A System Dynamics Model of the Kidney Transplants in the U.S.

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Abstract

In one of the most developed countries in the world, the United States of America, a crucial problem for the population remains unsolved: the huge waiting list for patients waiting for an organ transplant. On average, 21 people die each day while waiting for a transplant. The purpose of this paper is to analyze the current kidney transplant situation in the U.S., as well as to test by means of system dynamics modeling whether policies lead to an amelioration of the waiting list problem. Two different policies that balance effectiveness and social acceptance are implemented with the aim to improve the supply side of the system, i.e. the donation of kidneys. The main conclusions are that the implication of such policies are effective and necessary, but not sufficient. Further research in living donation is required to guarantee a sufficient solution to the problem.

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1 Introduction

In one of the most developed countries in the world, the United States of America, a crucial problem for the population remains unsolved: the huge waiting list for patients needing an organ transplant. On average, 21 people die each day while waiting for a transplant (OPTN, 2012).

In particular, kidney transplants are among the most solicited interventions (see **Figure 1**). Even though there exist alternatives such as dialysis for patients with end stage renal diseases, kidney transplantations represent a significant improvement in quality of life and longevity of the patients. However, the number of candidates for a kidney transplant on the waiting list continues to increase each year, while organ donation numbers remain flat, as displayed in **Figure 2**.

The purpose of this paper is to analyze the current kidney transplant situation in the U.S., as well as to study policies to ameliorate the waiting list problem through system dynamics modeling.

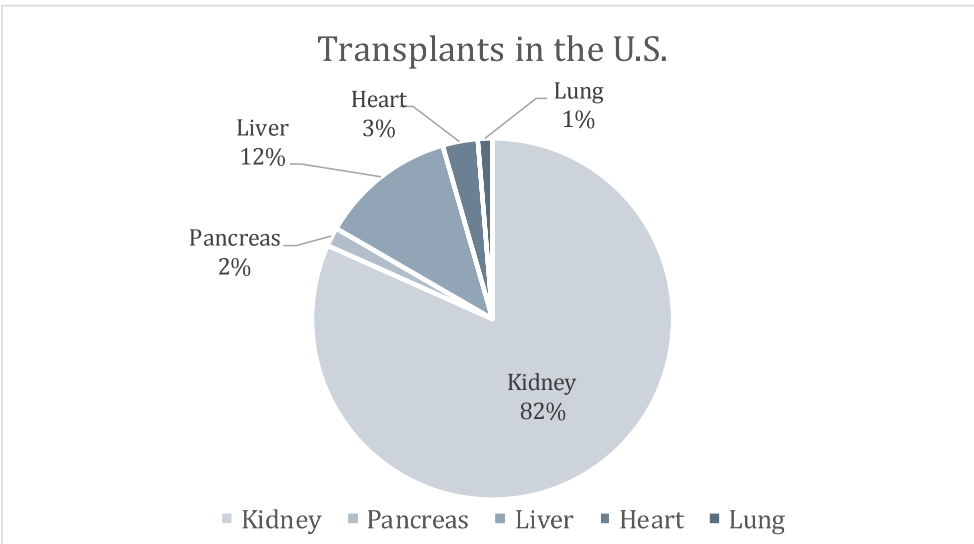

Figure 1: Distribution of organ transplants in the U.S. in 2011 (OPTN, 2012)

The rest of the paper is organized as follows: section 2 describes in more detail the problem situation, the usefulness of a system dynamics approach, and the boundaries of the analysis. Section 3 describes the conceptualization problem, as well as the development of the model. Different identifiable submodels are described in an attempt to present the modeling process in a comprehensive way. Both a highly aggregated causal loop diagram and a Sector-Diagram are also presented. Section 3 ends with a validation of the model. In section 4 four different KPIs are introduced, and the behavior of the model in the base scenario is presented. Section 5 presents two proposed policies that have the objective to revert the current tendency in which demand for kidneys increasingly surpasses supply. Finally, section 6 presents the conclusions of this paper, as well as suggestions for further research.

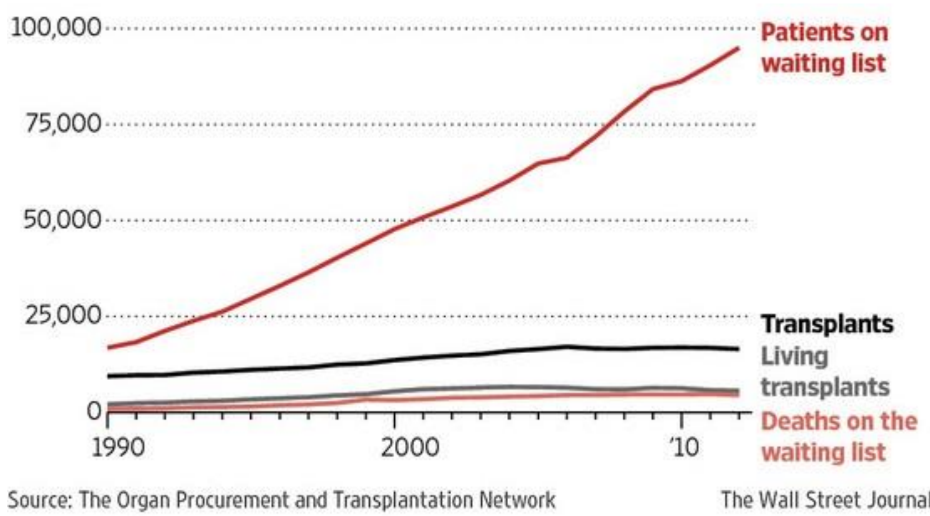

Figure 2: Evolution of patients on the waiting list and transplants from 1990 to 2013

2 Problem formulation

2.1 PROBLEM SITUATION IN THE U.S.

As indicated in **Figure 2**, the waiting list for a kidney transplant in the U.S. continues to increase every year. The real problem however lies in the consequences this rising tendency has for the life quality of the patients. Although there are currently some alternatives to organ transplantations, such as dialysis, and the future might bring extraordinary breakthroughs that could solve this problem, such as stem cells (EuroStemCell, 2013), the truth is that nowadays the only long lasting, quality solution for patients suffering from end stage renal diseases are kidney transplantations. The scope of this paper is limited to this issue.

Focused on the kidney transplantations, the size of the waiting list is one of the most controversial issues, and also the one that media coverage targets. There are however several other implications that need to be addressed if this problem is to be tackled. Hence, this paper divides the study and analysis of the kidney transplantations problem into the following issues:

- Increasingly large waiting list for kidney transplants in the U.S.
- High mortality of patients waiting for a long time in the waiting list. On average, 12 people die each day in the country while waiting for a life-saving kidney transplant.
- Many potential kidneys are lost every year because more than half of the population are not donors upon death.
- It is not easy to increase society's awareness of the problem.
- Unequal distribution of the problem according to the blood type of the patient.
- There are many ethical and moral issues, especially when it comes to encouraging donation.

2.2 SYSTEM DYNAMICS APPROACH

System dynamics is the main methodology used in this paper to study the problem of the kidney transplants in the U.S. because of three reasons. First, studying the global picture of kidney transplantations is a complex issue of dynamic nature.

Second, structural changes are required in order to solve the problem, which are relatively easy to test by means of system dynamics.

Finally, organ transplantations is also a field that, because of the big ethical implications and moral dilemmas implied, is not acceptable for real life testing. Studying this kind of system by means of system dynamics has the advantage that policies can be tested without actually needing to consider these kind of human issues: "*system dynamics allows to identify desirable system changes and test them in a virtual laboratory* " (Pruyt, 2013).

There already exist research in the field of chronic diseases (Homer, et al., 2004), addiction treatment policies (Nielsen & Wakeland, 2013) and organ donation (Hirsch, et al., 2012) using system dynamics. The approach followed in this paper is however different in that intends to capture the problem in a purely endogenous way, using the age chain of the U.S. as a starting point and projecting it over a long timeframe, 35 years. Furthermore, its scope is limited to kidney transplants.

Anyhow, the authors believe that different formulations of the same problem capture characteristics from different angles, give room for different policies, and eventually enhance the support in the decision making-process.

3 System Dynamics Model: Conceptualization, Development and Validation

Section 2 discussed the motivations to use System Dynamics in the study of the problem field and the testing of policies. This section presents the approach followed while modeling the problem situation, from the model conceptualization and to the model validation.

3.1 MODEL CONCEPTUALIZATION

Figure 3 summarizes the conceptualization of the problem. It includes the boundaries of the system, as well as the different subsystems that will be considered during the model development. The socio-technical complexity of the problem is represented by a supply and demand subsystem embedded in a social context characterized by ethical dilemmas and society sensitization.

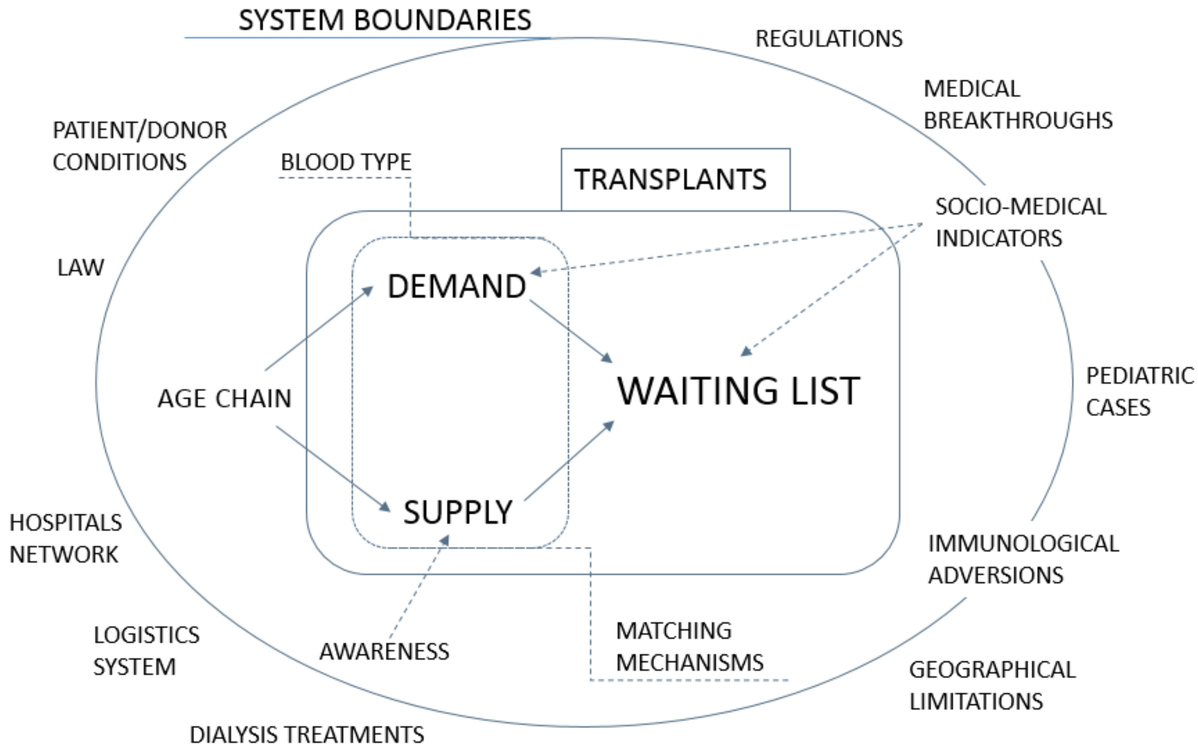

Figure 3: Conceptualization diagram

Incompatibilities among blood types add further complexity to the problem. Due to the fact that transplants between different blood types are not symmetric, chances of an individual to find a suitable kidney depend on the blood group she/he belongs to. The matching system of organ (kidney) transplantations according to the blood type of donors and recipients is shown in **Table 1**.

Table 1: Influence of blood types in the donor/recipient matching process

CAN DONATE TO		CAN RECEIVE FROM	
DONOR	RECEIVER	RECEIVER	DONOR
A	A, AB	O	O
B	B, AB	A	A, O
AB	AB	B	B, O
O	A, B, AB, 0	AB	A, B, AB, O

The timeframe considered is 35 years, allowing to explore the problem and to study the implication of policies on the system without having too much uncertainty regarding future technology developments and societal changes.

Table 2 contains data included in the model as starting point, corresponding to the year 2010. This will allow some preliminary validation using historical data.

Table 2: Initial values and constants in the model.

Parameter	Value	Units	Source
Initial waiting list for an organ transplant	83900	person	(OPTN, 2012)
Initial number of children under 12	5,08E+12	person	(CDC, 2015)
Initial number teenagers (under-age)	3,15E+12	person	
Initial number of adults	1,89E+13	person	
Initial number of retirees	4,47E+12	person	
Base net annual immigration	1E+09	person	(OIS, 2012)
Percentage of teenagers that need a kidney transplant	1.91E-05	1/year	(OPTN, 2012)
Percentage of adult people that need a kidney transplant	1.51 E-04	1/year	
Percentage of retirees that need a kidney transplant	5.66 E-05	1/year	
Teenagers death rate	3.93 E-04	1/year	(Sherry, et al., 2013)
Adult death rate	0.0033	1/year	
Retirees death rate	0.04	1/year	
Percentage of adult deaths in hospitals	0.27	Dmnl	(NVSS, 2013)
Percentage of families that approve a donation	0.365	Dmnl	(Kolata, 1995)
Fraction of adults donating upon death	0.4	Dmnl	(Makely, 2013)
Alive adults donation rate	3.2 E-05	1/year	(OPTN, 2012)
Kidneys transplanted per organ recovered	0.85	Dmnl	
Average time patients live before dying	8	year	(Graham, 2013)
Fraction of patients that accept the organ	0.8	Dmnl	(OPTN, 2012)
Fatality ratio of rejections	0,1	Dmnl	
Average sphere of influence	25	person	(Hampton, et al., 2016)

3.2 MODEL DEVELOPMENT

The highly aggregated causal diagram of **Figure 4** presents the essence of the model developed in this paper.

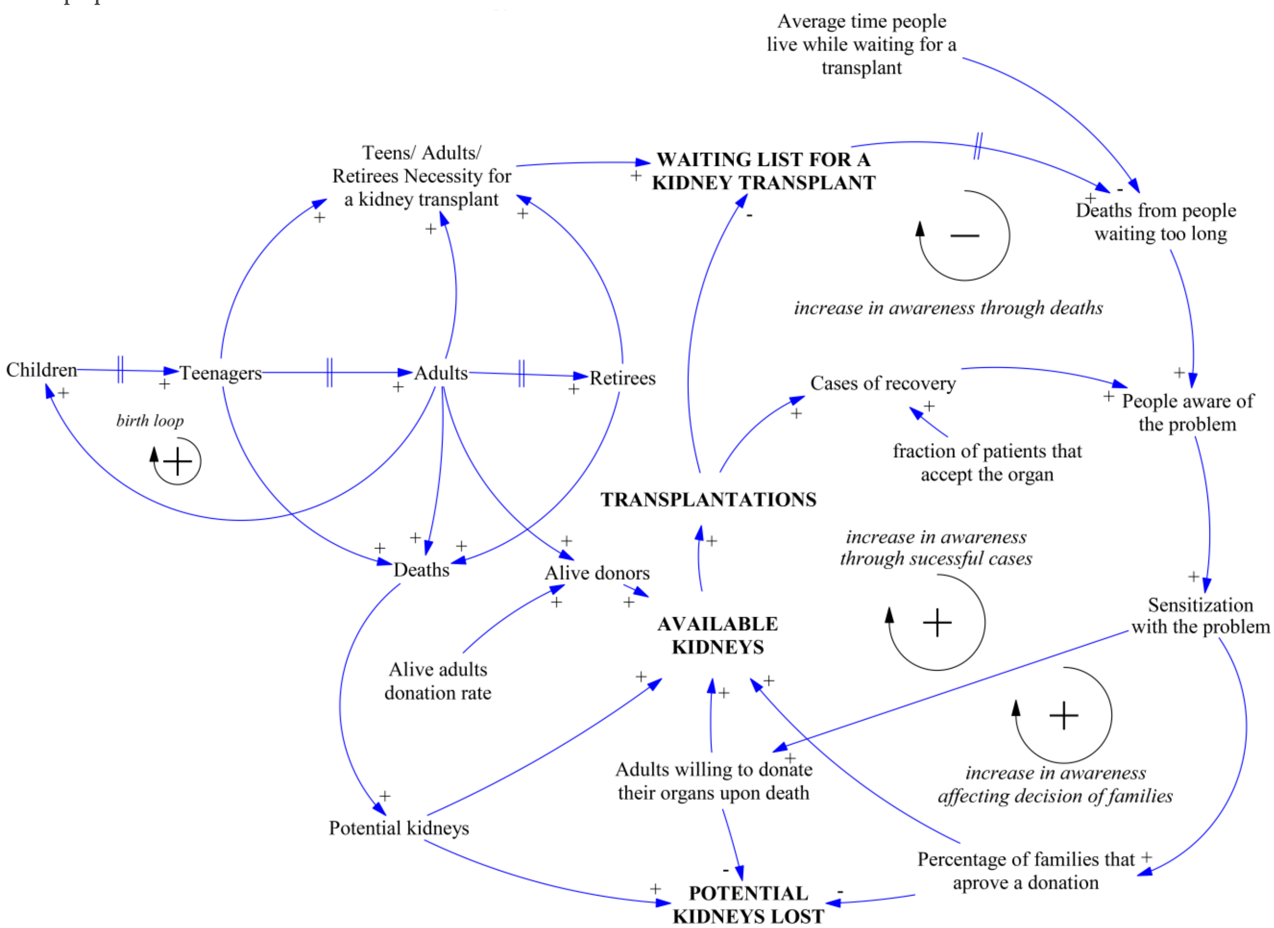

Figure 4: Highly Aggregated Causal Loop Diagram of the model

The variables of interest, which later will define the main KPIs, are the *waiting list for a kidney transplant*, the *transplantations,* the *available kidneys* and the *potential kidneys lost*. Note that, according to the conceptualization of the problem presented, these variables are influenced by demographic aspects (age chain, immigration etc.), medical aspects (organ rejections, blood type etc.) and social aspects (people aware of the problem, adults willing to donate their organs upon death, alive donors, etc.).

Taking the highly aggregated causal loop diagram as a starting point, the complete model was developed. The final model contains over 160 variables (over 360 if subscript equations, which will be introduced later, are considered), and is presented in **Figure 5** in the form of a Sector-Diagram., where the main submodels that conform the overall model have been identified. These submodels are described in subsequent sections. The complete Stock-Flow diagram can be found as an appendix.

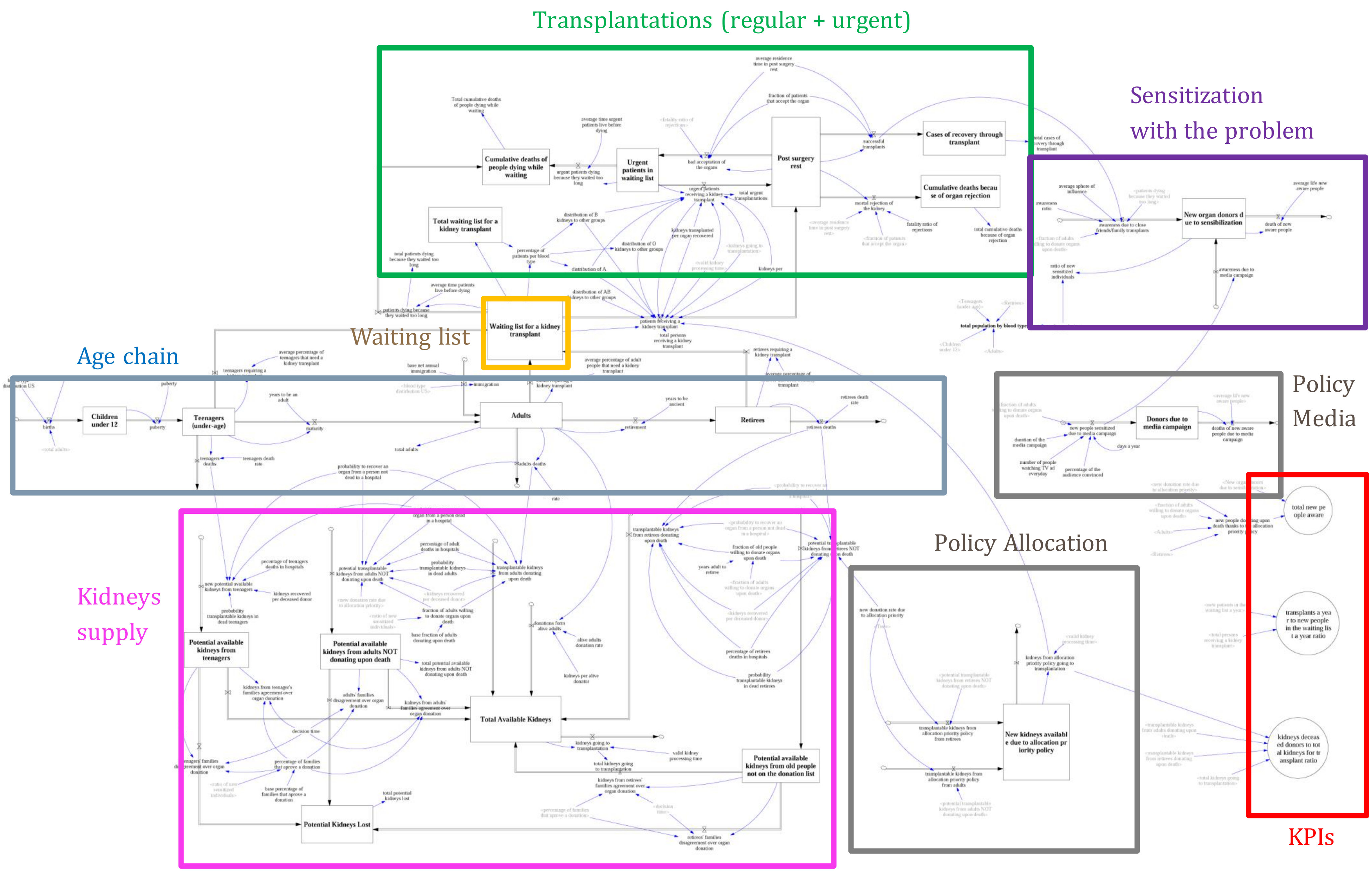

Figure 5: Sector-Diagram of the kidney transplants in the U.S. Different submodels are identified.

Understanding the different submodels presented in the Sector-Diagram of **Figure 5** is an easy and comprehensive way to understand the modeling approach followed in this paper. These different submodels are described below.

3.2.1 Waiting list, kidneys supply and transplantations

The issue of the increasing waiting list for a kidney transplant is modeled as a supply and demand problem, as depicted in **Figure 6**.

Figure 6: Waiting list as a function of the demand and supply for kidneys

The supply of kidneys comes from three major sources (**Figure 7**). These sources are the *people willing to donate upon death*, the *donations approved by families* (people that were not originally donating upon death but their relatives decided to approved a donation), and *alive donors*.

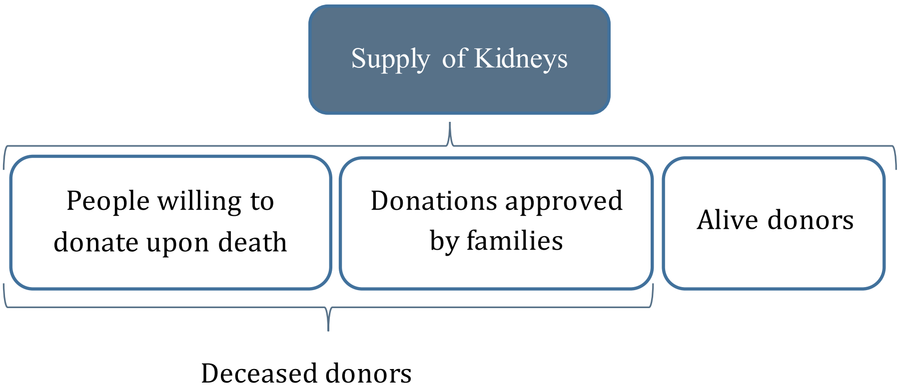

Figure 7: Main sources of the supply of kidneys present in the model

As for the demand part of the system, it has also been modeled as the sum of three sources: *teenagers*, *adults* and *retirees* (**Figure 8**).

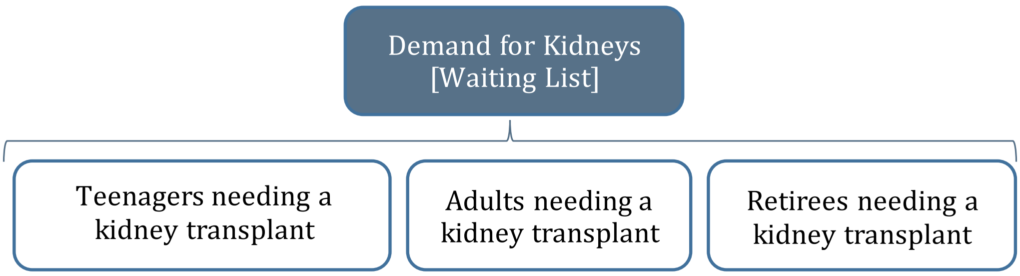

Figure 8: Breakdown of the demand for kidneys

Note that it has been assumed pediatric cases (children under 12 years old) are uncoupled from the rest. Kidneys coming or going from children are not compatible with the rest of the groups because of size reasons, and thus they have been excluded from the model. A dedicated model would be necessary to study pediatric cases.

3.2.2 Urgent cases

Just as in reality, urgent cases have been included in the model. Patients in the urgent waiting list get priority over those in the regular one. Thus, if there is an available kidney, it will only be used to satisfy the demand of the regular waiting list if there are no urgent cases. In the model, urgent patients are assumed to be limited to those that suffered some kind of non-fatal complication or problems during their transplant, and hence require a new intervention.

3.2.3 Age chain

The age chain sub-model is formed by 4 age groups: children under 12, teenagers (12-17), adults (18-65) and retirees (66 and over). A yearly net inflow of immigrants, which has been assumed to be constant, also forms part of the model.

This submodel is important because it pulls the dynamic of the general model. If the population grows, the necessity of transplants will grow and the available kidneys will grow too. In other words, both the supply and the demand for kidneys introduced in the previous section are a function of the population.

In the supply part of the model the three sources of kidneys depicted in **Figure 7** are defined as fraction rates of the population. These rates were obtained from the Kidney Annual Data Report of the U.S. (OPTN, 2012), and are not fixed over time, as they change with the society's awareness of the problem (see **3.2.4 Sensitization with the problem**).

The demand for kidneys is also specified by using a fraction of teenagers, adults and retirees needing a kidney transplant in the U.S. These values are also obtained from the same source, and their tendencies are determined using historical records.

3.2.4 Sensitization with the problem

When studying the evolution of the supply side of the problem, i.e. the kidney donors, it is necessary that the model capture the social essence and dynamics of the issue. A transplantation is an event that not only affects an individual, but also his sphere of influence: relatives and friends. Thus, in order not to miss a big part of the conceptualization of the problem, these extended social influence need to be modeled.

In the model, every time a patient receives a kidney, a fraction of the people on his/her sphere of influence are sensitized with the problem, becoming thus donors upon death. This positive feedback loop contributes to reduce the waiting list because more people become donors every time there is a successful transplant. The same happens when someone dies. Because of the traumatic situation of a relative or friend dying, some people get sensitized with the problem and become donors, creating a positive feedback loop that contributes to reduce the waiting list.

3.2.5 Introducing blood types: subscript formulation

Although the subscript formulation forms part of the equations of the model rather than of its structure, it is described here because of the impact it has on the behavior dynamics.

As explained during the model conceptualization (see **3.1 Model Conceptualization**), a more representative model of the problem of the kidney transplants in the U.S can be obtained if the different blood types of individuals and their implications on transplants are included in the model.

Data presented in **Table 1** showed that people belonging to blood type O are universal donors, i.e. they can donate to all the other groups. Similarly, blood type AB represents the universal receiver. An important conclusion that can be drawn from this table is that donors of type O have the greatest potential to reduce the waiting list, as they have the potential to satisfy the demand of all four blood types.A question that follows is what percentage of the population has blood type O. Statistics for the U.S. are shown in **Table 3**.

Table 3: Blood type distribution of the population of the U.S.

BLOOD TYPE DISTRIBUTION IN THE U.S.	
BLOOD TYPE	PERCENTAGE IN POPULATION
A	42%
B	10%
AB	4%
O	44%

This blood type distribution, as well as the implications it has in the supply-demand model, are introduced in the model by the means of subscript equations, with the objective to capture the extra complexity caused by organ incompatibilities.

3.3 MODEL VALIDATION

Before analyzing the behavior of the main model, a validation process is carried out to determine how useful it is in representing the kidney transplantation system in the U.S. under the system boundaries described in **3.1 Model Conceptualization**. Four validation tests are performed (Sterman, 2000):

- **Reproduction of past real data**: the tendencies of the waiting list can be confirmed for the period 2010-2015 by using past real data. According to the U.S. Department of Health & Human Services, the number of people waiting for a kidney transplant as of March 13th 2015 is 101,637, while the number provided by the simulation model is roughly 97,500.
- **Behavior anomaly test**: This test analyzes whether changing or deleting assumptions leads to anomalous behaviors. The following assumptions were tested:

- Constant Immigration: Was replaced by a lookup function in which immigration rose exponentially from 1 million people a year in 2010 to 5 million people a year in 2030, and remained constant from there on.
- Blood type of the immigrants is equal to that of Americans: These hypothesis was substituted, changing the blood type distribution of immigrants to an average of the blood type distributions in Europe.
- New people gets sensitized with the problem when close relatives/friends undergo a transplantation process: This hypothesis was deleted.

Results from this test are plausible and match the logics that the modification of these assumptions would imply in reality.

- **Extreme conditions behavior test**: The purpose of this test is to analyze whether the model responds plausibly under extreme conditions. The *fraction of patients that accepts a kidney during the transplant* and *average sphere of influence* (used to model the new people sensitized with the problem) are set to extreme values in four different experiments. Results are also satisfactory in this case, as the behavior is plausible given the starting conditions.
- **Sensitivity analysis:** A sensitivity analysis was carried out and proved that the model does not present behavior sensitivity under small variations in eight of the main parameters. These parameters and the range of variations used in presented in **Table 4**.

Table 4: Ranges of variation for the sensitivity analysis

Parameter	Lower bound	Current value	Upper bound
Probability to recover an organ from a person dead in a hospital	0.25	0.268	0.3
Probability to recover an organ from a person not dead in a hospital	0.006	0.008	0.01
Base percentage families that approve a donation	0.33	0.365	0.39
Base fraction of adults donating upon death	0.36	0.4	0.44
Alive adults´ donation rate	3.15E-05	3.19E-05	3.22e-05
Average percentage of adult people that need a kidney transplants	1.4 E-04	1.51 E-04	1.6 E-04
Average percentage of retirees that need a kidney transplants	5.15 E-05	5.663 E-05	6.15 E-05
Average percentage of teenagers that need a kidney transplants	1.7 E-05	1.91 E-05	2.1 E-05

4 Model Behavior: Base Scenario and Sensitivity Analysis

Simulating the base case scenario shows the behavior of the system if no policies were applied. Four main KPIs are defined as indexes to quantitatively assess the evolution of the simulation:

1. **KPI 1 – Total waiting list for a kidney transplant**: the number of people waiting for a kidney transplant in the U.S.

2. **KPI 2 – Ratio of *total transplants* over *new people in the waiting list* per year**:

$$\frac{\boldsymbol{Total\ transplants}\ [\boldsymbol{kidneys/year}]}{\boldsymbol{New\ people\ in\ the\ waiting\ list}\ [\boldsymbol{kidneys/year}]}$$

   This KPI measures the evolution of the waiting list in a period. While the first KPI represents the total cumulative waiting list, this one indicates variations of that cumulative number. If KPI2 < 1, there is more demand than supply for kidneys. The opposite happens when KPI2 > 1.

   Note that the waiting list can decrease even if this parameter is less than 1, because people not only leave the waiting list when they receive a transplant, but also when they die.

   The optimal situation would be a waiting list of 0 and this KPI equal to 1.

3. **KPI 3 – Percentage of *kidneys lost* over *total transplants* per year:**

$$\frac{\boldsymbol{Kidneys\ lost}\ [\boldsymbol{kidneys/year}]}{\boldsymbol{Total\ tansplants}\ [\boldsymbol{kidneys/year}]}$$

   Kidneys lost are defined as those potential transplantable kidneys that are not donated because the deceased person was not a donator upon death, and his relatives decided not to donate his/her organs.

   Thus, the higher this KPI, the higher the fraction of potential kidneys lost in year. Conversely, the lower this KPI is, the less room for improvement, as there are fewer potential transplantable kidneys lost.

4. **KPI 4 – New people aware of the magnitude of the problem:** cumulative number of people that becomes sensitized with the problem, as explained in **3.2.4 Sensitization with the problem**.

The choice of KPI 2 and KPI 3 is motivated by the fact that the population size in the U.S. is going to change over the timeframe considered (35 years), and these dimensionless KPIs avoid misinterpretations that other, simpler KPIs, such as the *total number of transplants in a year*, might bring. **Figure 9** displays the trends of all the defined KPIs in the base scenario.

Furthermore, confidence in the simulation results can be increased if a sensitivity analysis is performed. The ranges of variation of the parameters used for this analysis are the same to that presented in **Table 4**. Results are shown in **Figure 10**. It can be seen that even considering variations in 8 parameters, the behavior of all KPIs is only numerical sensitive, except for extreme cases in which the waiting list might maintain a steady state, where a slight behavioral sensitivity is shown.

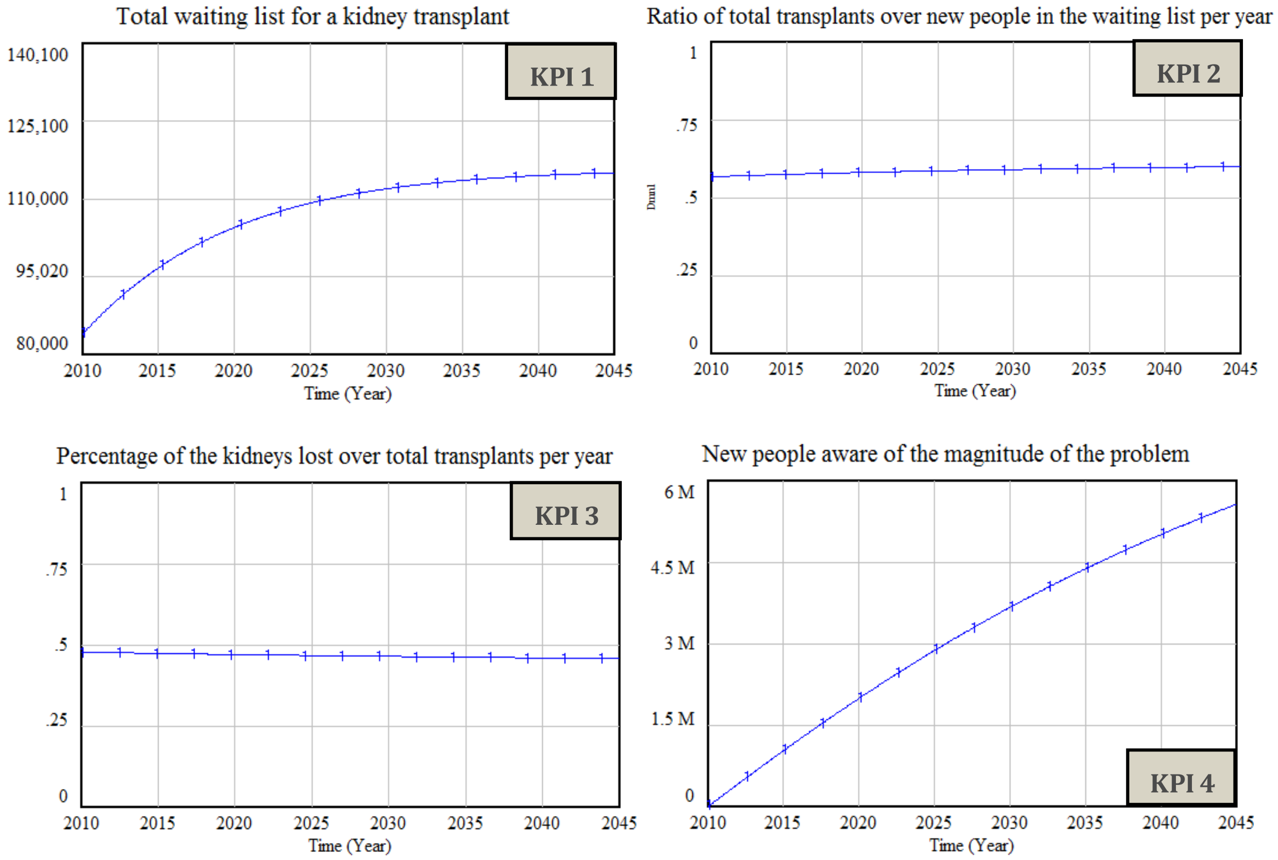

Figure 9: Behavior of the model in the base scenario

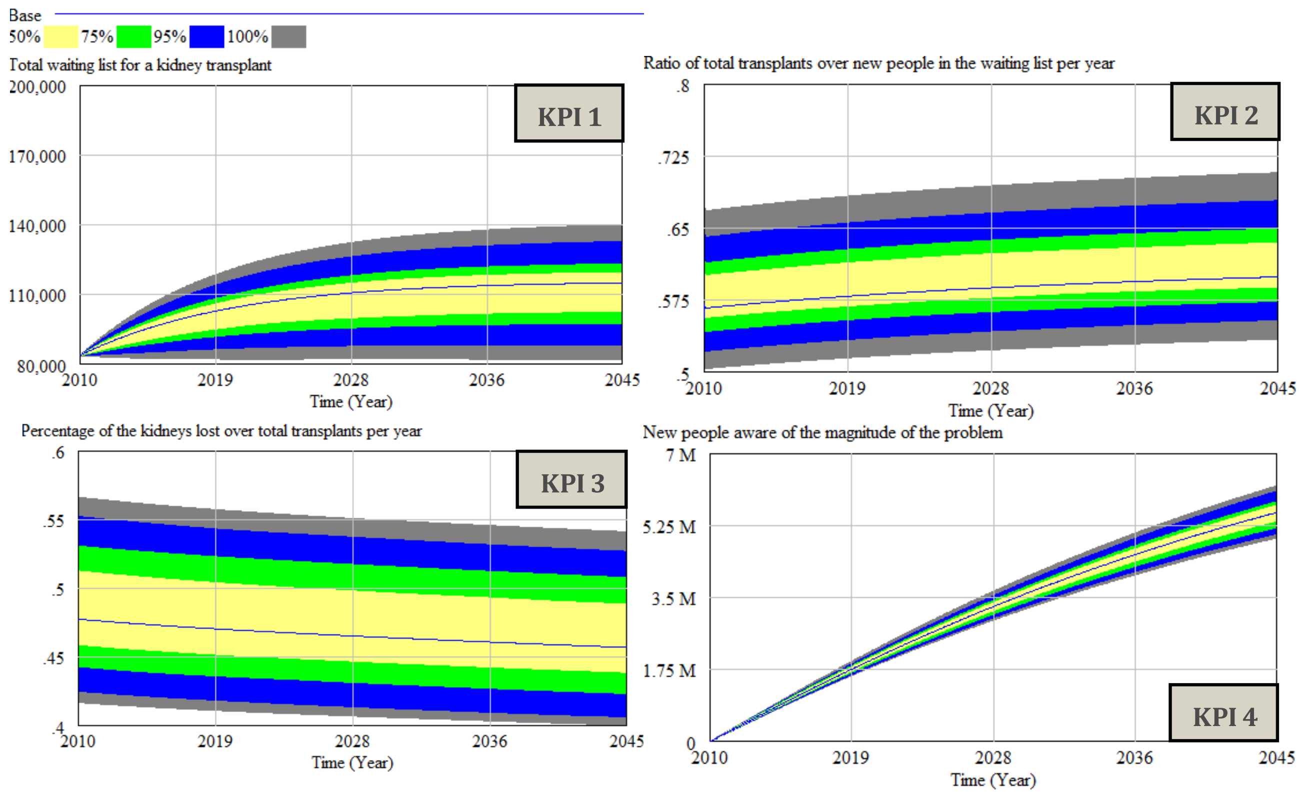

Figure 10: Behavior of the model under sensitivity analysis

5 Policy Analysis and Implementation

Results from the sensitivity analysis for the base scenario in **Figure 10** indicate that the issue of the huge waiting list in the U.S. is going to become bigger in the next decades. This tendency is also confirmed by external reports (OPTN/SRTR, 2013). Policy interventions are designed and tested in this paper in order to study alternatives that can potentially ameliorate this problem.

Two different policies are implemented. The first one has to do with a priority in allocation system, which would give advantages to close relatives of organ donors. The second studies the effects that a massive media campaign would have in the current donation ratio.

5.1 PRIORITY IN ALLOCATION POLICY

The basis of this policy is giving priority in the waiting list to the relatives of the people who were organ donors upon death, and whose organs could be used to transplant to other people. The authors hypothesized that such policy would largely increase the number of people donating upon death, while the ethical and moral consequences that it implies are not as negative as those from other incentives, such as fiscal or monetary (García-Gallont, 2014).

In other to exemplify how this policy would work, a hypothetical example case is considered: John, a 40-year family guy lives together with his wife and 2 daughters in the U.S. After finding out about this new policy, he decides to become an organ donor, and is asked to select three people that would benefit from this policy. He selects his wife and his two daughters. Sadly, after two years, John dies in a hospital after a complication during an appendicitis surgery. His organs are used to save 5 lives. Furthermore, if either his daughters or his wife need an organ transplant in the future, they will have priority in the waiting list.

The question that follows is: does this process actually improve the system? Would this policy lead to a decrease in the waiting list?

In order to prove the effectivity of the policy, the acceptance it would have is to be tested. For that purpose, a survey was carried out to find out what percentage of the non-organ donors would change their minds if this policy was implemented.

The survey introduced this policy to the respondents, and clarified it with a simple example similar to that previously presented. After that, it contained basically two main questions, plus some socio-demographic data. These two main questions were:

- *Are you an organ donor?*
- [If not an organ donor] *Would you start donating if the policy was implemented?*

The total sample consisted on 131 individuals. Results indicate that almost a 70% of non-donors would start donating if this policy was implemented, as illustrated in **Figure 11**.

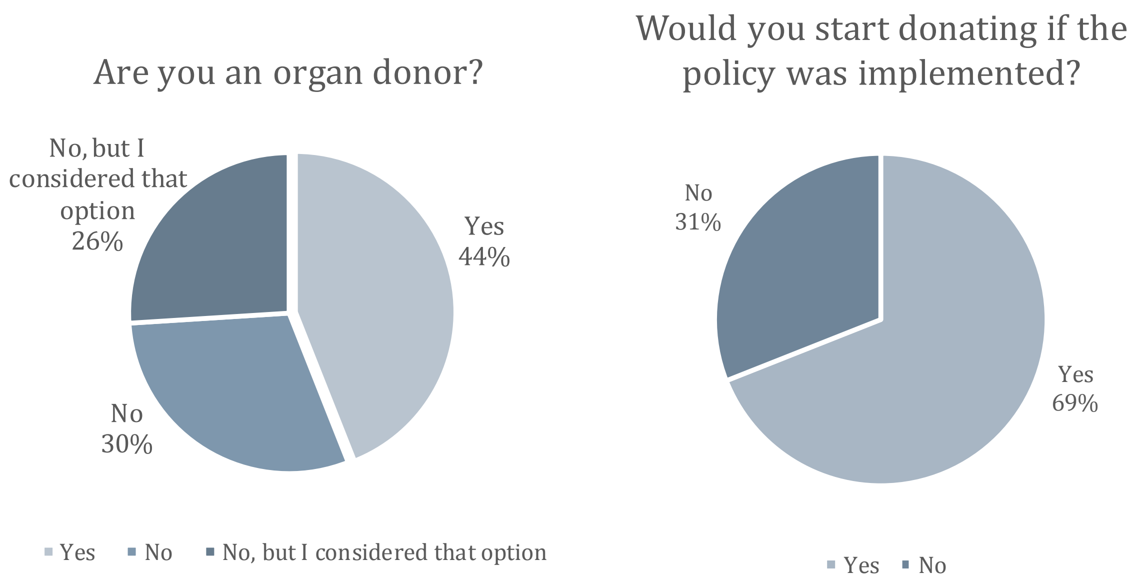

Figure 11: Main results of the survey regarding the allocation policy

Results in **Figure 11** show a potential of up to $(0.26 + 0.3) * 0.69 = 46.7\%$ new organ donors. But are these new donors really beneficial for the system? Or are the benefits from new donors offset by the new priority that some people would be given?

It is easy to verify that this policy would improve the system if the probability that an adult needs a kidney transplant, roughly 15 in 100,000 in the United States, is considered to be an average of the whole population. In that case, given that a person can select up to three other people who can benefit from the policy, chances that any of these people needs to be placed in the high priority list are only 0.045%. Thus, benefits from a new organ donor coming from this policy outweigh the complications that giving priority imply. These numbers are improved even further if overlaps in beneficiaries of this policy are considered, as probably two parents would both indicate their children.

Figure 12 displays the effects of the policy in a visual way. On the one hand, the implementation of the policy would boost the organ donors upon death. On the other hand, the waiting list itself would be affected due to the priority allocation some people would have. As it has been demonstrated that chances that a close relative need a kidney transplant are low, benefits from the supply side cover effects on the demand. It is important to note that this applies to cases in which a person's organs are actually used. If this is not the case, i.e. a person becomes an organ donor but his/her organs are not transplantable upon death, then neither the supply nor the demand would be affected.

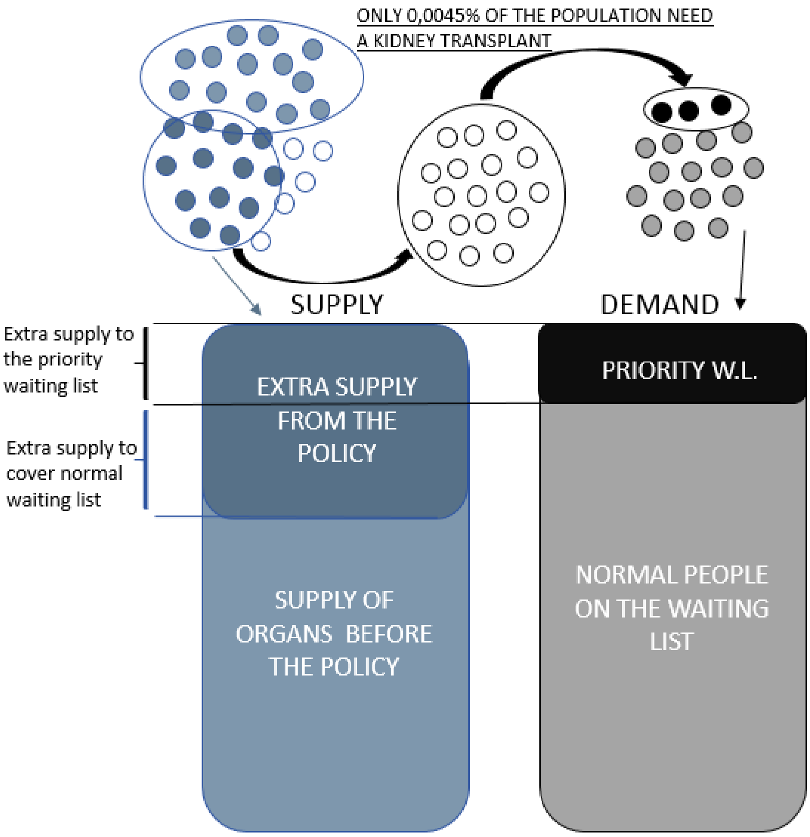

Figure 12: Visual scheme of the *Priority in Allocation Policy*

Some other complications have also been raised, as reported by some respondents during oral interviews about their opinions on the policy. Finding a compromise between urgent patients and patients that would be subject to this policy is one example, and would require further analysis.

When this policy is implemented in the model, the behavior is that shown in **Figure 13**, where the base behavior is compared to that in which the policy is implemented. Note that results from the survey, i.e. around 47% new donors, have been supposed to take place only years after the implementation of the policy, since a transition time is expected.

In order to test the robustness of the policy, the same sensitivity analysis that was performed before is repeated. Results are presented in **Figure 14*.***

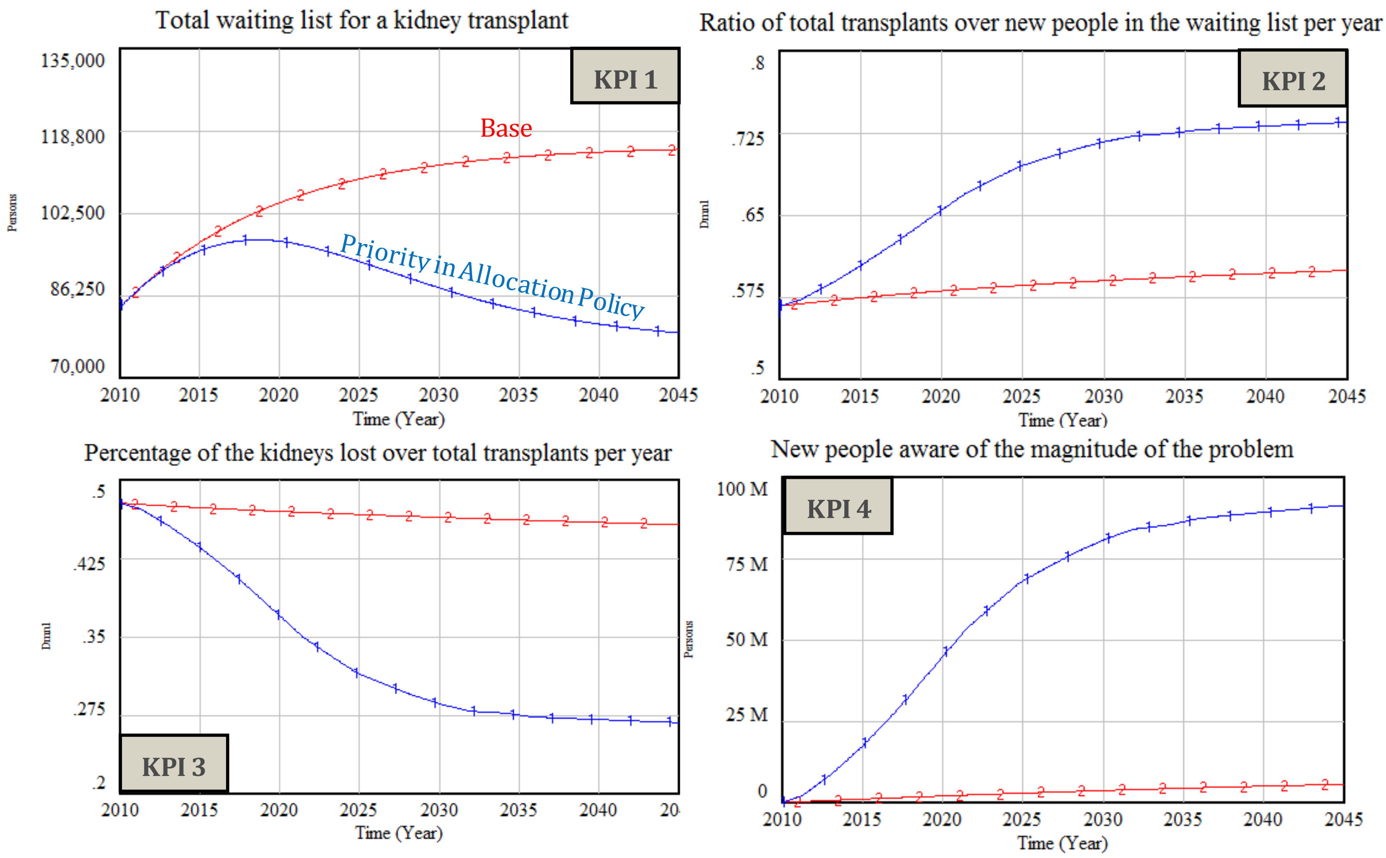

Figure 13: Comparison of the behaviors of the base and policy models

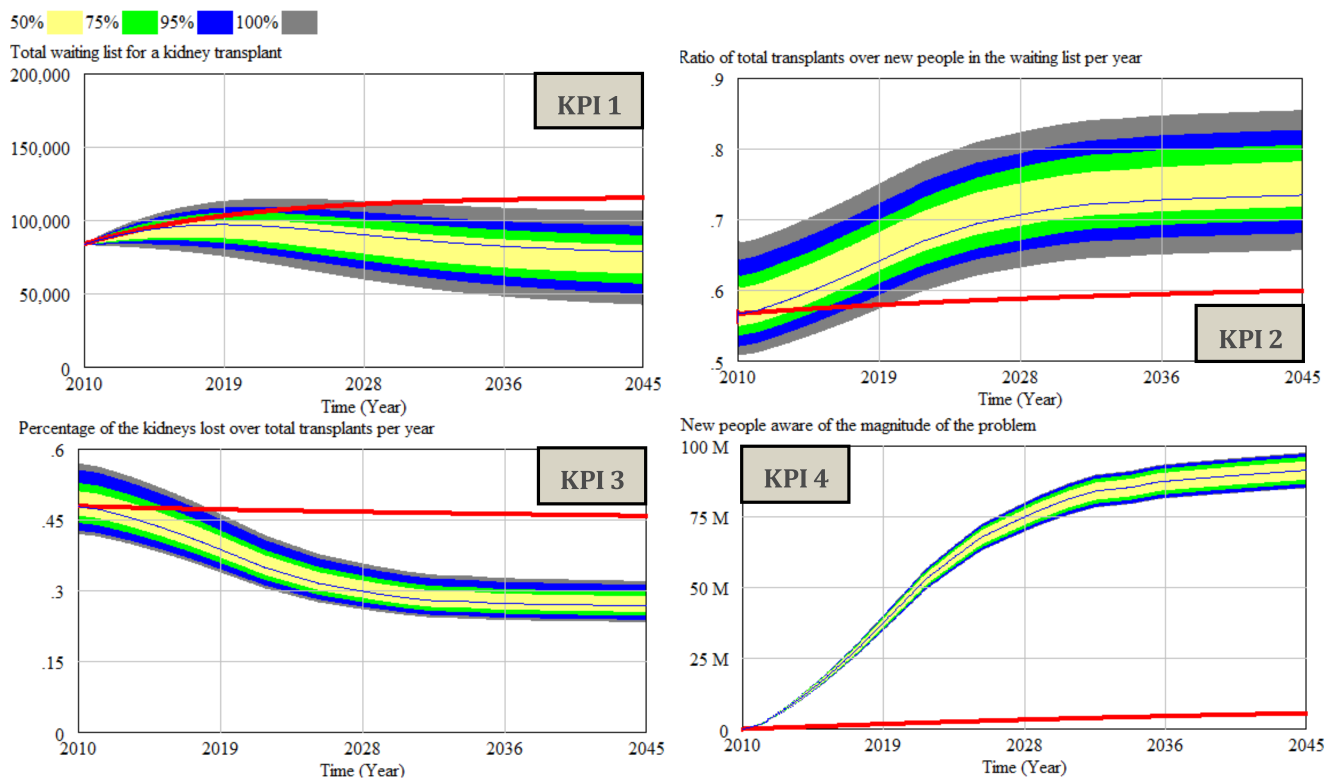

Figure 14: Sensitivity analysis of the priority in allocation policy. The base behavior is displayed as the red, thick line.

Results obtained indicate that the base behavior would greatly improve. The waiting list would revert its increasing tendency in about 5 years and the number of transplants would be around 75% of the new people joining the waiting list.

5.2 MASSIVE MEDIA CAMPAIGN

This policy focuses on increasing the number of people aware through media campaigns. Creating periodically TV, radio or on-line advertisements would increase the number of people aware of the problem and consequently would increase the number of kidneys donors. This media campaign is assumed to be carried out once a year during two months.

Currently there exist no reports or data concerning the implementation of such a policy when it comes to organ donations. Instead, the effect that the implementation of this policy would have are estimated by reviewing and extrapolating the effects of previous campaigns in general road safety (Delaney, et al., 2004), in preventing alcohol-involved crashes (Elder, et al., 2004) and in public health messages (Newbold & Campos, 2011).

Figure 15 shows the impact this policy would have on the behavior of the model. For comparison purposes, this figure also includes the behavior of the policy described in the previous section, as well as that of a combination of both policies. It can be concluded that implementing both policies at the same time is advisable, as their overlap is rather low, resulting in a further improvement of the problem situation.

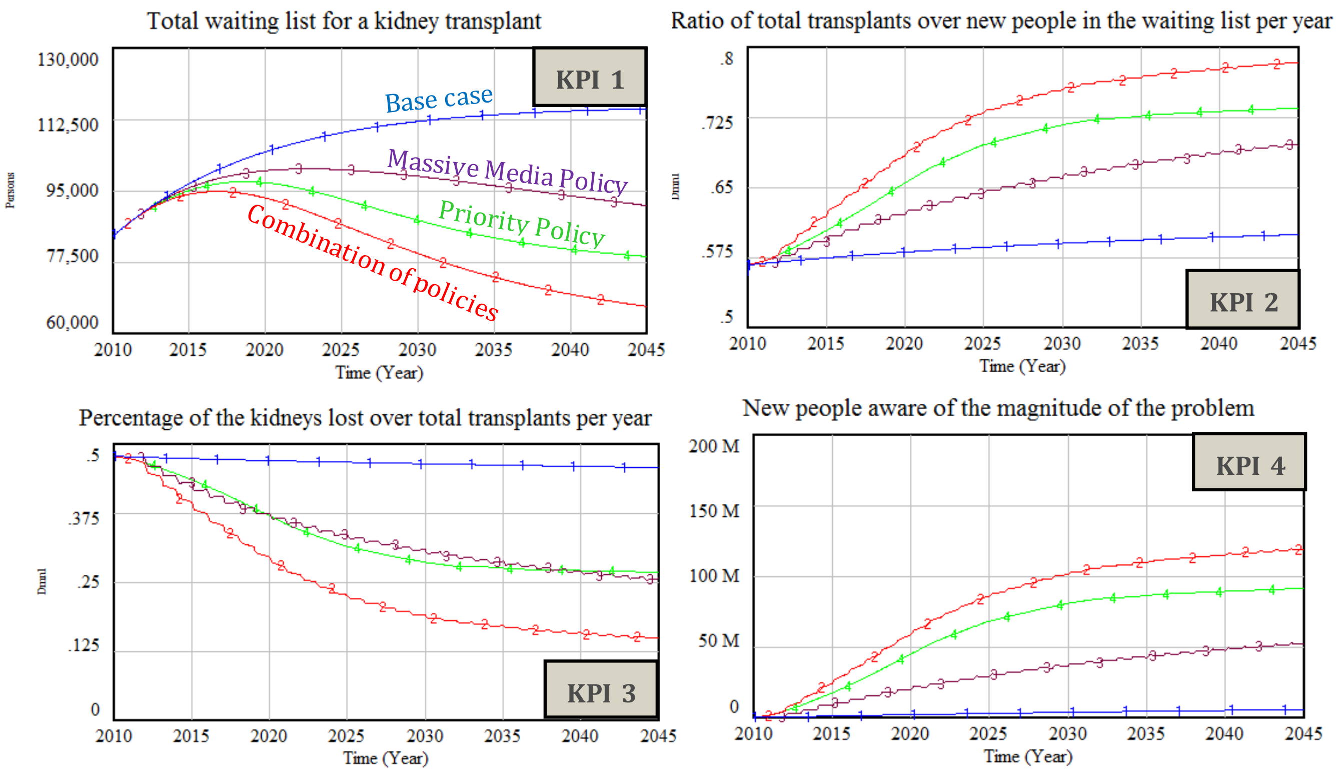

Figure 15: Comparison of the behavior of the KPIs in the base scenario and after the implementation of the policies

6 Conclusions and Further Research

6.1 CONCLUSIONS

This paper has descbried a system dynamics approach to explore and analyze the problem of the kidney transplants in the United Stated. The dynamics of the model depend not only on the population size, but also on social effects and blood type compatibilities. Results of the simulation indicate that the enormous waiting list for a kidney transplant in the U.S. will further worsen if no action is taken.

Two different policies have been implemented with the aim to improve the supply side of the system. As the most advantageous policies usually imply some ethical dilemmas, the policies chosen are a compromise between effectiveness and social acceptance. The compliance with the first proposed policy, the priority in allocation, was tested through a dedicated survey, which happened to be a great success. As for the second, the massive media policy, research reports from public health messages and road safety campaigns were used to estimate the impact and consequences this policy would have in the U.S. society. If treated separately, the priority in allocation policy saves more lives than the massive media campaign. In order to fully assess and compare both policies, an economic analysis should also follow. The costs of implementing each of the policies come from very different sources: developing a legal framework for the first one and massive advertisement for the second one. Further research is needed to come with realistic cost estimations, which could then be compared to other courses of action that are currently being undertaken, such as research in stem cells.

The most positive outcome is achieved when both policies are implementing at the same time. Because of the low overlap that the individual policies have in the system, this scenario outperforms those in which the policies are implemented separately. Note however that, although a combination of these policies play a big role in improving the behavior of the model, they do not guarantee a solution to the problem. More sources of organs are required if the waiting list is to be brought to zero. Although there is still room for improvement in kidneys coming from people donating upon death, organs coming from deceased donors are limited because the people dying a year is limited. Hence, encouraging living donation is an issue that should be further explored, as its potential is unlimited.

6.2 FURTHER RESEARCH

This paper has tried to use some innovative techniques in the exploration of the problem. The inclusion of blood types is an example of this approach. There are however many areas in which further research and research methods are needed. This section intends to summarize the main points that the authors regard as crucial when it comes to expanding the knowledge in this field.

First, pediatric cases should also be analyzed and included. Even though they are uncoupled from the rest of the transplantation cases, they still affect the social aspects of the model. In the same line of thought, a detailed analysis of the implications that different ages have in the waiting list need to be considered. In this paper, the waiting list has been treated as a whole. This was possible due to the age chain, which allowed for instance to realistically model the supply coming from retirees by using a much lower fraction of transplantable to donated organs. The authors however encourage further research in modeling the kidneys compatibility prior to a transplantation.

Second, as part of the everyday lives of thousands of people in end stage renal diseases, dialysis should also be model along with transplantations. Modeling how a combination of age renal disease stage and dialysis affect the allocation in the waiting list would further improve the results.

Third, geographical limitations should be considered. In this model, it has been assumed that 85% of the available kidneys are used for transplants, while the remaining 15% are lost (OPTN, 2012). These losses account also for difficulties in finding a match within a limited geographic area. Also, the cases of end-stage renal diseases are aggravated in some states, as shown in **Figure 16**. The authors suggest further research in how different geographies within the country affect the allocation and transportation of transplantable organs. Integrating the interstate collaboration required to maximize the distribution of kidneys will also shed more light into the problem.

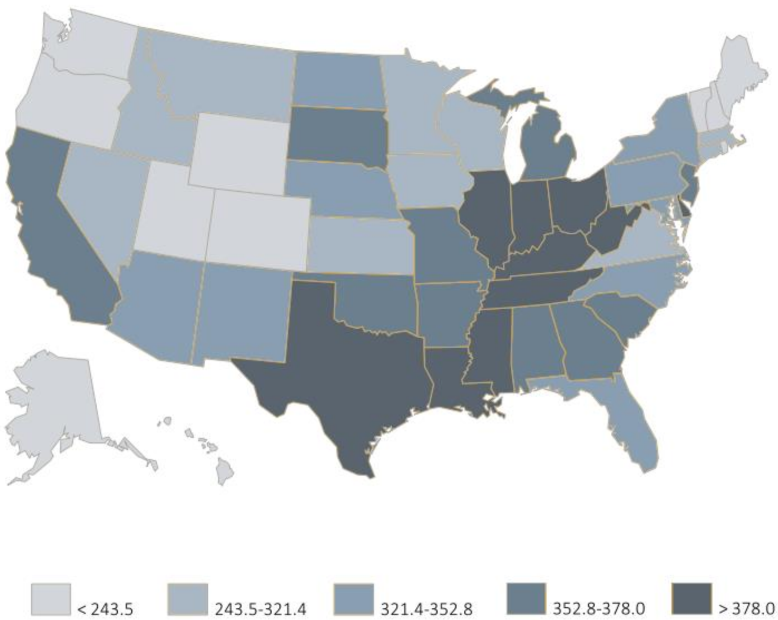

Figure 16: Map of the adjusted[1] incidence rate of ESRD, per million/year, by state, in the U.S. population, 2012 (United States Renal Data System, 2014)

Fourth, in an attempt to capture the complexity of the real system, the issue of urgent cases requires more exploration. The model hereby presented only labels as urgent cases those in which a previous surgery went wrong. Including other medical conditions is also necessary to expand the boundaries of the problem formulation.

Finally, as explained in the conclusions, more research is needed in the field of living donation. The social dimension of the problem will play an even bigger role in this case.

[1] Data Source: USRDS ESRD Database. Adjusted for age, sex, and race.

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