Complex System Methodology for Meta Architecture Optimization of the Kidney Transplant System of Systems

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***Abstract*— The demand for the kidney transplants is growing and far outweighs the supply of kidneys. With approximately 20 percent of kidneys discarded each year, there is an opportunity to develop a methodology to analyze the key performance attributes of the complex kidney transplant system of systems. In this paper we design and analyze a meta-architecture for the organ procurement system with a use case in the kidney transplant system. The complex systems and interfaces create emergent behavior that will affect the key performance attributes of Performance, Discard Rate, Observed over Expected Kidney Transplants, Affordability, and Acceptability. These key performance attributes, interfaces, and rules were developed from multiple interviews and events with the stakeholders of the systems. Fuzzy membership functions were used to assess the performance of the systems and then optimized using genetic algorithms. Two use cases were chosen with one donor and three donors to demonstrate the flexibility of the methodology to determine the meta-architecture for a given number of systems. The maximum overall value was obtained for each system of systems and participating systems were shown on a map. Future work includes development and integration of a systems of systems simulation to determine the effect of policy changes on the organ procurement systems.**

Keywords—Complex Systems, Organ Transplant, System of Systems, Meta Architectures

I. Introduction

According to the U.S. Renal Data System approximately 750,000 are affected by end-stage renal disease (ESRD) [1]. Two primary treatments for ESRD are dialysis and kidney transplant. While both treatments are required to meet the demand of treatment for ERSD, transplantation results in an improved quality of life and better survival outcomes on average [2]. The demand for kidney transplant far outpaces supply. In the US over 145,000 people are on the waiting list for kidney transplants, but in 2019 only 24,273 kidneys were transplanted [3]. As seen in Figure 1 the number of kidney transplant registrations as far outweighed supply. The demand for kidneys is expected to continually increase based upon the pervious years of 2010-2020.

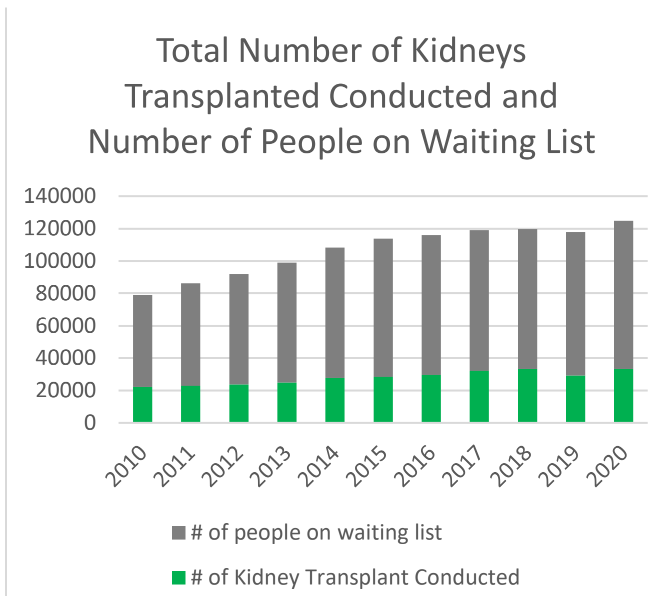

Fig. 1. Kidney Tranplants and # of people on waiting list [1]

Even with the large demand for kidney transplants, approximately 20% of procured deceased donors' kidneys are discarded in current practice [4]. Some of the discarded kidneys are medically necessary but even lower quality kidneys have been proven to be life-extending and cost effective for the appropriate candidates [5]. The discard rate of kidneys rises with measures of Kidney Donor Profile Index, which is a calculation utilizing several parameters of the kidney [6]. The high discard rate of high discard rate for higher KDPI scores indicates a potential opportunity for increased kidney utilization and optimization of the kidney transplant system of systems [7]. A brief analysis of literature could assist in the development of an optimized meta-architecture with a well-defined transplant system of systems.

The literature suggests multiple approaches that have been utilized to optimize systems of systems even in the organ transplant domain. Beliën et al develop a mixed integer linear programming long-term decision model to optimize the location of organ transplant centers [8]. The Lagrange theory related to the model is studied and presented as a mathematical model, based on networks, which addresses optimization of cost [9]. A bi-objective mathematical programming model that optimizes cost and time while considering organs priorities [10]. While these models optimize certain parts of the organ transplant systems of systems, they do not attempt to optimize the entirety of the systems of systems and identify an optimal meta-architecture. Haris and Dagli utilize architecture alternatives using genetic algorithms with fuzzy logic to optimizes multi-objective Key Performance Attributes with rule changes and constraints [11]. The SoS Explorer following methods defined by [12] utilize genetic algorithms of non-gradient descent with the use of fuzzy inference rules support selecting the optimal meta-architecture for KPAs. This approach has been used in other domains with complex system of systems such as cybersecurity[13], inspection systems [14], and the Department of Defense [15], but not in the healthcare space.

II. METHODOLOGY

A. Design-A-Thons and Interviews with Stakeholders

The first step was to understand and analyze the stakeholders, work processes, impactful capabilities, metrics, and current frustrations. The research team conducted three Design-a-thons to host tens of stakeholders from the kidney transplant community. The Design-A-Thons were two hours meetings with significant representation from the stakeholders. The first Design-A-Thon was used to define the systems and validate the initial workflows of the kidney transplant system based on tens of interviews conducted with the stakeholders. The second Design-A-Thon adjusted the workflows and introduced decision support systems [16]. The last design-a-thon we proposed metrics that would summarize the kidney procurement system for validation.

The stakeholders involved in the kidney transplant system are Organ Procurement Organizations (OPOs), Transplant Centers (TCs), and patients. The OPO is the system that owns the capability of providing kidney offers to the transplant centers. The OPO consist of several key personnel that were involved in the Design-a-thon including directors, manager, and kidney coordinators. The OPO wants to maximize the amount of kidney transplanted and sends the offers to various TCs in the designated area depicted by the United Network for Organ Sharing (UNOS). UNOS is the governing body of the entire kidney systems of systems and provide policy in addition to the patient merit list for the order in which patients are offered kidney transplants. The transplant center primary capability is to provide the kidney transplant. The primary personnel involved are the kidney coordinator and the transplant surgeon. These stakeholders and personnel formed the basis of the development of the KPAs and the capabilities of the systems.

B. Key Performance Attributes

The KPAs were developed and defined from the Design-A-Thons and the interviews with stakeholders of the kidney transplant system. KPAs are calculated by equations 1-6 defined as: systems, $S\ (X,\ i)$ =1 if the I system is participating in chromosome X, meta-architecture, and 0 if not. Interfaces, I (X, i, j) = 1 if the i and j system have an interface connection in chromosome X, and 0 if not. System characteristics are represented by the $Cxxx, i$ value of performance where 'xxx, i' indicates the characteristic value for system I. Variable δ represents the interfaces between active systems to be calculated in the objective function.

The performance KPA calculates the overall kidneys transplanted for the given participating systems. The Discard Rate KPA is the number of kidneys discarded by the system of systems. The OoverE is the observed kidney transplanted divided by the expected number of kidneys provided by UNOS. The credibility KPA is the Fscore of the Decision Support Systems. The Affordability KPA is a function of the initial and upkeep costs of each participating system and its interfaces. The

$$Performance\ = \sum_{i}^{Ns} S(X,i) * C_{kidneytransplanted,i} \prod_{j}^{Ns} [1 + \delta S(X,j) I(X,i,j)] \quad (1)$$

$$DiscardRate\ = \sum_{i}^{Ns} S(X,i) * (C_{Discardrate,i} \prod_{j}^{Ns} [1 + \delta S(X,j) I(X,i,j)] \quad (2)$$

$$OoverE = \sum_{i}^{Ns} S(X,i) * (C_{ExpectedvdObserved,i} \prod_{j}^{Ns} [1 + \delta S(X,j) I(X,i,j)] \quad (3)$$

$$Credibility = \sum_{i}^{Ns} S(X,i) * C_{Fscore,i} \prod_{j}^{Ns} [1 + \delta S(X,j) I(X,i,j)] \quad (4)$$

$$Affordability = 1 - \sum_{i=1}^{Ns} S(X,i) * [C_{Operating,i} + \sum_{j=1 \neq i}^{Ns} I(X,i,j)(C_{Inital,j})] \quad (5)$$

$$Acceptability\ = \sum_{i}^{Ns} S(X,i) * (C_{Usersurvey,i} \prod_{j}^{Ns} [1 + \delta S(X,j) I(X,i,j)] \quad (6)$$

Acceptability KPA is calculated by the feedback score given by each participating system and stakeholders. The optimal meta-architecture is calculated using a Simple SOGA genetic algorithm with 10,000 maximum evaluations.

C. Systems of Systems Explorer

SoS Explorer is a software tool written by the Engineering Management and Systems Engineering Department at Missouri S&T. It provides a framework for defining system of systems problems such that optimal architectures may be produced computationally. The overall performance of the architecture is determined by the objectives. These objectives may be defined using Python, MATLAB, or F#. The selected optimizer can then be used to generate optimum architectures which are displayed in the Graphical User Interface (GUI) and may be interacted with by the user. Solutions may also be stored as Excel Open XML files (XLSX) or graphically as Portable Network Graphics (PNG) images. For evaluation, the objectives require an architecture which, in this framework, is a set of systems and interfaces and information about the systems in terms of their characteristics, capabilities, and feasible interfaces. The objectives are evaluated by an optimizer, of which three evolutionary algorithms are included: NSGA-III, MaOEA-DM, and Simple SOGA. Both single and multiple objective optimizations are supported. Furthermore, constrained optimization is supported, and constraints may be added using Python, MATLAB, or F#.

D. Membership Functions & Fuzzy Assessor

To quantify the ambiguity of the KPAs a fuzzy assessor and membership functions were developed using MATLAB's fuzzy designer. The membership functions were chosen based upon the Design-A-Thons and interviews with stakeholders but can be updated with additional KPAs or update the membership functions based upon how the stakeholders' definitions of Low, Below Average, Average, Above Average, and High for the KPAs. The process is repeated with each KPA with the group of stakeholders to quantify the KPA.

The output example is a similar exercise with the stakeholder group, but in this case we are determining the fuzziness memebership for the overall objective, which is a function of all the KPAs. The membership function can represent membership functions such as very unacceptable, unacceptable, tolerable, desirable, and very desirable to represent the overall assessment of the meta-architecture chosen by SoS explorer. These membership functions have set rules such as if Performance, Discard Rate, and OoverE are low and Credibility, Affordability, and Acceptability are below average, then the overall output of the system is unacceptable. Thes rules are created to determine the output desirability of the overall systems of systems.

E. Rules

A set of rules are generated based upon stakeholder input for the fuzzy assessment of the objective function is created based upon each of the KPAs. Each of the KPAs are assessed to assess the desirability of the meta-architecture. An example would be if performance is low, discard rate is low, OoverE is low, credibility is low, affordability is below average, and acceptability is low, then the overall assessment is that the meta-architecture is very unacceptable. Another side of the spectrum example is if performance is high, discard rate is high, OoverE is high, credibility is above average, affordability is above average, acceptability is high, then the meta-architecture is very desirable. These rules create a KPA dimensional surface to determine the objective function of the meta-architecture of the system of systems

III. Results

Two use cases will be examined, the first where there is only one donor kidney, every only system has 2 options to choose from, and the optimal meta-architecture is calculated. The second use case there are 3 kidneys, three systems to select and the optimal meta-architecture is selected. The general methodology described previously is applied to both use-cases.

Figure 2 shows the gaussian membership function plot for the performance KPA. The fuzzy gaussian membership function plot shows the low, below average, average, above average, and high fuzzy membership functions. The performance is calculated using the equations previously discussed and rated based upon the fuzzy membership functions. The remaining KPAs were developed in using a similar methodology.

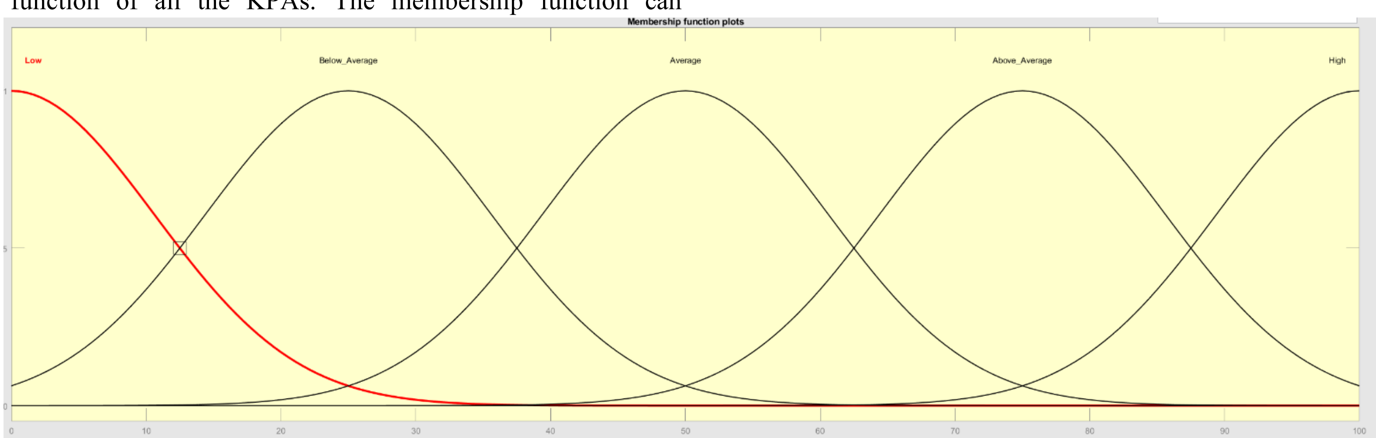

Fig. 2 Membership Functions for the Performance Key Performance Attribute

The objective function is illustrated in Figure 3 using a triangular fuzzy membership. The overall desirability is either very unacceptable, unacceptable, tolerable, desirable or very desirable based upon the rules and fuzzy memberships of the

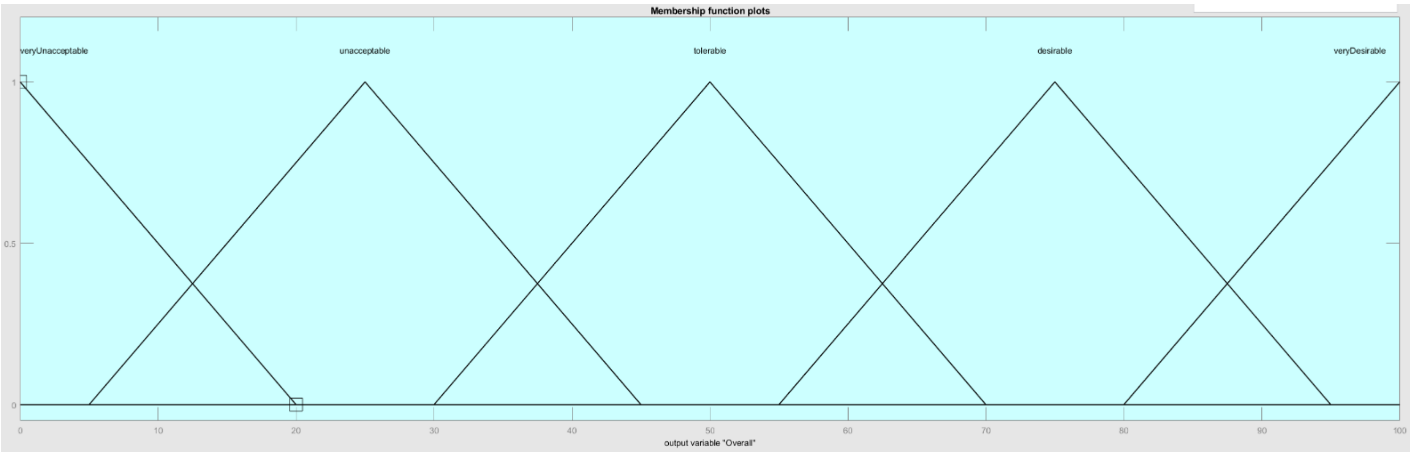

Fig 3. Membership Function of the Overall Assessment of the Selected Architecture

KPAs. Both the KPA memberships functions and the overall desirability of the meta-architecture were used is both use case 1 and use case 2.

Use case 1 utilizes a system of systems consisting of one kidney donor, two OPOs, two TCs, two OPHs, two ground

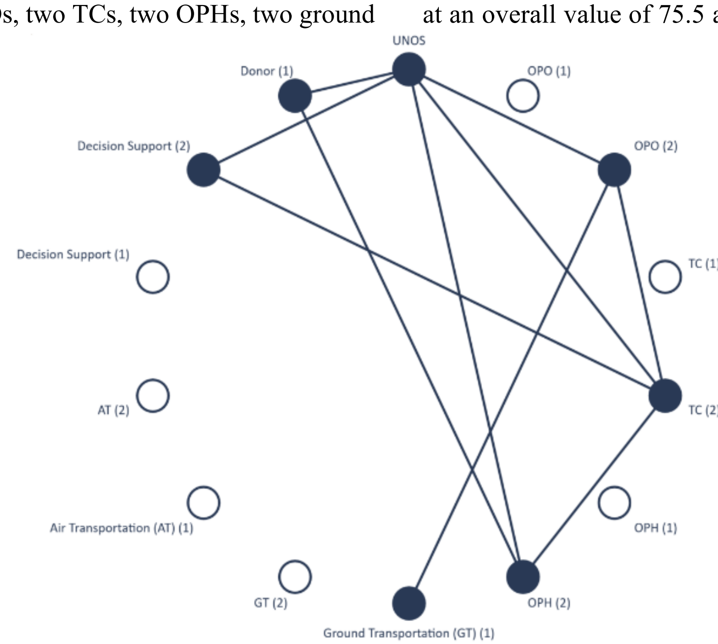

Fig 4. Meta Architecture Use Case 1

transportations, two air transportations, and two decisions support systems. Figure 4 shows each system, and their interfaces and interactions will each other. Each blue line shows a connection of Each of the systems were chosen to flex each of capabilities required for the system of systems. Each circle within Figure 4 that is shaded in blue represents that the system is participating in the meta-architecture. Each circle that is not shaded is not participating in the meta-architecture. Figure 5 shows which systems flex the capabilities required by the system of systems. UNOS provides the policy to attempt to optimize through constraints of the behaviors of the systems. OPO 2 provides the kidney offer to TC 2. These flexed capabilities are represented as True in the matrix. Figure 6 shows a map representation of Figure 5. The selected connections and system are show in green and the unselected systems are shaded in red.

The meta-architecture for use case one was calculated at an overall value of 75.5 and is desirable overall architecture based upon the fuzzy membership functions.

Use Case two expands on the flexibility of the meta-architecture demonstrating three donors and three of each of the systems. Figure 7 shows the meta-architecture, participating systems, and the connections between each of the systems. Figure 8 shows the capabilities provided to the overall systems of system by each individual system. Last, Figure 9 gives a visual example of what the optimal meta-architecture would look like to a user of the system. The map would identify the

	Capability Flexed							
	Provide Policy	Provide Kidney Offer	Transplant Kidney	Manage Donor Kidney	Transport Kidney	Provide Prediction	Recover Kidney	Provide Kidney
UNOS	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
OPO (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
OPO (2)	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
TC (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
TC (2)	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
OPH (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
OPH (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
Ground Transportation (GT) (1)	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE
GT (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Air Transportation (AT) (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
AT (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Decision Support (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Decision Support (2)	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE

Fig. 5. Capabilities Provided By Systems in Meta-Architecture Use Case 1

Fig. 6. Map of Meta-Architecture with selected participating systems Use Case 1

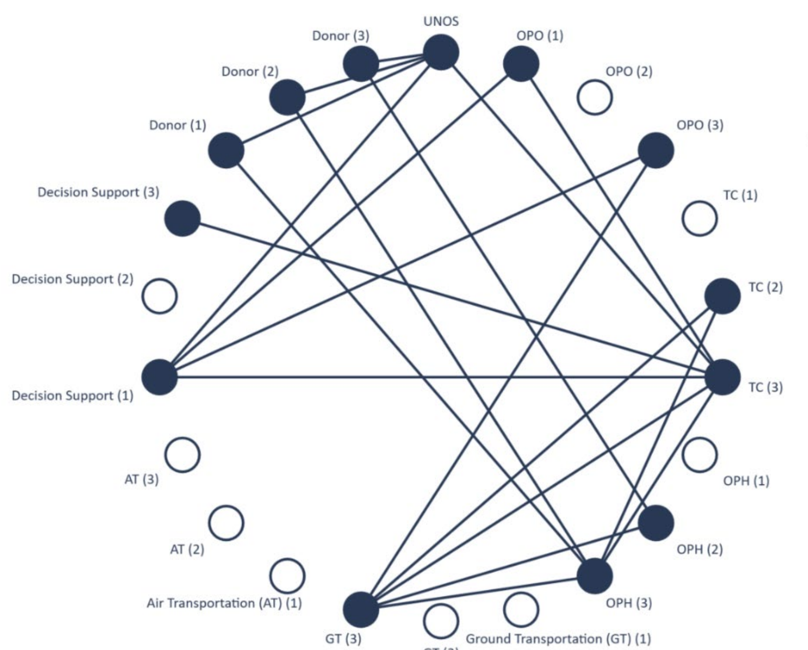

Fig 7 Meta-Architecture of Use Case 2

optimal OPH, OPO, and TC to maximize the KPAs for a given

	Capability Flexed							
	Provide Policy	Provide Kidney Offer	Transplant Kidney	Manage Donor Kidney	Transport Kidney	Provide Prediction	Procure Kidney	Provide Kidney
UNOS	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
OPO (1)	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
OPO (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
OPO (3)	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
TC (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
TC (2)	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
TC (3)	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
OPH (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
OPH (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
OPH (3)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
Ground Transportation (GT) (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
GT (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
GT (3)	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE
Air Transportation (AT) (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
AT (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
AT (3)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Decision Support (1)	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
Decision Support (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Decision Support (3)	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
Donor (1)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE
Donor (2)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE
Donor (3)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE

Fig. 8. Capabilities Provided By Systems in Meta-Architecture Use Case 2

kidney donor. The meta-architecture for use case 2 was optimized with a value of 73.8 based upon the KPAs. The optimized meta-architecture is deemed desirable due to its 73.8 overall desirability value.

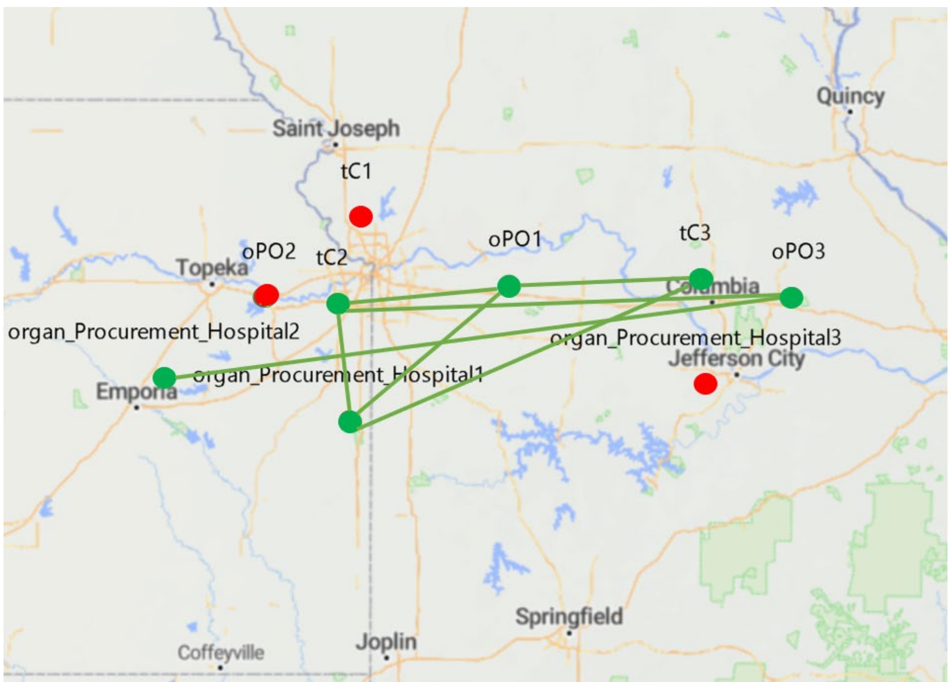

Fig. 9. Map of Meta-Architecture with selected participating systems Use Case 1

IV. Conclusion and Future Work

A methodology was created for the organ procurement systems of systems to optimize a meta-architecture for selecting the best participating systems for a given set of donor kidneys. Utilizing the KPAs, fuzzy membership functions, rules, and genetic algorithms, two use cases were optimized for the most objective value to the systems. The methodology allows for organ procurement stakeholders to further develop or create new KPAs and fuzzy membership functions to optimize their system of systems. Future work is incorporating and integrating the meta-architecture methodology into Anylogic to perform predictive simulation as an agent-based simulation. Two use cases were developed with one have one donor and another consisting of three donors. The meta-architecture was developed and optimized with fuzzy rules set and a genetic algorithm to optimize the desirability as a function of the KPAs. This methodology can be changed with an expanding list of stakeholders among the organ transplant community and can be run in real time to create an optimal meta-architecture for numerous kidney in hoped to reduce kidney discard.

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[1] Ersoy, Ozge Ceren, et al. "A Critical Look at the U.S. Deceased - donor Organ Procurement and Utilization System." Naval Research Logistics, vol. 68, no. 1, John Wiley & Sons, Inc, 2021, pp. 3 - 29, doi:10.1002/nav.21924.

[2] Hart A, Lentine KL, Smith JM, Miller JM, Skeans MA, Prentice M, Robinson A, Foutz J, Booker SE, Israni AK, Hirose R, Snyder JJ. OPTN/SRTR 2019 Annual Data Report: Kidney. Am J Transplant. 2021:21 Suppl 2:21-137. doi: 10.1111/ajt.16502. PMID: 33595191.

[3] Mohan S, Chiles MC, Patzer RE, Pastan SO, Husain SA, Carpenter DJ, Dube GK, Crew RJ, Ratner LE, Cohen DJ. Factors leading to the discard of deceased donor kidneys in the United States. Kidney international 2018:1:94(1):187-98.

[4] Axelrod DA, Schnitzler MA, Xiao H, Irish W, Tuttle - Newhall E, Chang SH, Kasiske BL, Alhamad T, Lentine KL. An economic assessment of contemporary kidney contemporary kidney transplant practice. American Journal of Transplantation 2018:18(5):1168-1176.

[5] Alhamad T, Axelrod D, Lentine KL: The Epidemiology, Outcomes, and Costs of Contemporary Kidney Transplantation. In: Himmelfarb J, Ikizler TA, editors. Chronic Kidney Disease, Dialysis, and Transplantation: A Companion to Brenner and Rector's the Kidney. Elsevier; 2019.

[6] Aubert O, Reese PP, Audry B, Bouatou Y, Raynaud M, Viglietti D, Legendre C, Glotz D, Empana J, Jouven X, Lefaucheur C, Jacquelinet C, Loupy A. Disparities in acceptance of deceased donor kidneys between the United States and France and estimated effects of increased US acceptance. JAMA internal medicine 2019:179(10):1365-1374.

[7] Hosny A, Parmar C, Quackenbush J, Schwartz LH, Aerts HJWL. Artificial intelligence in radiology. Nat Rev Cancer: 2018:18(8):500–510. Doi: 10.1038/s41568-018-0016-5

[8] Beliën, Jeroen, et al. "Optimizing the Facility Location Design of Organ Transplant Centers." Decision Support Systems, vol. 54, no. 4, Elsevier B.V, 2013, pp. 1568–79, doi:10.1016/j.dss.2012.05.059.

[9] Caruso, Valeria, and Patrizia Daniele. "A Network Model for Minimizing the Total Organ Transplant Costs." European Journal of Operational Research, vol. 266, no. 2, Elsevier B.V, 2018, pp. 652–62, doi:10.1016/j.ejor.2017.09.040.

[10] Ersoy, Ozge Ceren, et al. "A Critical Look at the U.S. Deceased - donor Organ Procurement and Utilization System." Naval Research Logistics, vol. 68, no. 1, John Wiley & Sons, Inc, 2021, pp. 3 - 29, doi:10.1002/nav.21924.

[11] Haris, K., Dagli, C. Adaptive Reconfiguration of Complex System Architecture. Complex Adaptive Systems, Volume 1. 2011.

[12] Pape, L., Giammarco, K., Colombi, J., Dagli, C., Kilicay-Ergin, N., & Rebovich, G. (2013). A fuzzy evaluation method for system of systems meta-architectures. Procedia Computer Science, 16, 245-254.

[13] L. Ashiku and C. Dagli, "Cybersecurity as a Centralized Directed System of Systems Using SoS Explorer as a Tool," 2019 14th Annual Conference System of Systems Engineering (SoSE), 2019, pp. 140-145, doi: 10.1109/SYSOSE.2019.8753872.

[14] M. M. Karim and C. H. Dagli, "SoS Meta-Architecture Selection for Infrastructure Inspection System Using Aerial Drones," 2020 IEEE 15th International Conference of System of Systems Engineering (SoSE), 2020, pp. 23-28, doi: 10.1109/SoSE50414.2020.9130538.

[15] Lesinski, G., Corns, S. M., & Dagli, C. H. (2016, July). A fuzzy genetic algorithm approach to generate and assess meta-architectures for non-line of site fires battlefield capability. In Evolutionary Computation (CEC), 2016 IEEE Congress on(pp. 2395-2401). IEEE.

[16] Threlkeld, R., Ashiku, L., Canfield, C., Shank, D., Schnitzler, M., Lentine, K., Axelrod, D., Battineni, A. C., Randall, H., and Dagli, C. Reducing Kidney Discard with Artificial Intelligence Decision Support: The Need for a Transdisciplinary Systems Approach. Retrieved from https://par.nsf.gov/biblio/10299348. Current transplantation reports

[17] Mohan S, Chiles MC, Patzer RE, Pastan SO, Husain SA, Carpenter DJ, Dube GK, Crew RJ, Ratner LE, Cohen DJ. Factors leading to the discard of deceased donor kidneys in the United States. Kidney international 2018:1:94(1):187-98.

[18] Axelrod DA, Schnitzler MA, Xiao H, Irish W, Tuttle - Newhall E, Chang SH, Kasiske BL, Alhamad T, Lentine KL. An economic assessment of contemporary kidney contemporary kidney transplant practice. American Journal of Transplantation 2018:18(5):1168-1176.

[19] Alhamad T, Axelrod D, Lentine KL: The Epidemiology, Outcomes, and Costs of Contemporary Kidney Transplantation. In: Himmelfarb J, Ikizler TA, editors. Chronic Kidney Disease, Dialysis, and Transplantation: A Companion to Brenner and Rector's the Kidney. Elsevier; 2019.