape did not change, the patient interarrival rate changed considerably over time. For example, in one DSA, the patient interarrival rates for a blood type A kidney went from 17.4 days between patients in 1990 to 3.38 days between patients in 2009.

A patient may be removed from the system if they become too sick to transplant prior to receiving a kidney offer. In KSIM, when a patient arrives to the system, they are assigned a "removal time" by which if they have not received a kidney transplant by that time, we assume that the patient is too sick for transplantation and is removed from the waitlist. Removal time distributions were determined for each DSA, blood type, and year combination. From OPTN kidney transplantation data, we captured the amount of time between listing for transplantation and their removal from the transplant waitlist for each patient removed from the transplant waitlist prior to transplantation. Exponential distribution was the best fitting distribution for all combinations tested 90% (4176) of the times. The next best-fitting distribution candidate was the Gamma distribution (325 (7%) of distribution fittings) and the third best-fitting distribution was the Log-Logistic distribution (139 (3%) of distribution fittings).

3.2 Organs

Organs are donated in each DSA for transplantation according to a DSA-specific interarrival time distribution. For each DSA, blood type, and year combination, the overwhelming best fitting distribution of organ interarrival times is the Exponential distribution (4547 (98%) of distribution fittings). The next best-fitting distribution was the Gamma distribution (70 (1.5%) of distribution fittings) and the third best-fitting distribution was the Weibull distribution (23 (.5%) of distribution fittings). The interarrival rate considerably varied across DSAs for each blood type. For each DSA, while the best-fitting distribution shape did not change, the interarrival rate changed over time, but not as dramatically as was found for patient interarrival times.

Once donated, each organ is distributed to according to the governing geographic kidney allocation policy. With some allocation policy-specific probability, the donated organ may be allocated from the DSA of procurement to another DSA. To simulate current allocation policy, these probabilities are calculated annually from retrospective OPTN kidney allocation data.

A summary of the best-fitting distributions for all patient and organ input parameterizations are shown per DSA in Table 1.

Table 1: Summary of best-fitting input parameter distributions.

	Best Fitting Distribution N (%)								
	Patient Interarrival Time			Patient Removal Time			Organ Interarrival Time		
DSA	Exp	Gamma	Lognorm	Exp	Gamma	Log-Log	Exp	Gamma	Weibull
1	75 (94%)	4 (5%)	1 (1%)	72 (90%)	6 (7%)	2 (3%)	79 (99%)	1 (1%)	0 (0%)
2	77 (96%)	3 (4%)	0 (0%)	70 (88%)	6 (7%)	4 (5%)	79 (99%)	1 (1%)	0 (0%)
3	78 (98%)	2 (2%)	0 (0%)	74 (93%)	5 (6%)	1 (1%)	77 (96%)	2 (3%)	1 (1%)
4	75 (94%)	3 (4%)	2 (2%)	76 (95%)	4 (5%)	0 (0%)	78 (98%)	1 (1%)	1 (1%)
5	77 (96%)	3 (4%)	0 (0%)	71 (89%)	6 (7%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)
6	77 (96%)	2 (3%)	1 (1%)	73 (91%)	5 (6%)	2 (3%)	78 (98%)	2 (2%)	0 (0%)
7	75 (94%)	4 (5%)	1 (1%)	73 (91%)	6 (8%)	1 (1%)	79 (99%)	1 (1%)	0 (0%)
8	77 (96%)	3 (4%)	0 (0%)	70 (88%)	7 (8%)	3 (4%)	79 (99%)	0 (0%)	1 (1%)
9	77 (96%)	3 (4%)	0 (0%)	73 (91%)	4 (5%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)
10	77 (96%)	3 (4%)	0 (0%)	73 (91%)	5 (6%)	2 (3%)	78 (98%)	2 (2%)	0 (0%)
11	78 (98%)	2 (2%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	79 (99%)	1 (1%)	0 (0%)
12	74 (93%)	4 (5%)	2 (2%)	72 (90%)	6 (7%)	2 (3%)	78 (98%)	1 (1%)	1 (1%)
13	77 (96%)	3 (4%)	0 (0%)	73 (91%)	6 (8%)	1 (1%)	78 (97%)	2 (3%)	0 (0%)
14	78 (98%)	2 (3%)	0 (0%)	75 (94%)	3 (4%)	2 (2%)	78 (98%)	1 (1%)	1 (1%)
15	75 (94%)	4 (5%)	1 (1%)	74 (93%)	4 (5%)	2 (2%)	79 (99%)	0 (0%)	1 (1%)
16	78 (98%)	2 (2%)	0 (0%)	72 (90%)	5 (6%)	3 (4%)	78 (98%)	2 (2%)	0 (0%)
17	77 (96%)	3 (4%)	0 (0%)	73 (91%)	6 (8%)	1 (1 %)	77 (97%)	2 (2%)	1 (1%)
18	78 (98%)	2 (2%)	0 (0%)	71 (89%)	7 (9%)	2 (2%)	80 (100%)	0 (0%)	0 (0%)
19	77 (96%)	3 (4%)	0 (0%)	71 (89%)	6 (8%)	3 (3%)	79 (99%)	1 (1%)	0 (0%)
20	77 (96%)	3 (4%)	0 (0%)	72 (90%)	5 (6%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)
21	76 (95%)	4 (5%)	0 (0%)	71 (89%)	6 (8%)	3 (3%)	79 (99%)	1 (1%)	0 (0%)
22	77 (96%)	3 (4%)	0 (0%)	70 (88%)	7 (9%)	3 (3%)	79 (99%)	0 (0%)	1 (1%)
23	75 (94%)	3 (4%)	2 (2%)	73 (91%)	5 (6%)	2 (3%)	78 (98%)	0 (0%)	2 (2%)
24	78 (98%)	2 (2%)	0 (0%)	73 (91%)	6 (8%)	1 (1%)	79 (99%)	1 (1%)	0 (0%)
25	73 (91%)	4 (5%)	3 (4%)	72 (90%)	6 (8%)	2 (2%)	79 (99%)	1 (1%)	0 (0%)
26	76 (95%)	4 (5%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	78 (98%)	2 (2%)	0 (0%)
27	77 (96%)	3 (4%)	0 (0%)	73 (91%)	5 (6%)	2 (3%)	79 (99%)	1 (1%)	0 (0%)
28	77 (96%)	3 (4%)	0 (0%)	70 (88%)	7 (9%)	3 (3%)	79 (99%)	1 (1 %)	0 (0%)
29	76 (95%)	4 (5%)	0 (0%)	70 (88%)	6 (8%)	4 (5%)	77 (96%)	2 (3%)	1 (1%)
30	76 (95%)	4 (5%)	0 (0%)	71 (89%)	6 (8%)	3 (3%)	78 (98%)	2 (2%)	0 (0%)
31	77 (96%)	3 (4%)	0 (0%)	73 (91%)	5 (6%)	2 (3%)	77 (96%)	2 (3%)	1 (1%)
32	76 (95%)	4 (5%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	79 (99%)	1 (1%)	0 (0%)
33	77 (96%)	3 (4%)	0 (0%)	73 (91%)	6 (8%)	1 (1%)	78 (98%)	2 (2%)	0 (0%)
34	74 (93%)	4 (5%)	2 (2%)	69 (86%)	7 (9%)	4 (5%)	78 (98%)	2 (2%)	0 (0%)
35	77 (96%)	3 (4%)	0 (0%)	73 (91%)	4 (5%)	3 (4%)	78 (98%)	1 (1%)	1 (1%)
36	78 (98%)	2 (2%)	0 (0%)	72 (90%)	5 (6%)	3 (4%)	78 (98%)	2 (2%)	0 (0%)
37	77 (96%)	3 (4%)	0 (0%)	73 (91%)	4 (5%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)
38	76 (95%)	4 (5%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	78 (97%)	2 (3%)	0 (0%)
39	76 (95%)	4 (5%)	0 (0%)	71 (89%)	6 (7%)	3 (4%)	79 (99%)	0 (0%)	1 (1%)
40	75 (94%)	3 (4%)	2 (2%)	71 (89%)	7 (9%)	2 (2%)	79 (99%)	1 (1%)	0 (0%)
41	76 (95%)	4 (5%)	0 (0%)	71 (89%)	6 (8%)	3 (3 %)	79 (99%)	1 (1%)	0 (0%)
42	77 (96%)	3 (4%)	0 (0%)	72 (90%)	5 (6%)	3 (4%)	77 (96%)	1 (1%)	2 (3%)
43	76 (95%)	4 (5%)	0 (0%)	73 (91%)	5 (6%)	2 (3%)	79 (99%)	1 (1%)	0 (0%)
44	77 (96%)	3 (4%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	78 (98%)	2 (2%)	0 (0%)
45	75 (94%)	3 (4%)	2 (2%)	71 (89%)	5 (6%)	4 (5%)	79 (99%)	1 (1%)	0 (0%)
46	73 (91%)	5 (6%)	2 (3%)	71 (89%)	7 (9%)	2 (2%)	78 (98%)	1 (1%)	1 (1%)
47	77 (96%)	3 (4%)	0 (0%)	71 (89%)	6 (7%)	3 (4%)	78 (98%)	2 (2%)	0 (0%)
48	78 (98%)	2 (2%)	0 (0%)	73 (91%)	5 (6%)	2 (3%)	77 (96%)	2 (3%)	1 (1%)
49	77 (96%)	3 (4%)	0 (0%)	72 (90%)	5 (6%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)

50	76 (95%)	4 (5%)	0 (0%)	71 (89%)	6 (7%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)
51	77 (96%)	3 (4%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	78 (98%)	1 (1%)	1 (1%)
52	74 (93%)	4 (5%)	2 (2%)	72 (90%)	4 (5%)	4 (5%)	78 (98%)	1 (1%)	1 (1%)
53	77 (96%)	3 (4%)	0 (0%)	71 (89%)	6 (7%)	3 (4%)	78 (98%)	2 (2%)	0 (0%)
54	77 (96%)	3 (4%)	0 (0%)	71 (89%)	7 (9%)	2 (2%)	78 (98%)	1 (1%)	1 (1%)
55	77 (96%)	3 (4%)	0 (0%)	72 (90%)	6 (8%)	2 (2%)	79 (99%)	1 (1%)	0 (0%)
56	74 (93%)	4 (5%)	2 (2%)	72 (90%)	5 (6%)	3 (4%)	77 (96%)	2 (3%)	1 (1%)
57	80 (100%)	0 (0%)	0 (0%)	74 (93%)	5 (6%)	1 (1%)	79 (99%)	0 (0%)	1 (1%)
58	77 (96%)	2 (3%)	1 (1%)	71 (89%)	6 (7%)	3 (4%)	79 (99%)	1 (1%)	0 (0%)
All	4410 (95%)	184 (4%)	46 (1%)	4176 (90%)	325 (7%)	139 (3%)	4547 (98%)	70 (1.5%)	23 (0.5%)

** Exp = Exponential, Lognorm = Lognormal, Log-Log = Log-Logistic

3.3 Simulation Structure

KSIM is initialized with DSA patients who are listed for kidney transplantation on January 1, 1990. This waitlist initialization can be easily changed if the simulator wants to simulate a different timeframe. The next patient arrival time and organ arrival time are calculated for each DSA and subsequently the system overall. The simulation is driven by three main events: (1) patient arrivals, (2) patient deaths, and (3) organ arrivals. Figure 1 shows pictorially the flow of patients and organs throughout KSIM.

When a patient arrival is the next event to occur, the patient is added to the end of the DSA's waitlist queue. They are assigned a "removal time" from their DSA's removal time distribution. If the new patient's removal time is less than the minimum removal time of all other patients on the waitlist, the arriving patient is flagged as the next patient to potentially die on the waitlist. The total number of arrivals to the system and to the DSA itself are updated. The next arrival time to the DSA is calculated and the next overall patient arrival time is adjusted if necessary. The total simulation time is updated.

If a patient's death is the next event to occur, the patient is removed from their corresponding DSA's waitlist queue. The patients listed after the dying patient are moved up in placement in the waitlist. The amended DSA waitlist is searched to determine the next potential patient to die awaiting transplant. The next patient death in any DSA is adjusted if necessary. The total deaths in the system and the DSA are updated. The total simulation time is adjusted.

If an organ arrival is the next event to occur, the DSA with which the donated kidney is to be allocated to is determined. The patient at the front of the DSA's waitlist being allocated the kidney is assumed to accept the kidney and is removed from the waitlist. The patient's time to transplant is stored as the time elapsed between the patient's arrival to the system and the current total simulation time. The total transplants in the system and the DSA is updated and the total simulation time is adjusted. The next organ arrival to the DSA is determined and the next overall organ arrival time is adjusted if necessary.

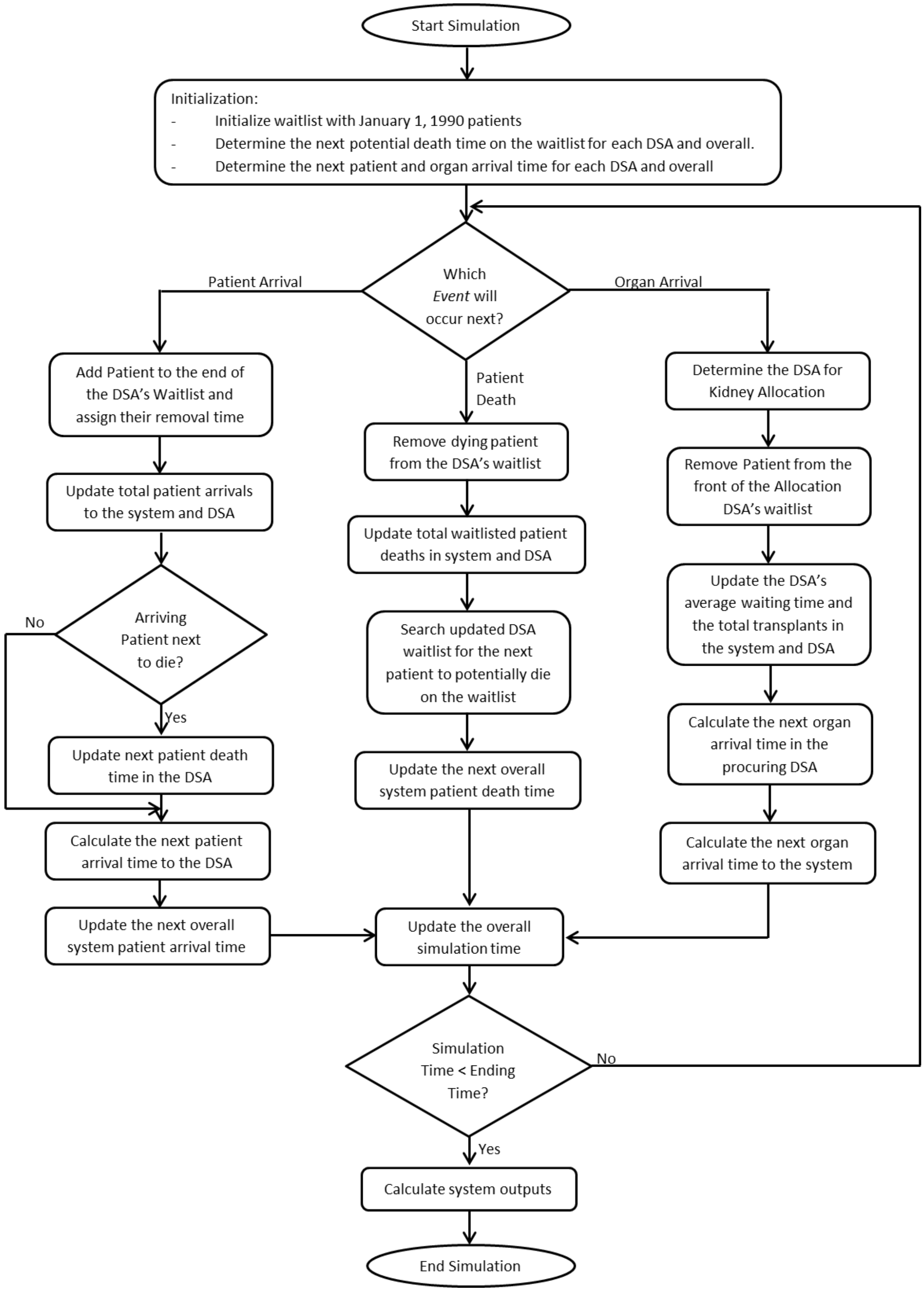

Figure 1: Systematic flowchart of KSIM.

3.4 System Outputs

Three system outputs are calculated annually to represent potential system geographic disparity metric. Average waiting time to transplantation is calculated as the average waiting time of all transplant recipients in a DSA each year. The probability of death on the waitlist is captured per DSA annually as the ratio between total DSA waitlist deaths and the total DSA waitlist arrivals by the end of a particular year. Similarly, the probability of transplant is calculated annually per DSA as the ratio between the number of DSA transplants and the total number of DSA waitlist arrivals by the end of a particular year.

4 KSIM IMPLEMENTATION

KSIM was implemented using C++ for each patient blood type individually. KSIM was replicated 100 times per blood type to best estimate KSIM system outputs. To ensure the accuracy of KSIM results when testing alternative allocation policies, KSIM 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 KSIM provided a suitable translation of kidney transplantation system dynamics.

Validation was completed for each system output using t-tests to explain the goodness of fit and 95% confidence interview on the relative error between simulated and actual system outputs. These tests were completed for each DSA, blood type, and year combination per system output. For simplicity, we provide a representative example of our testing for one DSA's average waiting time accuracy.

In this DSA, patient interarrival time, organ interarrival time, and patient removal time distributions were Exponentially distributed. Simulated and actual average waiting times to transplantation are shown per blood type in Figure 2. All t-tests concluded that there was not a significant difference between simulated and actual average waiting times ($p > 0.05$). Percent relative error 95% confidence intervals are shown in Table 2 per blood type and year. The maximum 95% confidence interval upper bound never exceeded 10.2% relative error. Similar results were found for all other DSAs and system outputs. From this analysis, we conclude that KSIM provides valid estimates of kidney transplantation system outputs.

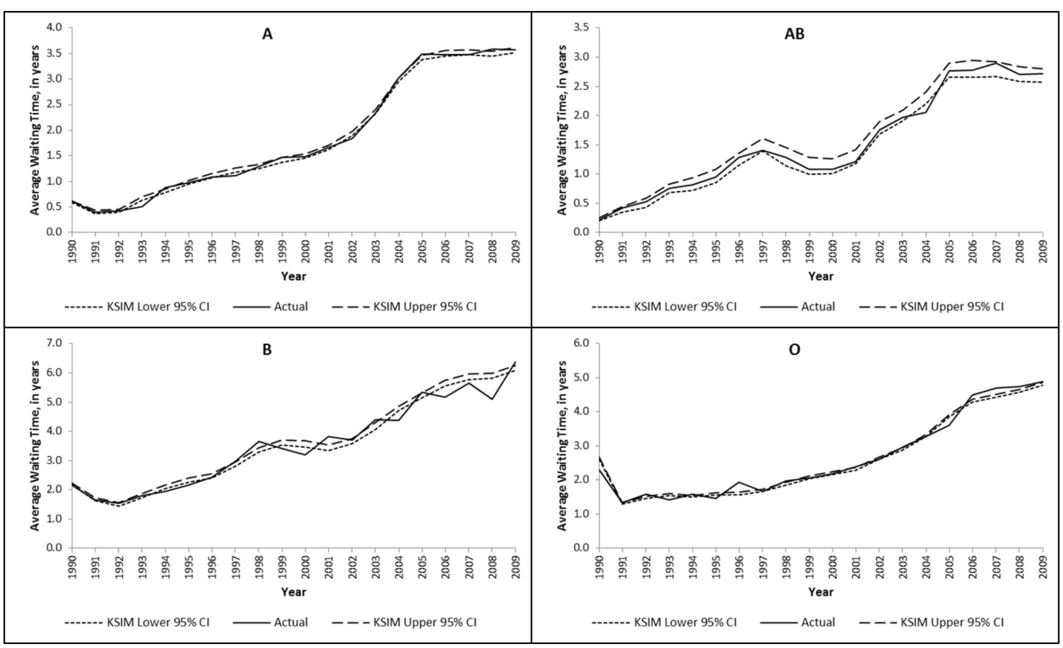

Figure 2: 95% confidence interval (CI) KSIM average and actual average waiting times in a DSA.

Table 2: 95% confidence interval on percent relative error of KSIM average waiting times in a DSA.

Year of Study	Blood Type			
	A	AB	B	O
1990	(4.32% - 6.02%)	(4.93% - 7.68%)	(4.84% - 6.44%)	(7.10% - 9.15%)
1991	(3.91% - 4.47%)	(2.81% - 5.74%)	(4.36% - 7.87%)	(6.43% - 9.34%)
1992	(3.53% - 4.85%)	(3.26% - 8.57%)	(5.18% - 6.35%)	(5.95% - 7.87%)
1993	(4.48% - 4.90%)	(4.97% - 7.71%)	(3.09% - 5.02%)	(4.85% - 7.58%)
1994	(2.30% - 3.13%)	(6.11% - 7.70%)	(1.92% - 5.97%)	(6.98% - 9.85%)
1995	(3.87% - 4.83%)	(6.76% - 8.54%)	(2.79% - 6.81%)	(5.76% - 8.44%)
1996	(5.55% - 6.76%)	(2.94% - 4.56%)	(2.27% - 5.96%)	(7.05% - 9.45%)
1997	(5.41% - 5.91%)	(3.03% - 4.94%)	(5.35% - 8.63%)	(7.00% - 9.23%)
1998	(3.57% - 5.02%)	(6.55% - 8.16%)	(4.56% - 7.43%)	(7.46% - 9.72%)
1999	(4.33% - 5.97%)	(8.50% - 10.14%)	(4.33% - 7.56%)	(7.06% - 9.37%)
2000	(2.12% - 2.54%)	(7.50% - 9.81%)	(6.73% - 7.75%)	(6.69% - 8.96%)
2001	(7.39% - 8.36%)	(3.63% - 6.12%)	(2.32% - 5.63%)	(6.41% - 8.91%)
2002	(7.34% - 8.37%)	(2.23% - 3.16%)	(6.59% - 9.22%)	(5.16% - 6.86%)
2003	(5.75% - 7.55%)	(1.56% - 2.18%)	(5.53% - 8.20%)	(4.67% - 6.18%)
2004	(4.72% - 6.20%)	(1.89% - 2.36%)	(6.00% - 8.82%)	(3.08% - 4.31%)
2005	(4.41% - 6.15%)	(1.72% - 2.47%)	(5.84% - 7.82%)	(6.48% - 7.91%)
2006	(4.91% - 6.61%)	(1.92% - 2.71%)	(6.80% - 9.52%)	(4.23% - 5.65%)
2007	(5.05% - 6.68%)	(1.73% - 2.44%)	(6.16% - 8.34%)	(5.05% - 6.66%)
2008	(4.97% - 6.93%)	(1.84% - 2.53%)	(4.70% - 7.78%)	(3.84% - 5.17%)
2009	(4.72% - 6.45%)	(1.68% - 2.34%)	(5.37% - 7.19%)	(3.43% - 4.66%)

5 CONCLUSIONS AND FUTURE RESEARCH

In this paper, we have introduced a discrete event simulation, KSIM, that models the kidney transplantation system at the DSA-level. The simulation model design was explained and efforts taken to best represent all KSIM input distributions was discussed. KSIM was validated using actual kidney transplantation system data from 1990 through 2009 to ensure KSIM is ready for use by the transplantation community to test alternative geographic organ allocation strategies.

Current work is underway with transplant system stakeholders to design alternative organ allocation strategies using optimization modeling (Davis et al. 2013). KSIM will be used to simulate the impact of various proposed policies in order to iteratively refine alternative geographic allocation strategies. In completing this work in collaboration with transplant system stakeholders, it is our hope that KSIM will prove beneficial in the struggle to reduce geographic disparities in kidney transplantation.

ACKNOWLEDGMENTS

This work is funded by the National Science Foundation award CMMI-1131568, the Agency for Healthcare Research and Quality Health Services Research Dissertation Award R36 HS021078-01, and the Northwestern Transplant Outcomes Research Collaborative (NUTORC). The content of this work is the responsibility of the authors alone and does not necessarily reflect the views or policies of the Department of Health and Human Services, nor does mention of trade names, commercial products, or organizations imply endorsement by the US Government. The authors would like to thank the members of NUTORC for their opinions and suggestions for this work.

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