ORGAN TRANSPLANTATION LOGISTICS: CASE FOR TURKEY

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by
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June 2012

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ABSTRACT

ORGAN TRANSPLANTATION LOGISTICS: CASE FOR TURKEY

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Organ transplantation is one of the fundamental and effective treatment techniques for the patients who have critical health problems. However, while 3,930 organs were transplanted to the patients in 2011, there still exist 20,954 people waiting for a suitable organ as of April 2012 in Turkey. Even though the exact numbers are different; the situation of well developed countries like USA is not very different in terms of organ donation and patient ratio. Thus; matching - defined as finding the best recipient for a donated organ- is very crucial for the overall organ transplantation process. There are mainly two different ways of matching in the applications: centralized and hierarchical method. In the centralized method, all patients and donors are monitored and matching is coordinated centrally. In the hierarchical method, the matching process is coordinated via a bottom-up hierarchy. The application in Turkey is also hierarchical, coordinated by nine regional coordination centers and one national coordination center. Due to the nature of the matching application in Turkey, the cluster of each regional coordination center is crucial. There are many dynamics of the transplantation process like cold ischemia time -the duration that the organ survives without blood circulation-, operation times and specialized hospitals and teams.

In this thesis, we study the organ transplantation logistics mainly focusing on the Turkish application. We provide mathematical models that consider the problem specific requirements like ischemia time. We also consider two-mode transportation since airplanes or helicopters are also used widely in organ transportation. Finally, we also developed a simulation model to observe the hierarchical nature of the system and to evaluate the performance of the mathematical model outputs. Both mathematical model and simulation model outcomes based on Turkish data were compared with actual regional coordination center locations of Turkey.

Keywords: Healthcare Systems, Organ Transplantation, Mixed Integer Programming

ÖZET

ORGAN NAKLİ LOJİSTİĞİ: TÜRKİYE VAKASI

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Organ nakli, ancak organ nakli ile iyileşebilecek hastalar için uygulanan çok önemli bir tedavi yöntemidir. Ancak, genel duruma baktığımızda Türkiye'de 2011 yılında toplam 3930 organ bağışlanmış, 2012'nin başında organ bekleyen hasta sayısı 20954 olarak Nisan 2012'de açıklanmıştır. Bağış sayıları ve bekleyen hasta sayısı arasındaki bu fark sadece Türkiye'de değil, Amerika gibi diğer tüm gelişmiş ülkelerde de bu sorunla karşılaşılmaktadır. Bu nedenle bağışlanan bir organın en uygun alıcıyla eşleşme süreci tüm organ nakil süreçlerindeki en önemli süreçlerden biridir. Genel olarak eşleşme yöntemleri iki farklı şekilde yürütülmektedir: merkezi ve hiyerarşik yöntem. Merkezi yöntemde, tüm bağışlanan organlar ve organ bekleyen hastalar merkezi tek bir listeden eşleşmektedirler. Hiyerarşik yöntemde ise bağışlanan organ alt tabandan başlayarak yukarıya doğru (şehir, bölge ve ülke) uygun alıcıyı aramaktadır. Organ nakli süreçleri Türkiye'de bir ulusal koordinasyon merkezi ve buraya bağlı 9 bölge koordinasyon merkezi tarafından yürütülmekte olup hiyerarşik yöntemle eşleşmeler sağlanmaktadır. Hiyerarşik eşleşme yönteminin performansı bölgelerin yapısıyla bağlantılı olduğu için bölgelerdeki bölge koordinasyon merkezlerinin yerleri ve buralara atanan iller büyük önem kazanmaktadır. Organ nakli incelendiğinde soğuk iskemi süresi – bağışlanan organın içinde kan akışı olmadan dayanabildiği süre – ameliyat süreleri ve nakil merkezleri ve ekipleri gibi faktörler bulunmaktadır.

Bu tezde organ nakli lojistiğinin Türkiye uygulaması üzerine çalıştık. Bu çalışmada matematiksel modelleme ile problemin temel kısıtlar doğrultusunda bölgelerin oluşturulması amaçlanmıştır. Ayrıca iki farklı ulaşım tipinin bir arada dikkate alındığı matematiksel modelleme ile de gerçek sistemde sıkça kullanılan helikopter kullanımı modele yansıtılmıştır. Ayrıca bir benzetim modeli de oluşturarak matematiksel model çıktılarının gerçek hayat uygulamasında nasıl performans göstereceği değerlendirildi. Tüm çalışmada Türkiye'ye ait bilgiler kullanıldı ve sonuçlar mevcut sistemle karşılaştırıldı.

Anahtar Kelimeler: Sağlık Sistemleri, Organ Nakli, Karışık Tamsayılı Programlama

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Chapter 1

Introduction

Organ transplantation is one of the important techniques to treat patients when other treatment techniques do not respond successfully. However, there exists a huge gap between the numbers of donors and patients waiting for an organ. This is a worldwide problem. In the United States, 17 patients die every day while they are waiting for an organ (Cleveland Clinic, 2012). Therefore, in an environment with organ shortages, the organ transplantation processes should be perfectly operated. Furthermore, the organs cannot live out of body for a long time. The time that an organ can stand without blood circulation is called ischemia time that varies with respect to organ type. Since there is a time bound for the survival of the organ, the organ should be operated into the patient's body as quickly as possible. Moreover, there are two ways of search to match the donated organ with the patient in the organ transplantation system: centralized and hierarchical methods. In centralized method, there is one waiting list for patients in nationwide based on organ type. From that list the candidate patient is selected for matching. In the hierarchical method, the candidate patient is searched from local, regional and national levels. If a country applies a hierarchical search to find the candidate recipient, the clustering takes an important role for the successful organ transplantation system in that country. Each cluster represents what the time bound is between donor cities and patient cities. This is one of the important measures because this informs which organs can be carried from the donor to the recipient city with what type of vehicle. If the regions require airway transportation, then the region does not perform successfully since airway transportation is not a continuous transportation option due to availability of vehicle, weather conditions etc. Moreover, number of potential donors at each region and the number of patients in the regions also create fairness problem in the system, since if one region has many potential donors, then the waiting patients in that region have the advantage to find a matching organ effectively. Therefore, in the hierarchical search based systems, clustering has a significant role in the organ transplantation system.

In the literature, there exist operations research studies based on organ transplantation system. In the soft operations research studies, generally, the managerial problems are tackled. In the hard operations research based studies, simulation modeling is mostly used to analyze the matching criteria of donated organ with the recipient such as blood type and waiting time of the patient in the waiting list. To the best of authors' knowledge we have encountered only four papers applying mathematical modeling approach into organ transplantation system.

In this study, we focused on the logistics problems in the organ transplantation system for Turkey case where hierarchical method is used for matching operations. Our aim is to locate some regional coordination centers and allocate the cities to the regional coordination centers that maximize the number of organ flow at each region. With this perspective, cities having high number of potential donors and cities having high number of patients are allocated to the same regional coordination center. Therefore, the organ matching is aimed mostly to be in the regional level. In another perspective, the travel time of the organ decreases with decreasing probability of matching in different regional coordination centers.

We used both mathematical and simulation modeling to solve the problem and analyze the solutions. By using mathematical modeling approach, we find the optimal locations of regional coordination centers while allocating cities to these centers by considering ischemia time of the organs that maximizes regional organ transplantation level for each region. Moreover, we added two mode transportation opportunity to decrease the transportation time bound from donor city to recipient city for each region. Also, we aim to balance the regions with equity constraints in terms of total number of potential donors and total number of patients at each region.

The simulation model enables us to represent stochastic nature of the organ transplantation system with the hierarchical structure for organ specific cases. Therefore, we use simulation modeling to evaluate the performance of the solution obtained from the mathematical models.

The computational results are based on data from Turkey and this study considers the actual organ transplantation procedures in Turkey.

The general information about organ transplantation system and procedures are stated in chapter 2. Initially, the terminology used in the organ transplantation system and the system dynamics are given. Then, organ transplantation system in the world is presented before describing Turkish organ transplantation system. Each step of the organ donation in Turkey is explained. At the end of this chapter, the problem definition is stated.

At chapter 3 literature review is conducted. The literature review mainly consists of location literature based on p-median and covering problems, healthcare studies in operations research and studies specifically based on organ transplantation systems in operations research.

The model developments are explained at chapter 4. We presented our mathematical model formulations based on only highway option and two mode transportation option. The models are explained in detail. Also, the equity constraints are stated in this chapter. Then, the simulation model structure is presented. The simulation variables, assumptions, the behavior of the model and key performance indicators are presented at chapter 4.

The parameter settings of both mathematical models and simulation model and computational results of all models are presented at chapter 5. All parameters are based on either directly real life data or derived real life information. The computations are constructed on several problem sets such as heart, liver and kidney cases and for given number of regional coordination centers with minimum travel time bound. Moreover, the equity constraints are also performed on these cases. For the simulation model, heart, liver and kidney cases are run. Then, the obtained solutions are compared with the current system. At the last chapter, the summary of this study with the interpretation of the solutions are presented.

Chapter 2

Organ Transplantation Logistics and Problem Definition

2.1. General Information about Organ Transplantation

To understand the importance of organ transplantation, concepts and reasons of organ transplantation must be comprehended. Organ is defined as the groups of different structured tissues performing specialized tasks (Dictionary.com, 2012). When the organs are not able to function properly and if any treatment does not exist to save the organ, then the organ transplantation becomes the only way to cure the patient. All organs are not able to be transplanted. The organs and tissues that can be transplanted are "liver, kidney, pancreas, heart, lung, intestine, cornea, middle ear, skin, bone, bone marrow, heart valves and connective tissue" (Cleveland Clinic, 2012) .

Organ donation is "the donation of biological tissue or an organ of the human body, from a living or dead person to a living recipient in need of a transplantation" (Wikimedia Foundation, 2012). The person who donates his/her organ is the organ donor shortly 'donor' and the person who receives the organ is the 'recipient' (Cleveland Clinic, 2012). A person can donate more than one organ and these organs can be transplanted to different or same recipients (WebMD, 2012). As organ transplantation has an importance in the treatment; organ transportation is one of the key processes in today's healthcare sector. It is indicated that there is a tremendous gap between the number of donors in the system and the patients waiting for a new suitable organ everywhere in the world (Wikimedia Foundation, 2012). This is one of the major problems in organ transplantation since this gap increases cumulatively every year. It is stated that in the United States, every day, 17 people die while waiting an organ; more than 80,000 patients wait for a healthy organ (Cleveland Clinic, 2012), and 4,100 patients are added to waiting lists every month (Department of Health & Human Services USA, 2012). In Turkey, while 3,930 organs were transplanted in 2011, there exist 20,954 people waiting for a suitable organ as of April 2012 (Ankara Numune Egitim ve Arastirma Hastanesi, 2012).

In the organ transplantation procedure, the donations can be sustained from the living donors or the cadavers. A living donor donates one of his/her kidney or a part of his/her liver to a patient and living donor can live without donated organ after the transplantation. Cadaver can be the person whose brain death is declared by the officials in a hospital or a person who died in an accident. For kidney operations, approximately 20 % of the transplantations are conducted from the cadavers (Genc, 2009) and the rest from living donors, mainly family members. In 2011, 3,001 organs are donated from living donors and only 334 of the donations are from cadavers (Ankara Numune Egitim ve Arastirma Hastanesi, 2012). To understand both the process and restrictions in organ transplantation and to learn the organ transplantation system in Turkey, we conducted many interviews with a member of the national organ transplantation coordination center, Dr. Eyup Kahveci. He shared the statistics about the donors, and emphasized the dominance on living donors. In Turkey, the majority of the vital organ needs are for kidney, liver, heart, pancreas and lungs. However, living donors can only donate kidney or liver. Thus, for hearts and lungs, the process relies on cadavers (Bruni et al., 2006).

The donated organs do not live out of donor's body for a long time. Cold ischemia time is the time that the organ can stand in the absence of the blood supply (Referance.md, 2012). Cold ischemia time is the total of the durations of three processes of organ transplantation as organ removal surgery, transportation of the donated organ and organ implementation procedure to the recipient, respectively (Referance.md, 2012). The donated organ should be operated into the candidate patient within the cold ischemia time bound. Otherwise, the organ becomes functionless (Belien et al., 2012). Table 2-1 depicts the ischemia time of organs. As can be seen from Table 2-1, the longest ischemia time in hours belongs to pancreas and the shortest ischemia time belongs to heart.

Table 2-1 Transplantable Organs with their Ischemia Times

	Living Donor	Cadavers	Ischemia Time (hours)	Reference
Heart		+	5	(Bruni et al. 2009)
Liver	+	+	12	(Bruni et al. 2009)
Kidney	+	+	18	(Bruni et al. 2009)
Pancreas		+	30	(Greussner, 1984)
Lung		+	6	(Shea and Venkatesh, 2012)
Intestine		+	8	(Oltean, 2010)
Cornea		+	12	(KZN Cornea and Eye Assoc., 2012)

The donated tissues can stand outside without losing their functions for a long time. There are two choices of usage of a transplanted tissue. If there is a candidate recipient for the donated tissue at that time, and then in between 24-48 hours depending on the tissue type, it should be transplanted (Welsh Kidney Patients' Association, 2002). If there does not exist a candidate, then the tissues can be stored in special conditions as in -70 or - 80 Celsius cold, within special liquids for maximum 5 years (Feelgood Entertainment, 2012).

Organ transplantation can be conducted only at specialized hospitals. In most of the hospitals with operating rooms and intensive care units, kidney transplantation is possible. Any hospital which has specialized operating rooms, intensive care units and specialized doctors, is a candidate for organ transplantation hospital. In a heart transplantation hospital, transplantation of kidney and liver are also possible. If liver can be transplanted then it is also possible to transplant kidney. There is a hierarchical structure among heart - liver - kidney operations in the hospitals.

Dr. Kahveci implied that, the operation times of the organs are different. He stated these times approximately in minutes for heart, liver and kidney in the Table 2-2.

Table 2-1 Cold Ischemia Time Details of Durations for Three Operations at Heart, Liver and Kidney

	Organ Removal Surgery Time	Time Left for Transportation	Organ Implementation Surgery Time
Heart	10	220	70
Liver	45	405	270
Kidney	60	570	450

Also observe that, nearly 8.5 hours is required for kidney operations, nearly 5 hours for liver and nearly 1.5 hours for heart operations.

From now on, we will use ischemia time term in this study to refer the approximate transportation time bound for an organ and cold ischemia time refers total time that organ can keep its function.

2.2 Organ Transplantation in the World

Organ transplantation procedures have both similarities and differences for each country. Some countries prefer to create clusters under organ transplantation coordinators to organize all the organ transplantation related processes efficiently. One of the basic process in organ transplantation system is the 'matching' which is the process of finding the best recipient for the donated organ. There exist many criteria for matching such as "tissue match, blood type, length of time on the waiting list, immune status, distance between the potential recipient and the donor and the degree of medical urgency (for heart, liver, lung and intestines)" (United Network for Organ Sharing, 2012).

There are two main types of procedures for matching: centralized method and hierarchical method. In the centralized method, there is a single waiting list within an entire country. Here, priority can be given to the patients based on best match of organ or some other criteria. Moreover, countries using single waiting list may create a group of countries that combines waiting lists such that if one of the countries have a donor, then the best candidate is searched from that combined list without consideration of country of the recipient. For example, Eurotransplant is such an organization which coordinates the assignment of donated organs. The members of the Eurotransplant are Belgium, Germany, Croatia, Luxembourg, the Netherlands, Austria and Slovenia (Belien et al., 2012). Whenever an organ is donated within any of these countries, Eurotransplant conducts the matching process within the combined list of all the countries.

In the hierarchical method, the priority is given to local recipients. This local area can be considered as hospital, city or region. There may be several layers of this hierarchical procedure. When an organ is donated, recipients in the same hospital will be searched first, if there is no suitable candidate then the recipient will be searched within the city. Same procedure is applied for all layers in the hierarchical order.

The transportation process of the organ, which is very important due to ischemia time, may also vary. Some countries prefer to subcontract the transportation process to certain agencies. In this case, the agency is responsible for all the operations related to the transportation. Usually, the countries using centralized system utilize transportation agencies. Within the hierarchical system the transportation is under the jurisdiction of the region coordinators.

To the best of the authors' knowledge, there exist three countries whose organ transplantation operations are stated explicitly in the literature. Belgium, where the centralized method is applied, is not divided into clusters and it is a member of Eurotransplant so that its organ waiting list is also added to the common list of other countries. Moreover, there exists a shipping agency to carry the donated organ from donor's hospital to the recipient's hospital (Belien et al., 2012). The United States and Italy, where hierarchical method is applied, have the same characteristics such that each country is divided into regions for the coordination and they have hierarchical method to find the best matching recipient in their systems (Stahl et al. 2005, Kong et al., 2010 and Bruni et al., 2006). The organ transplantation system in Turkey is also hierarchical and is explained in more detail in the next section.

2.3 Organ Transplantation in Turkey

In organ transplantation system, the supply of the organs is very crucial. The statistics about transplantation numbers between 2002 – 2011 (first 10 months) from living and cadavers for Turkey is represented in Table 2-3 which is provided by Dr. Kahveci.

Table 2-3 The Transplantation Numbers in 2002-2011

Between 2002-2011 Living and Cadaver Transplantatlion Statistics												
	DONORS (Brain Dead with Family Permission)			KIDNEY			LIVER			HEART		Sum of trans. from Living Donors
	Used	Waste	*Total*	Donor		Total	Donor		Total	Total	Sum of trans. from Cadavers	
				Living	Cadaver	Number	Living	Cadaver	Number	Number		
2002	102	9	111	361	189	550	77	82	159	20	**291**	**438**
2003	105	12	117	428	177	605	88	86	174	23	**286**	**516**
2004	136	11	147	529	246	775	133	112	245	33	**391**	**662**
2005	153	21	174	653	273	926	200	124	324	36	**433**	**853**
2006	143	22	165	692	257	949	205	114	319	45	**416**	**897**
2007	223	22	245	911	391	1,302	264	209	473	61	**661**	**1,175**
2008	242	20	262	1,248	417	1,665	390	212	602	50	**679**	**1,638**
2009	262	36	298	1,919	443	2,362	363	229	592	54	**726**	**2,282**
2010	246	26	272	2,148	400	2,548	489	208	697	87	**695**	**2,637**
2011 first 10 months	263	19	282	1,816	413	2,229	378	212	590	74	**699**	**2,194**
TOTAL	**1,875**	**198**	**1,791**	**10,705**	**3,206**	**13,911**	**2,587**	**1,588**	**4,175**	**483**	**5,277**	**13,292**

Table 2-3 shows that kidney is the most donated organ. The reason is due to the living donors' opportunity to donate their kidneys. Donated kidneys from cadavers are also high when this number is compared with other organ donations from cadavers. At Table 2-3, the column 'waste' represents the total number of cases where the organs could not be used for several reasons in that year even if the donation is accepted by the family of the patient. Note that, the column 'donors' in the table does not include the number of living donors. Therefore, kidney and livers have extra column representing number of living donors.

In the Turkish organ transplantation system, all the organ transplantation operations are coordinated by a branch of the Ministry of Health in Turkey. This branch is the national organ transplantation coordination center (NCC) which coordinates the nine regional coordination centers (RCC) in Turkey. NCC is responsible from the managerial and strategic level decisions in this organization while RCC coordinates the organ transplantation between the cities. Each city is assigned to exactly one regional coordination center. Figure 2.1 depicts the current RCC locations and corresponding assignments in the Turkish organ transplantation system.

Figure 2.1 The Actual RCC Locations and the Assignments in Turkey

The organ transplantation capable hospitals which are specialized in one organ type are in limited number and these hospitals do not exist in each city. The number of transplantation centers in Turkey is represented in Table 2-4.

Table 2-4 The Cities with Transplantation Centers

Kidney Transplantation Centers	
City	Number of Centers
Adana	2
Ankara	10
Antalya	2
Bursa	1
Denizli	1
Edirne	1
Erzurum	1
Eskisehir	1
Gaziantep	2
Istanbul	21
Izmir	7
Kahramanmaras	1
Kayseri	1
Kocaeli	2
Konya	2
Malatya	1
Mersin	1
Samsun	1
Trabzon	1

Liver Transplantation Centers	
City	Number of Centers
Adana	5
Ankara	10
Antalya	3
Bursa	1
Diyarbakir	1
Erzurum	1
Istanbul	9
Izmir	3
Samsun	1

Heart Transplantation Centers	
City	Number of Centers
Adana	1
Ankara	6
Antalya	1
Istanbul	4
Izmir	2

Lung Transplantation Centers	
City	Number of Centers
Istanbul	2

In the Turkish organ transplantation system, the search for best matching potential recipient and donated organ is based on hierarchical approach. Each patient who needs transplantation is registered to a transplantation capable hospital without considering the patient's home city. That hospital can be considered as the responsible hospital of that patient. All the information regarding the patient is stored in the database of that hospital. These patients generate a waiting list for each specific organ in that hospital.

In the hierarchical method, each layer has the following information:

- Each transplantation hospital holds waiting lists of patients for each organ type.

- Each city has a list of existing transplantation hospitals. This list is ordered by the date of the last transplantation.
- Each RCC holds a list of cities allocated to this RCC
- NCC has all the list of RCCs

Matching a donor with a recipient in Turkey has two cases in general: The first case is the emergent case. When an organ is donated, firstly the search is conducted within countrywide in order to see if there exists an emergency patient waiting for that organ.
In this case; the organ (which is eligible for that patient) is directly sent to that patient without considering the RCC assignment hierarchies. However, in the regular case the hierarchical matching is conducted. When there is a donor in a hospital, the hierarchical perspective for the search of a best matching candidate is as follows: Initially, the database of donor's hospital is searched for a possible candidate at the waiting list. If the suitable matching candidate cannot be found, the search for candidates is enlarged to the hospitals of the donor's city. If again there is no match, the search is enlarged to the cities assigned to the same RCC. The last step is to look for the candidate within entire Turkey which requires NCC connections. Until a suitable recipient is found, all RCCs searched within their connected cities. In Figure 2.2, the organ transplantation process in Turkey is schematized.

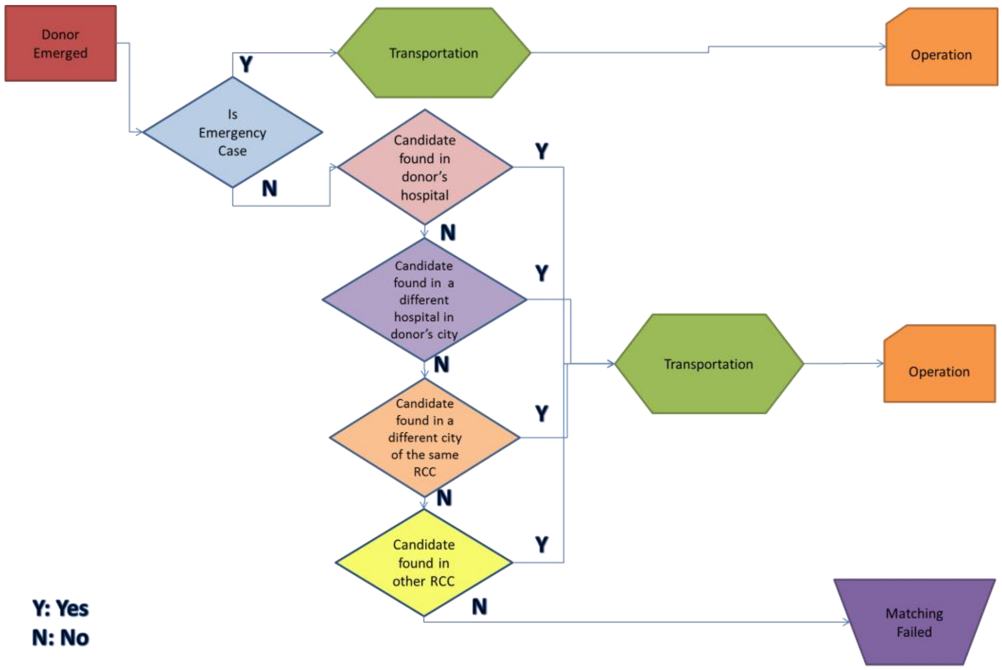

Figure 2.2 Organ Transplantation Process in Turkey

The transplantation operation is under the jurisdiction of the hospital that the patient is registered. Once a match is found, the transplantation doctors travel to the hospital of the donor and remove the organs. Then the doctors travel back to their hospital to operate on the recipient. Depending on the distance between the hospitals, the travel time of the round trip of the doctors is carried out by specialized vehicles (if time permits) or by airplanes / helicopters. Even though it is not the first concern, the cost of the process should also be considered. Figure 2.2 depicts that matching and transportation of the organ are the major processes in the system. Since donated organs are really scarce with respect to the demand, no waste is aimed.

2.4. Problem Definition

We see from Figure 2.2 that clustering and RCC locations have a significant impact in an organ transplantation system. When the actual RCC locations and their allocated cities are investigated, we see that the longest travel time between any two cities belonging to the same RCC does not exceed the transportation time of the cold ischemia time for kidney in the territorial distance in minutes (Table 2-5). For the heart case, only the Bursa RCC can hold the transportation time bound in their approximate diameter. In other regions, at least one transplantation center in that region violates the heart transportation time. For the liver case, only Malatya- Hakkari pair violates the transportation time for liver transplantation. In Table 2-5 more detailed results are represented for Istanbul, Ankara and Diyarbakir RCCs and the rest is in the Appendix 1. Pink colored blocks represent the violation on the transportation time for heart and blue colored block represent for violation at liver case. The green colored cities represent the RCC of that chart.

Table 2-5 Territorial Distances between Donor City and Recipient City in Turkey

Istanbul RCC			
Tranpslantation Center / Donor City	istanbul	Edirne	Kocaeli
Istanbul	0	153	74
Edirne	153	0	227
Kirklareli	141	41	215
Tekirdag	88	93	162
Kocaeli	74	227	0
Sakarya	99	252	25

Ankara RCC		
Tranpslantation Center / Donor City	Ankara	Eskisehir
Ankara	0	155
Eskisehir	155	0
Bolu	127	192
Zonguldak	179	238
Bartin	189	297
Karabuk	143	281
Kastamonu	163	319
Cankiri	87	243
Corum	161	317
Kirikkale	50	205
Kirsehir	123	271
Yozgat	144	299
Nevsehir	183	331
Aksaray	150	295

Diyarbakir RCC		
Tranpslantation Center / Donor City	Diyarbakir	Malatya
Diyarbakir	0	167
Malatya	167	0
Adiyaman	137	123
Elazig	102	65
Sanliurfa	117	179
Mardin	63	231
Batman	67	234
Bitlis	139	289
Siirt	125	292
Van	251	382
Sirnak	188	355
Hakkari	314	481

When we considered the characteristics of each region, we observe two contradicting perspectives. In one perspective the total number of population in a region is aimed to be low. This kind of clustering leads low number of patients in the waiting lists; however, also decreases the percentage of finding the candidate recipient in the waiting lists. On the contrary the advantage of this perspective is the waiting time of the patient in the waiting list is minimized. For example, Antalya, Bursa, Erzurum and Samsun RCCs have the total number of population approximately lower than 5.5 million (See Appendix 2). Second perspective motivates adding as many cities as possible to the same RCC. This approach increases the total number of people in that region and thus increases the probability of finding a best matching candidate recipient in the same RCC. However, this increases the patients' waiting time in the waiting lists. For instance, Istanbul, Adana, Ankara, Izmir and Diyarbakir RCCs have at least approximately 9 million people in their regions (See Appendix 2). In Istanbul RCC, the population is over 17 million with the highest populated region. When we compare the characteristics of the RCCs, these two differently constructed regions lead unfairness in the system. Therefore, one perspective should be targeted and applied to be fair to the candidate recipients considering the tradeoffs of both methods.

In the transportation of the organ, the helicopters or planes cannot be used anytime due to weather conditions, schedule time of planes or existence of vehicle at that time in that city. Therefore, the highway distance between donor and recipient cities should be considered as a significant constraint while deciding RCC locations and the cities assigned to each RCC.

When these facts are analyzed, it cannot be stated that the current system is well structured. Therefore, in this study the aim is to find the best RCC locations and corresponding clusters considering organ transplantation system dynamics such as ischemia time bound and the potential cities for transplantation. These considerations are essential and directly affect the problem due to the priority on finding organ in each cluster. Therefore, the objective is to maximize the match within each RCC. The main considerations are: ischemia time of organs, different transportation modes (car, helicopter, or airplane), the availability of transplantation hospitals in the jurisdiction of each city and the number of potential donors and recipients for each city.

This study aims to reorganize the organ transplantation system in the strategic level using mathematical modeling and simulation modeling approaches. By using mathematical modeling the locations of RCCs (the managerial level locations) of the organ transplantation system and the allocation of cities to those RCCs will be decided. One of the basic criteria during this clustering phase is the transportation time of the ischemia time. Initially we develop a model based on highway distances only. Then, we enhance this model considering air transportation option. Then, the system behavior is analyzed via a simulation model. Especially the hierarchical matching of the organ transplantation system with the proposed RCC locations and allocations is tested with the help of the simulation model.

In the simulation; our objective is to compare the performance of the outcomes of the mathematical model and the actual system. The probabilistic dynamics in the nature of the problem such as the possibility of matching in different levels (local, regional, and national) and vehicle availability are all considered in the simulation model.

Chapter 3

Literature Review

In general sense, the organ transplantation can be considered a variation of cold chain transportation. Cold chain is defined as temperature controlled supply chain (Wikimedia Foundation, 2012). In cold chain problems, a certain temperature level (or interval) must be satisfied from production to sales including loading, transporting and handling phases (Salin and Rodolfo, 2003). Some products such as ice-cream, frozen foods or vaccines are considered as perishable goods due to the temperature requirements. Although organ can be considered as perishable and it needs specialized equipment as in the cold chain studies, these problems differ from each other. The most significant difference is time bound. In the cold chain, the products can stand for certain amount of time (days, weeks, months or years) after production when the requirements are satisfied. However, when the organ transplantation system is deeply investigated, it appears that organ transplantation procedures do not fit to the cold chain concept. In organ transplantation system, the time for organ without perishing is just taking hours, which is difficult to manage with traditional cold chain methods. Moreover, the studies in cold chain mostly focus on temperature control to decrease the risk of perishability of items (Lugosi and Battersby, 1990, Matthias et al., 2007 and Miller and Harris, 1994) while organ transplantation studies focus on transportation and transfer of organ in specified time limit. Also, in the cold chain, the perishable goods can be refrozen in several time intervals during the transportation of the good to increase the stand time. However, this technique is not possible for the organ.

In the broader sense, our problem fits into healthcare management system. For the solution methodology, we follow network location literature. In this chapter, the literature review is presented considering network location problems, operations research in healthcare systems and finally the specific organ transplantation studies.

Network location problems are categorized into two main types of problems as point-location and path-location (Tansel et al. 1983). In this study, point-location problems, specifically p-median and covering problems are studied due to their closeness to our problem.

In 1964, Hakimi proposed the p-median problem. The p-median problem is selecting a subset of p-numbers among potential distribution center (DC) locations, such that total weighted distance from cities to DCs is minimized (Hakimi, 1964). This problem is formulated as an integer programming formulation by Revelle (Revelle, 1970). For fixed p, problem can be solved in polynomial time (Owen and Daskin, 1998) and for varying p size; the problem is proved to be NP-Hard (Kariv and Hakimi, 1979). Therefore; there exist many algorithms and heuristics to solve the p- median problems (Maranza 1964, Teitz and Bartz 1968, Narula et al. 1997 and Galvão 1980). There exist many variations of the p-median problem such as 1- median problem, p- median problem with Euclidean distance, p-median problem with spatial distance, conditional p-median and dynamic p-median problem (Hale and Moberg, 2003). Due to its flexible structure, p-median is often used to describe real life problems. Some examples are public facilities such as schools, pharmacies, health care services (Daniel and Marianov, 2004). Obviously, some of the real life problems need some additional constraints over classical p-median formulation.

Consideration of total cost minimization or travelling time may not be sufficient to represent some real life problems. If a facility has a time bound to travel (*i.e.*, emergency cases) then the problem cannot be described by using p-median formulation. Facilities must be located to cover a minimum distance or time to their demand nodes. This perspective is represented in another basic location problem known as covering problem. There are two major types of covering problem. The first one is "location set covering problem" (LSCP) proposed in 1971 by Toregas et al. The LSCP may also include the cost of locating facilities. If the demand weights are different between clients, second type of covering problem, Maximum Covering Location Problem (MCLP) can be used. This problem includes weight (population) of nodes. Its objective is maximizing the number of covered costumers or demand by locating p number of facilities. The number of facilities (p) is fixed and this problem is defined by Church and ReVelle (Church and ReVelle, 1974). Church and ReVelle showed that, a variation of p-median problem is equivalent to MCLP. This variation can be performed by adjusting distances between clients by using weights.

In previous paragraphs the network location literature was presented briefly. We now review operations research in healthcare literature. When the history of healthcare system related studies are investigated, the first study we found was conducted in 1911 by F. Gilbreth as the time study of surgery and delays (Benneyan, 2012). In 1959, the first queuing and scheduling studies in healthcare studies were conducted by Smalley et al. (Benneyan, 2012). Many branches of healthcare system such as "clinical information system, hospital inventory optimization, nurse scheduling, cancer screening optimization and total quality management" (Benneyan, 2012) are investigated and applied with operations research tools to find solutions to the problems.

Brandeau et. al. (2004), categorizes the operations research studies in healthcare systems into three sets; "Healthcare Operations Management" (HOM), "Public Policy and Economic Analysis" (PPEA) and "Clinical Applications" (Brandeau et al., 2004). Organ transplantation studies can be considered both in Healthcare Operations Management and Public Policy and Economic Analysis sets.

A subset of HOM studies is given as "Location of Healthcare Facilities". In this subset, healthcare location literature is given into three major perspectives as "accessibility", "adaptability and "availability". Accessibility problems aim to provide accessibility to the health service. In this type of problems, patients should reach the health service to be located or vice versa. The adaptability based studies focuses on location decisions in future uncertainty conditions such as the decision of location of a hospital. Availability problems consist of location decision problems for short term time intervals. Due to its nature, organ transplantation system can be considered in both accessibility and adaptability groups (Brandeau et al. 2004).

The matching policies in the organ transplantation system are regulated by the Ministry of Health. Therefore, organ transplantation system studies can also be considered as part of public policy. To support this thought, in the Operations Research and Healthcare: A Handbook of Methods and Applications, a study titled "A Model for Kidney Allocation" is given in the public policy section (Brandeau et al. 2004). Therefore, due to their close structure, organ transplantation system can be considered in the field of public policy.

Non-medical organ transplantation system based studies are increasing in recent years. In this area most of the studies are country base case studies which can be considered as soft operations research application. For example, Genc (2008) conducts a study on the Turkish organ transplantation system which states the managerial problems in the procurement of organ during the transplantation process. Uehlinger et al. (2010) performs a study on Switzerland; the effects of the changed law about cold ischemia time and organ transportation are considered and compared with the old case by using statistical data. In Spanish case, the researchers' objective is finding the optimal production for the organ transplantation centers in Spain (Deffains and Ythier, 2010).

Most of the organ transplantation system related papers are focusing on just organization and managerial components of organ transplantation system. In a study, for the Turkish organ transplantation system, the supply chain management of kidney transplantation process is studied. The aim of the paper is the analysis and improvement of the logistics operations of donated kidney to the recipient (Genc 2009). In another study which is based on the system in the United States, efficiency of organ procurement organizations is measured (Ozcan et al. 1999).

The matching of the donated organ with a recipient is one of the most critical and important process in the organ transplantation logistics. There is a study which considers the liver transplantation matching operations. In this study, based on the health status of the patient, an index is constructed for priority of urgent cases. Patients in the end-stage of liver disease have priority over other patients in the waiting lists according to this study (Thompson et al. 2004). Another article about the liver transplantation matching operations considers the effect of waiting time as a selection measure for the potential recipient (Freeman et al, 2002). Moreover, Bertsimas et al. (2001) constructs a matching model for kidney transplantation waiting patients on waiting lists considering fairness and effectiveness.

In general, most of the articles analyze and evaluate alternative policies for the waiting list management for liver transplantation case such as at the United Kingdom case (Ratcliffe et al., 2001) and the U.S. case (Thompson et al., 2004). Taranto et al. (2000) studies the national organ allocation model on simulation for kidney transplantation to allocate the donor organ and the recipient. Harper et al. (2000) differently from other allocation studies, focuses on multiple kidney allocation policy proposals to observe the affects by using simulation tool.

Apart from these soft OR models, to the best of authors' knowledge, there exist four studies which are dealing with organ transplantation system with discrete mathematical programming.

Former study of organ transplantation logistics using mathematical modeling is conducted by Stahl et al. (2005). This study is focused on liver transplantation system in the United States to allocate the donated organ to the recipient. The authors propose a very basic set partitioning type formulation where the regions are created with depth search method. In this method, the regions are created with contiguous number of OPOs with an upper bound (cannot exceed 9 OPOs in the same region). Cold ischemia time is considered to find the probability of matching of liver can be conducted or not. In other words, when the distance between donor city and recipient city increases, the matching probability decreases. This factor is used at objective function and equity constraint. The required data are obtained from either references or by assumptions with several data (Stahl et al. 2005).

Bruni et al. (2006) consider organ transplantation logistics of Italy. In Italy, the organ matching is similar to both Turkish and American cases. The matching is conducted with a hierarchical structure: local, regional and national wide. There exist three inter

regional centers shaped based on historical boundaries. These three centers are analogous of organ procurement organizations (OPO). These centers do not create a complete region; *i.e.*, the cities connected to these centers do not create a single region. This structure directly represents the inefficiency at the organ transplantation system in Italy. This unbalanced and separated cities connected to same center leads both high travel cost and risk of not transferring the donated organ to the transplantation center on time. In Italy, there are 20 transplant centers for heart, 14 transplant centers for liver, 33 transplant centers for kidney and totally 105 provinces. In this study, authors' aim is to increase the efficiency and equity in the organ transplantation system. They modeled a mixed integer linear programming to find optimal locations of OPOs, donor hospitals and transplantation centers to obtain an efficient system and equalize the waiting lists in general of country. In Italy case, each OPO is assumed to host one main transplantation center. When organ is matched with a patient, the transplantation is conducted in that transplantation center. In this study, the mathematical formulation is based on classical p-median formulation with additional equity constraint. The equity constraint performs in the formulation to obtain "the smallest maximum waiting list size" for the recipients.
In the mathematical formulation, the travel time from donor hospital to transplantation hospital is controlled with ischemia time bound. The authors assume that, all organs are traveled to the transplantation hospital by airway and all recipients travel to the transplantation hospital by highway. The objective of the model is to minimize the total travel distance in the system, which considers the ischemia time as radius. The analysis are conducted to compare the current system with proposed system considering various p values, different ischemia time boundaries (heart, liver and kidney) and the equity levels E. (Bruni et al. 2006).

Kong et al. (2010), also consider the American liver transplantation system as Stahl et al. (2005) paper. In this study, set partitioning perspective is same as Stahl et al.'s paper. The difference of this study is the way of creating regions and the solution methods.

Kong et al. provide a mixed integer programming with the branch and price perspective to create regions considering matching probability of donor city with the recipient city. The objective function is still same which is maximizing intra-regional flow of the organ at each region. Since the provided model is a NP hard problem, they also derived a heuristic to create regions in polynomial time. This study benefits from UNOS data for the computational results (Kong et al. 2010).

In 2012, Beliën et al. studied the Belgium case. They focus on locating the transplantation centers for each specialized organs and transportation agencies to transport the organ. In Belgium, each hospital does not have transplantation capability. Therefore, when the donor exists in that kind of hospital, these hospitals need to send the donated organ to a transplantation center. To prevent the complications in the system, each hospital is assigned to one transplantation center in Belgium. There are 8 transplantation centers in Belgium. 6 of these transplantation centers can conduct the transplantation of the 5 types of organ. 1 transplantation center is specialized on heart and the remaining is specialized on kidney.

When the donor exists in the system, the organ allocation procedure is as follows: when the donated organ is matched to the candidate recipient, the transplant coordinator of the donation occurred hospital and his team remove the donated organ. Then, the organ is transferred to the recipient's transplantation center by the shipping agent. The donated organ is not only carried by shipping agent, but also carried by plane since Eurotransplant coordinates the organ transplantation of 7 countries.

When the recipient is found in a hospital of a different country, the shipping agent carries the donated organ to the airport. If the donated organ which is coming from abroad is matched with a recipient in Belgium, the shipping agent takes the organ from airport and carries it to the recipient's hospital.

The authors use mixed integer programming formulation based on p- median model. Their model considers five organs respectively: heart, liver, lung, kidney and pancreas. These organs are considered having maximal cold ischemia time imposing extra constraints on the model. In this mathematical formulation, the objective is to minimize the total transportation time between donated organ city and the transplantation center. The constraints are for budget, fixed number of shipping agencies, and supply and demand of the organ flow equations for both domestic and international cases. The data about Belgium case states that the donor hospitals are selected as the hospitals having operating rooms. Therefore, the number of donor hospitals is 150 and 8 of 150 perform also as a transplantation center. There are 1135 municipalities and 5 airports. The ischemia time for Belgium case is not binding since the longest duration from a donor hospital to a transplantation center is 142 minutes which is much less than the strictest time bound (heart). 12 scenarios are generated, based on budget restriction, maximal cold ischemia times and covering restrictions. The numerical results considering cold ischemia time in the objective function, budget constraint and non-binding time covering constraint lead centralization in the locations of transplantation centers (Belien et al. 2012).

In summary, in all of the explained studies, the objective is either maximizing organ flow at each region or minimizing the total travel time (distance). The studies usually consider ischemia time as a constraint. They also try to include certain constraints and parameters for equity.

What we propose in this thesis is similar to Italian and American studies in the most general sense. We aim to locate RCCs (instead of OPOs). The donor- recipient matching criteria is hierarchical in Turkey and so is in Italy and the United States. However, we approach the problem from a different perspective. Instead of minimizing total travel time, we focus on maximizing total match in the first layer of the hierarchy. Also, we do not calculate all potential regions for the country; our mathematical model finds the optimal regions itself. Considering the perishable nature of the organ and short ischemia times, it is very crucial to find a match in the early stages of the hierarchical structure. In that sense, our study brings a different perspective. In addition, all 4 studies consider one type of transportation mode, whereas we enhance our model by including 2 different modes. With the help of simulation, we are also able to analyze the performance of the suggested locations and allocations. To the best of authors' knowledge, simulation modeling is only used at this study to observe the performance of the mathematical model solutions at hierarchical method within stochastic nature.

The summary of studies providing mathematical models based for organ transplantation system is presented in Table 3-1. We also include the current proposed model.

Papers	Applied Country	Considered Organs	Decisions	Objective Function	Modeling Approach	Clustering Criteria
Stahl et al. 2005	The United States	Liver	Creating OPO clusters	Maximize intra regional flow	Set partitioning	Max. 9 OPOs per region considering ischemia time
Bruni et al. 2006	Italy	Heart, Liver, Kidney	Location of transplantation centers, OPOs and donor cities based on organ type	Minimize total travel time	P-median with equity constraint	Cold ischemia time bound from transplant center to OPO
Kong et al. 2010	The United States	Liver	Creating OPO clusters	Maximize intra regional flow	Set partitioning	The percentage of matching for donated organ with a recipient
Belien et al 2012	Belgium	Heart, Liver Kidney, Lung, Pancreas	Location of transplantation centers based on organ type	Minimize total travel time	MIP with supply and demand flow balances and budget constraint	Cold ischemia time bound from donor hospital to transplantation center
Our study	Turkey	Heart, Liver Kidney	Location of RCC s.t. donor and recipient cities are allocated to RCCs	Maximize intra regional flow	MIP for location, allocation and clustering with two mode transportation	Cold ischemia time between donor and recipient cities with each cluster

Table 3-1 Mathematical Model Based Studies in Organ Transplantation System

Chapter 4

Model Development

In this chapter, the mathematical models and simulation model are explained. Two mathematical models are developed. In general both of the models consider

- The travel time between a donor and a recipient city which are allocated to the same RCC should not exceed the transportation time of the ischemia time for the donated organ.
- Each city is allocated to exactly one RCC
- Total number of RCCs is given

The first model is based on highway distances. In the second mathematical formulation two mode vehicle options is added to the model. Some cities cannot be allocated to some of the RCCs due to the transportation time of the ischemia time bound from one city to transplantation center within territorial distance. This perspective increases the probability of finding the best matching candidate recipient in the same RCC.

In our study, we also include the equity constraints to balance total organ flow for each region. This is one of the important perspectives of organ transplantation system. If a region has low number of donors, the recipients of that region would not find the most adequate organ easily. If a region has high number of recipients with respect to its donor emerging level, then the recipients would stay longer in their waiting list. Therefore, we propose 3 different sets of constraints for satisfying equity. We analyze them all in the sequel.

Then we use simulation to test the performance of the model outputs. In the simulation model, the outputs of the mathematical model (RCC locations, allocated cities to these RCCs and helicopter assignments) are given to the simulation model to observe the performance of the mathematical model solutions under different scenarios. Simulation model enables us to add many features of the organ transplantation system such as more than one organ donation from same donor, 3 layered hierarchical structure, updated waiting lists for each organ for each organ transplantation center, emergent case and regular (elective) case options.

In the following sections, the details of mathematical models and simulation model are stated.

4.1. Mathematical Models

During the mathematical model development, we considered the problem as a strategic level decision making problem. The location of the RCCs and finding its allocated cities are the major problems in the mathematical models.

4.1.1. Model 1: The Basic Model

Sets:

M the node set for potential donor's city {1…m}

N the node set for cities with transplantation hospitals, $N \subset M$

R the node set for potential RCC location. We use $R = N$

Parameters:

O_i the supply of total number of donated organs (without considering organ type), $i \in M$

b_{ij} travel time between nodes (by highway), $i \in M$, $j \in N$

d_j organ demand of nodes, $j \in N$

p total number of RCCs

T ischemia time

Decision Variables:

$$z_k : \begin{cases} 1 \; if \; RCC \; is \; located \; at \; k \; , k \in N \\ 0 \; otherwise \end{cases}$$

$$x_{ik} : \begin{cases} 1 \; if \; i \; is \; served \; by \; RCC \; at \; k, i \in M, k \in N \\ 0 \; otherwise \end{cases}$$

$$y_{ij}^k : \begin{cases} 1 \; if \; i \; supplies \; to \; demand \; node \; j \; served \; by \; RCC \; k \; , i \in M, j, k \; \in N \\ 0 \; otherwise \end{cases}$$

Then, the basic model is

$$\text{Max} \sum_i \sum_j \sum_k O_i . d_j . y_{ij}^k \quad (1)$$

s.t.

$$\sum_k x_{ik} = 1 \qquad \forall\, i \in M \quad (2)$$

$$\sum_k z_k = p \quad (3)$$

$$y_{ij}^k = x_{ik} . x_{jk} \qquad \forall\, i \in M, j, k \in N \quad (4)$$

$$x_{ik} \leq z_k \qquad \forall\, i \in M, k \in N \quad (5)$$

$$b_{ij} . y_{ij}^k \leq T \qquad \forall\, i \in M, j, k \in N \quad (6)$$

$$x_{ik}\, , y_{ij}^k, z_k \in \{0,1\} \qquad \forall\, i \in M, j, k \in N \quad (7)$$

The objective function (1) maximizes the intra-regional organ flow for each RCC. Each city is assigned to exactly one RCC by the constraint set (2) and (7). Constraint (3) fixes the number of RCCs to p. (4) satisfies two cities which are allocated to same RCC must have a donor city –recipient city connection between each other. $(5)^{th}$ constraint forces to open RCC when x_{ik} is provided by the model. $(6)^{th}$ constraint is the ischemia time bound. This constraint enforces that the travel time between donor city and recipient city should not exceed the ischemia time. Last constraint set is for the binary variable restrictions.

Observe that constraint (4) is nonlinear which can be linearized by using the method provided by McCarl and Spreen (1997). Linearizations of constraint (4) are:

$y_{ij}^{k} \leq \frac{x_{ik}+x_{jk}}{2}$ $\quad\quad\quad\quad$ $\forall\ i \in M, j, k \in N$ $\quad\quad$ (4')

$y_{ij}^{k} \geq (x_{ik} + x_{jk}) - 1$ $\quad\quad\quad\quad$ $\forall\ i \in M, j, k \in N$ $\quad\quad$ (4'')

4.1.2. Enhanced Model: Two Mode Transportation

In this model, the helicopter availability is integrated to model 1 to solve tightened ischemia time bound problems.

Additional Parameters:

u_{ij}: helicopter travel time between nodes, $i, j \in M$

h: number of helicopters in total

Additional Decision Variables:

$$hc_i: \begin{cases} 1 \text{ if helicopter connection is used for node i}, i \in M \\ 0 \text{ otherwise} \end{cases}$$

The model with two mode transportation option is

Max (1)

s.t. (2,), (3), (4'), (4''), (5), (7)

$\sum_i hc_i = h$ $\quad\quad\quad\quad$ $\forall\ i \in M$ $\quad\quad$ (8)

$(b_{ij}.\, y_{ij}^{k}) - ((b_{ij} - u_{ij}).\, hc_i) \leq T$ $\quad\quad$ $\forall\ i \in M, j, k\ \in N$ $\quad\quad$ (9)

$hc_i \in \{0,1\}$ $\quad\quad\quad\quad$ $\forall\ i \in M$ $\quad\quad$ (10)

In this model, objective function (1), 2nd to 5th and 7th constraints are same as in model 1. In the (8)th constraint the total number of helicopters is fixed to h. At (9)th constraint, the purpose is the same with the (6)th constraint. However in this model the representation changes. In this model, if a city does not have a helicopter, the formulation returns to same as (6)th constraint. If a city has a helicopter then, the travel time should be measured with helicopter travel time. (10)th constraint is the binary variable representation of hc_i.

4.1.3. Equity between Regions

While model 1 and model 2 are maximizing total organ flow within clusters, there may be unbalanced clusters with respect to the number of potential donors and number of patients in these clusters. Thus, we considered three types of equity constraints.

Equity Constraint 1

For each pair of clusters (RCCs and their assigned cities) the ratio of potential donations for each cluster should be bounded by a certain percentage.

M: big number

C: threshold value

$$\frac{\sum_i x_{ij} * O_i + M * (1 - z_j)}{\sum_i x_{ik} * O_i} \geq C/100 \qquad \forall\, j, k \in N \qquad (11)$$

Here $M * (1 - z_j)$ is required so that the numerator does not yield 0 for cities which are not RCCs.

Equity Constraint 2

For each pair of clusters (RCCs and their assigned cities) the ratio of the number of patients in each cluster should be bounded by a certain percentage.

M: big number

C: threshold value

$$\frac{\sum_{\mathrm{i}} x_{ij} * d_i \; + M * (1 - z_j)}{\sum_{\mathrm{i}} x_{ik} * d_i} \geq C/100 \qquad \forall\, j, k \in N \qquad (12)$$

Equity Constraint 3

The ratio of total number of donated organ to the total number of candidate recipient for each region should be greater than a constant.

C: threshold value

$$\frac{\sum_{\mathrm{i}} x_{ik} * O_i}{\sum_{\mathrm{i}} x_{ik} * d_i} \geq \; C/100 \qquad \forall\, j \qquad (13)$$

(11), (12) and (13) are added model 1 and the results are compared. These are stated in chapter 5.

4.2. Simulation Model

The mathematical model provides optimum RCC locations and corresponding allocations. In order to measure the performance of the proposed solution, we needed a simulation model which can handle stochasticity in the organ transplantation system. Hence we constructed a simulation model to represent the performance of the proposed solution.

The essential elements of the simulation model are donors, type of donated organs, matching operation and travelling of the donated organ with alternative vehicles. The simulation model represents all the processes of the organ transplantation system in an abstract level. In the simulation model, our major aim is to observe the performance of the mathematical model outputs within a hierarchical structured system. Figure 4.1 is the illustration of the developed simulation model in general.

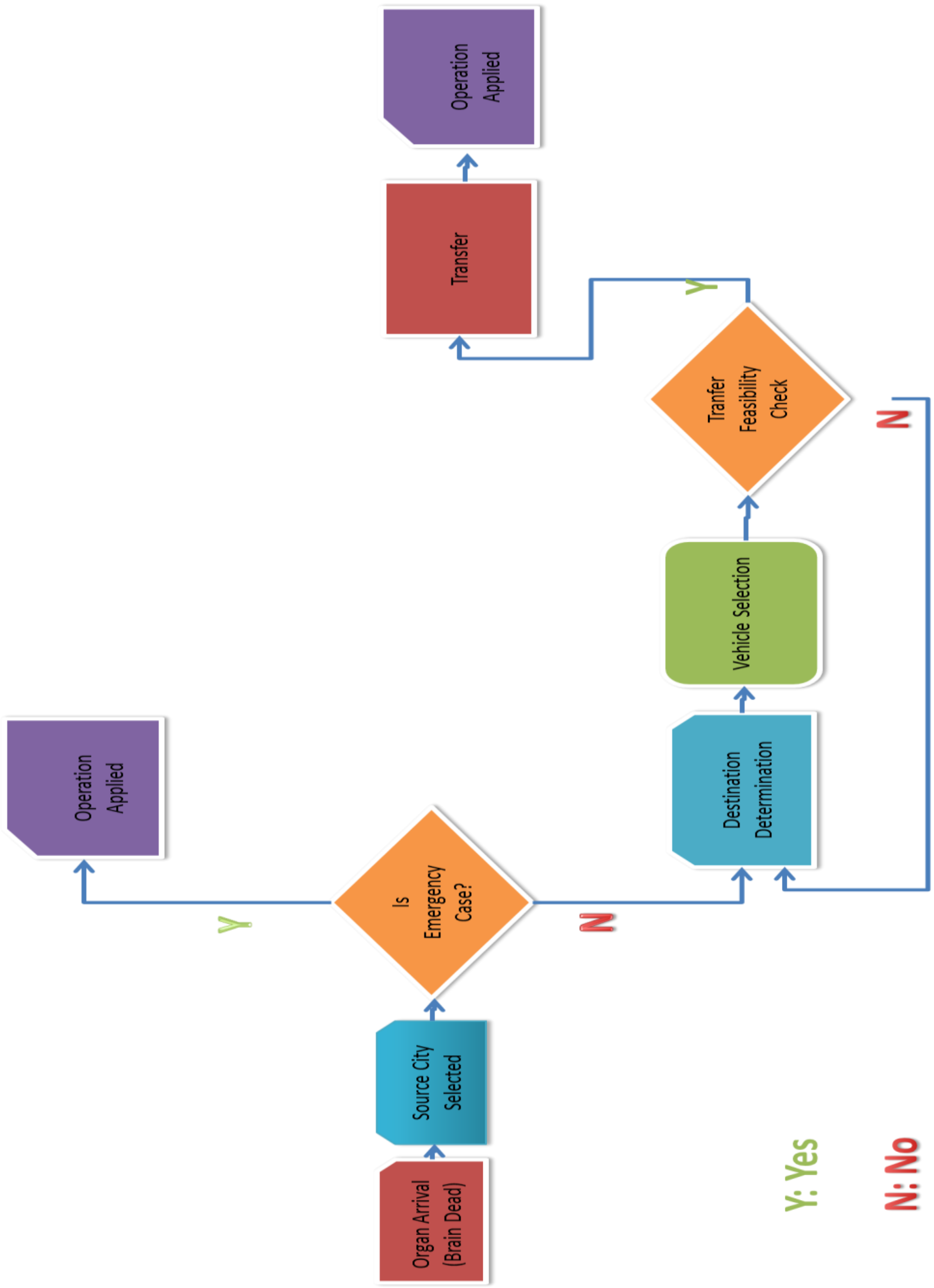

Figure 4.1 Simulation Model Illustration in General

The entity of the simulation model is chosen as donors. Process starts when a donor emerges. Donor can donate at least one of his/her organs kidney, liver or heart. He/she can also donate all of them. Then, the donor's city is assigned with an empirical distribution. The decision module checks if there exists an emergent patient in the system. If it results with emergent case, then without considering the patient's location, the donated organ is directly sent to the patient's city. In that case, the selected vehicle is usually plane or helicopter. Since we are considering emergent case, the transportation time is not significantly measured because the objective is to transfer the organ to the patient.

For nonemergency cases; when there is a patient waiting for the donated organ, then the destination of the organ; *i.e.*, the candidate recipient's city is defined hierarchically via the following steps:

Initially with a certain probability, the donated organ is matched with a recipient from donor's city. In local search case; *i.e.*, the donor and recipient match is found in the same city, the probability of this case is $1-\left(1-\frac{x}{100}\right)^{N}$ where x/100 represents the percentage of finding donor and recipient in the same city and N is the population number of the recipient's city. In this case, the organ is directly sent to the recipient's hospital, the transportation time is omitted and the operation is assumed as if it is done.

If the matching does not occur within the same city, donor's RCC starts to search candidate recipient from the list of hospitals assigned to it. In this step, first ranked city in the RCC waiting list (in the donated organ's type waiting list) can be matched with donor city with the probability of same as local search case *i.e.* $1-\left(1-\frac{x}{100}\right)^{N}$ where N represents the population of the first ranked candidate recipient's city and x/100 represents the percentage of matching the donor and this candidate recipient city. If the first ranked city is not matched with donor city, same search continues in the order of city list in the RCC with respect to considering their populations. If donor city and recipient city can be matched in the same RCC then, the order of selected city is updated to the last rank of the list. Then, the transportation phase directly starts.

When the corresponding RCC cannot find a best matching city in its region, NCC starts to find a candidate recipient. NCC contacts with the top ranked RCC in its list. This RCC starts to search from its first ranked city. When this RCC cannot find the best recipient through its city list, the searching process ends. Then the second ranked RCC in the list of NCC searches as stated. When the RCC finds a candidate recipient from its city, then the rank of the RCC is the last order in the list of NCC. These updated lists for RCCs and cities are differentiated for each organ in the simulation model.

When the matching process of the donated organ and candidate recipient is completed, the transportation of the organ is conducted via several options. If there is a helicopter in the donor's city, then the organ is carried by helicopter. Otherwise, if the distance between cities is less than ischemia time of the organ, then organ is transferred via highway. As a last option, if there are airlines at both donor's city and recipient's city, then the planes can be available in the system for carrying the organ. If all transportation options cannot be used, then a new recipient is searched.

The simulation inputs can be classified in three parts as parameters, simulation variables and system variables. The parameters of our simulation model are travel times between cities via highway and airway. The simulation variables are dealing with the ranking of the cities for each RCC for each organ and the ranking of the RCCs for the NCC level. These variables change during the simulation run. The system variables are RCC locations and allocated cities to these RCCs and the number of RCCs in the system.

Finally, the transplantation is assumed to be performed successfully. We omitted to include the case of fail; since the organ is matched with another candidate recipient from selected recipient's city in any case.

We can list key performance indicators of the simulation model as follows;

- Total number of successful transplantations within the same RCC
- Total number of matching of a donated organ with a recipient at different RCCs
- Usage percentages of the highway, helicopter and plane

The representation of the model is in the Figure 4.2

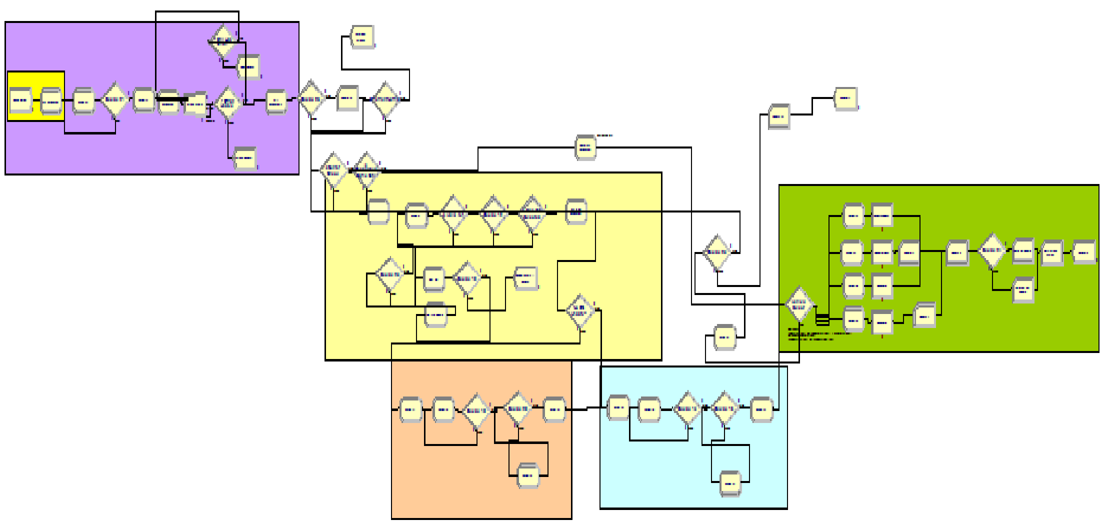

Figure 4.2 The Arena Representation of the Simulation Model

Chapter 5

Computational Results

In this chapter, the computational results of mathematical models and the simulation model are presented in detail. Since this study is based on a real life problem, actual data of problem is needed both for mathematical models and simulation model. Initially, the parameters of the models are explained. Then the outcomes of both models are discussed with comparison of actual case of Turkey.

5.1. Results of Mathematical Model

5.1.1. Parameter Settings

For the mathematical model structure, sets for donor cities, recipient cities and potential RCC locations are required. Since all cities in a country may have potential donors, all of them are included in the set of donor cities. Therefore all 81 cities in Turkey are in the set of donor cities. The recipient cities are the set of cities where transplantation operations are conducted. In Turkey, the number of transplantation centers is limited and these centers do not exist at each city. Moreover, transplantation centers are differentiated based on organ type. There are 59 kidney, 34 liver, 14 heart transplantation centers in 19, 9, 5 different cities respectively (as detailed in chapter 2). Since our model deals with multiple types of organ, we need to define largest possible candidate set. Therefore, we take our candidate set as large as possible, which corresponds to the cities with kidney transplantation hospitals because this set also contains same cities of liver and heart transplantation centers. There is only one exception for a city that do not have kidney transplantation center while having a liver transplantation center, Diyarbakir. Therefore, including that one city to the set of kidney transplantation cities, we get the set of recipient cities, which are 20 in number. This inclusion is a meaningful assumption since in liver transplantation centers kidneys can also be transplanted. Lastly, the potential RCC locations are selected same as the recipient cities for the managerial easiness. We assumed that RCC can coordinate the organ transplantation related issues easily when there is a transplantation center in that city. Therefore; the number of potential RCC locations is 20, same as recipient cities.

In the mathematical model, the number of donated organs (without considering organ type) for each city and the number of recipients on the waiting lists on each transplantation center is needed for approximating organ flow. Since we could not obtain exact data for these parameters, we made estimation for these numbers. To obtain the total number of donated organs for each city, we used data obtained from Dr. Kahveci (Figure 5.1).

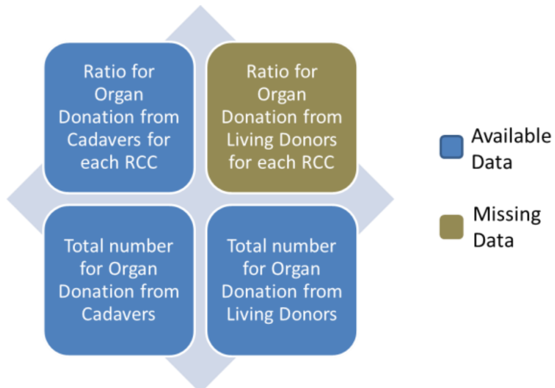

Figure 5.1 Available and Missing Data Chart for Organ Donation

Dr. Kahveci provided us the ratio of donations from cadavers in 2011 per 10000 of population for each RCC (Table 5-1). We use these numbers to obtain the number of potential organ donation from cadavers for each city which are allocated to their RCC. Dr. Kahveci also provided us the total number of organ donations from cadavers and from living donors in 2011. Therefore, we obtained the number of total donor ratio for each RCC. Then these RCC specific ratios are multiplied with the population of each city which is in its RCC. Then, the potential number of donors is found for each city (Figure 5.2).

Table 5-1 Organ Transplantation Ratios per 10000 Population for RCCs from Cadavers and Living Donors

RCC	Total Number of Transplantation from Cadavers	Total Number of Transplantation from Living Donors	Total Number of Transplantation
ISTANBUL	3.3	29.65	32.95
BURSA	4.6	41.33	45.93
IZMIR	8.8	79.07	87.87
ANTALYA	9.8	88.05	97.85
ANKARA	5.4	48.52	53.92
ADANA	4.3	38.64	42.94
SAMSUN	3.5	31.45	34.95
ERZURUM	0.8	7.19	7.99
DIYARBAKIR	0.7	6.29	6.99

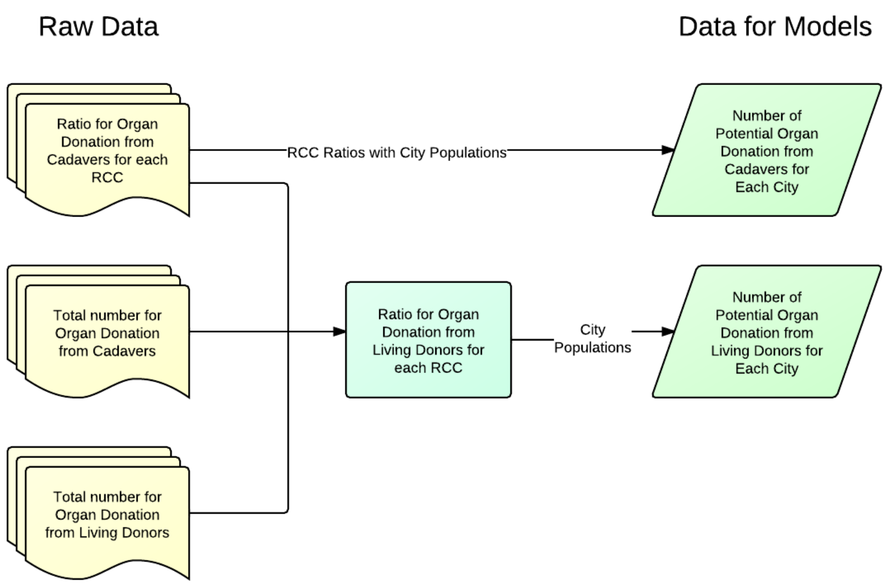

Figure 5.2 Revision of Data for Model Input

In order to estimate the total number of recipients for each transplantation center, we assume that number of patients in each organ transplantation capable hospital is the same. In Turkey, there are 19,403 patients waiting for an organ in 2011(Ankara Numune Egitim ve Arastirma Hastanesi, 2012). Dr. Kahveci provided us the total number of successful organ transplantation ratios for each RCCs. Then, we scaled these statistics to 19,403 patients to find number of patients at each RCC. Then, to find number of patients in RCC waiting lists; we scaled total number of hospitals that can perform organ transplantation on that city (without considering organ type) to the number of patients in that RCC. Therefore, the approximate number of patients at each city within their waiting lists is obtained. The number of transplantation centers at each city is presented at chapter 2. The RCC transplantation ratios are stated at Appendix 3.

The data of terrestrial travel time between two cities is obtained from General Directorate of Highways (Karayollari Genel Mudurlugu, 2012). The travel time between Ankara-Istanbul is considered as a sample for helicopter flight duration between two cities. By terrestrial travel time, Ankara-Istanbul is approximately 4.5 hours and travel time by helicopter is 1.5 hours (MEDAIR, 2012). Therefore, helicopter flights between two cities are considered as one third of the terrestrial travel time between two cities.

The number of RCC locations and transportation time bound of the cold ischemia time are parametrically changed during the calculations. For the organ specific transportation times, Dr. Kahveci provided the approximate transportation time for heart is 220 minutes, liver is 405 minutes and kidney is 570 minutes as detailed in Chapter 2.

The demand and supply values used in the mathematical models are presented at Appendix 4 and Appendix 5.

5.1.2 Solutions of Mathematical Models

In this part, initially Model 1 outputs are presented and then equity constraints are integrated to Model 1. The threshold values of the equity constraints are found and some of the Model 1 solutions including equity constraints are presented. Then, Model 2 findings are presented. Finally, the current organ transplantation objective values and solutions are compared with the proposed model values. The mathematical models are coded on Cplex with GAMS 22.3 solver and solved by the Gurobi 4.6.1 (GAMS Development Cooperation, 2006 and Gurobi Optimization, 2011). The map illustrations are presented using MapLoc (Cay, 2011).

5.1.2.1 The Model 1 Results for Ischemia Time fixed Case

Primarily, the ischemia times of heart, liver and kidney are studied. The minimum number of RCC locations (p) is found with respect to these times and then the objective value of these problems is calculated. At Table 5-2, the ischemia time (in minutes) for these organs, minimum number of p values for these times and objective values are presented. For this case; model 1 is parametrically solved for each p≤9 and the minimum p value which gives feasible solution is presented. 10^8

Table 5-2 Model 1 results for fixed ischemia times

Organ	T	p	Objective Value x 10^8
Heart	220	-	Infeasible
Liver	405	6	19.92
Kidney	570	4	33.50

For the heart case, the problem results are infeasible due to Hakkari. The nearest transplantation center to Hakkari is Diyarbakir and the duration between Hakkari and Diyarbakir is 314 minutes which violates the 220 minutes time bound.

For the liver case, T is 405 minutes and the minimum required number of p is 6. This case resulted with the RCCs which are Bursa, Diyarbakir, Mersin, Kayseri, Konya and Trabzon. The figure 5.3 represents the clusters of these RCCs.

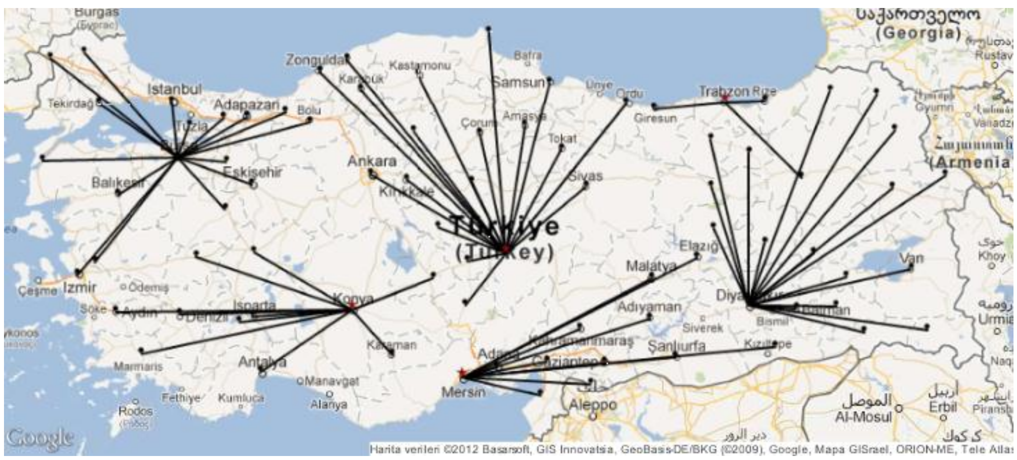

Figure 5.3 Model 1 for Ischemia Time is 405 minutes and p is 6

First we state our critical observations regarding the solutions. In the model, the ischemia time is checked between each transplantation center and all of the cities in a cluster. The model selects one of the cities with transplantation centers as RCC arbitrarily. Thus, for example, for the liver case, clustering around RCC Konya, the RCC location could also be Ankara or Samsun without losing from optimality. At Table 5-3, for liver case, RCC locations obtained from the model and the alternative RCC locations are presented.

Table 5-3 Alternative RCC Locations for Alternative Optimal Solution for Liver Case

RCC	Other Potential RCC Locations
Bursa	20,22,26,34,35,41
Diyarbakir	-
Mersin	1,27,46,44
Kayseri	6,55
Konya	7
Trabzon	25

Another critical observation is due to assignment of cities. Observe that not all cities are assigned to nearest RCC clusters. This is mainly to increase the inter cluster movement.

Observe from Figure 5-3 that, Erzurum is allocated to Trabzon instead of Diyarbakir (which is closer). If we force Erzurum to be allocated to Diyarbakir instead of Trabzon, the problem results with infeasibility since the time between Hakkari and Erzurum is 618 minutes. Erzurum is also a transplantation capable city and, if we include Erzurum in the Diyarbakir RCC, we should also check the time bound between Erzurum and the other cities assigned to this cluster.

For the kidney case, the ischemia time is 570 minutes and the minimum number of p is 4. The RCC locations are Erzurum, Kocaeli, Konya and Trabzon. The Figure 5-4 presents RCCs with their allocated cities.

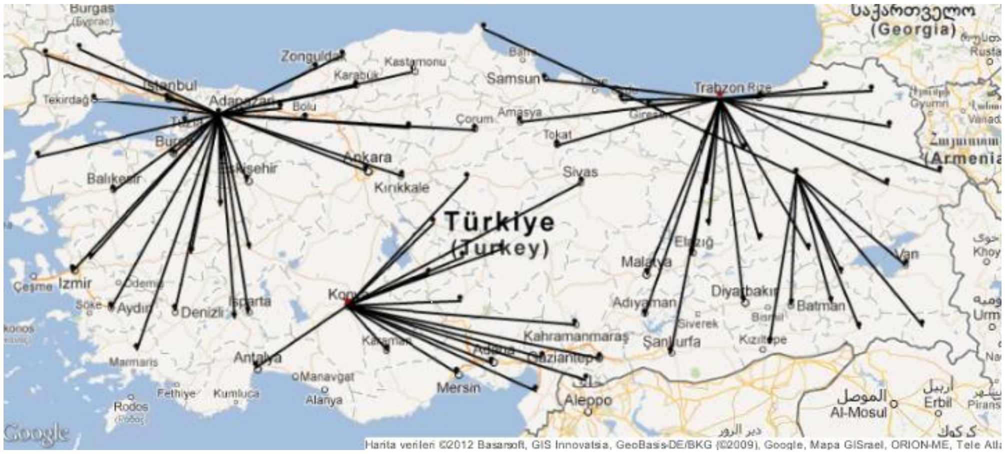

Figure 5.4 Model 1 for Ischemia Time is 570 minutes and p is 4

Again, if we force Sinop allocation to Trabzon RCC instead of Erzurum RCC, in this case, the objective value decreases by 0.11%. Thus, in order to maximize within cluster organ flow, some cities are assigned to RCC which are not necessarily the closest ones.

5.1.2.2 Model 1 Results for fixed number of RCCs

Now, for model 1, the number of RCCs is given and T is parametrically decreased until infeasibility. The results are presented at Table 5-4.

Table 5-4 Model 1 Results for given number of p with Minimum T Values

p	Minimum Possible T	Objective Value x 10^8
9	314	18.75
6	374	19.39
4	537	32.98

For 9 RCC locations, as in current system, the minimum travel time is 314 minutes. The location of RCCs are Antalya, Bursa, Diyarbakir, Edirne, Erzurum, Gaziantep, Mersin, Samsun and Trabzon and the resulting clusters are represented at Figure 5.5.

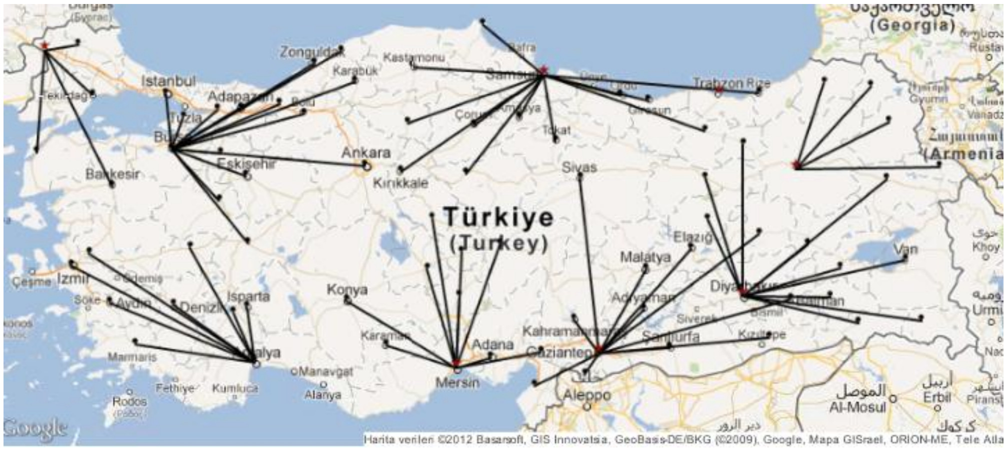

Figure 5.5 Model 1 for given number of p is 9 and Ischemia Time is 314 minutes

When the number of RCCs is fixed to 6 (the minimum required number of p for liver ischemia time), the transportation time is decreased to 374 (instead of 405) and the resulting RCCs are Ankara, Diyarbakir, Mersin, Eskisehir, Erzurum and Kocaeli. These RCC locations and their clusters are represented at Figure 5.6.

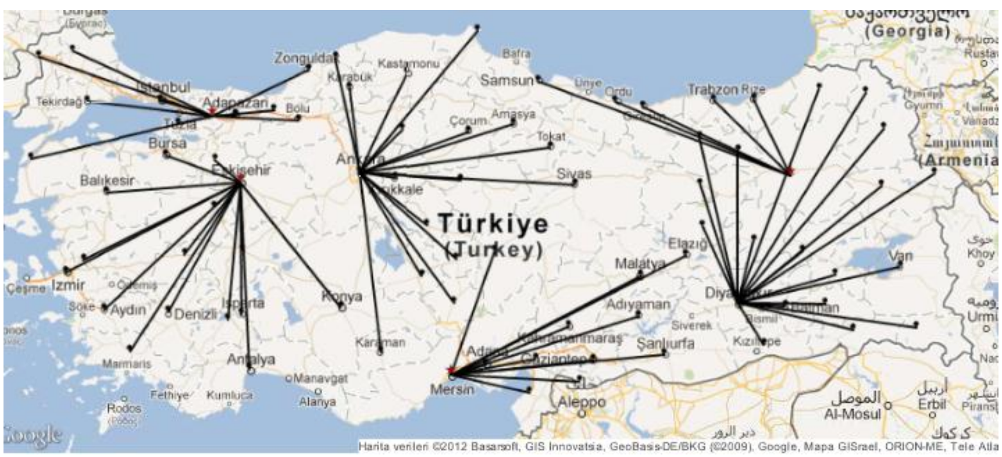

Figure 5.6 Model 1 for p is 6 and Ischemia Time is 374 minutes

When number of p is chosen 4 (the minimum number of required RCC for kidney ischemia time), the transportation time is found as 537 minutes. The resulting RCCs are Diyarbakir, Erzurum, Eskisehir and Kayseri. The clusters of these RCCs are represented in Figure 5.7.

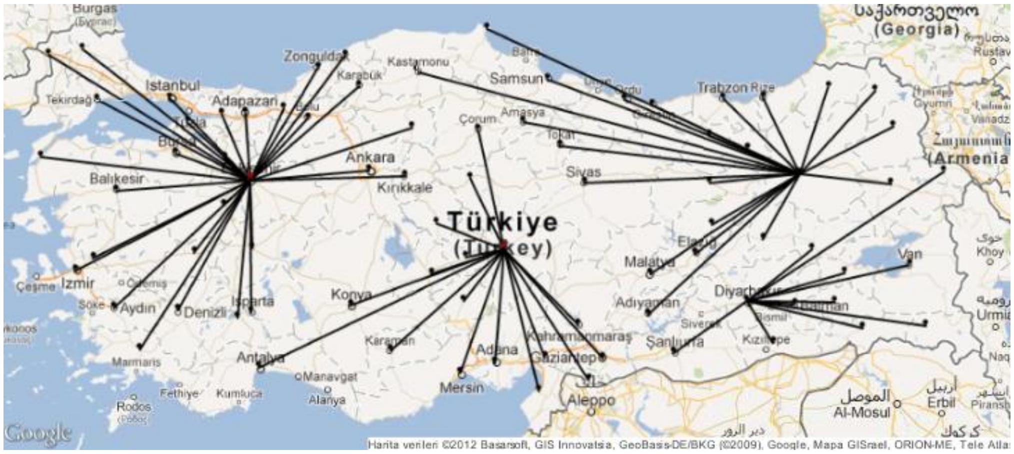

Figure 5.7 Model 1 for p is 4 and Ischemia Time is 537 minutes

When Model 1 is analyzed, we observed that when the number of RCC locations increases, due to smaller clusters, the duration between cities is shortened and the objective value decreases. This decrease is based on the objective function; *i.e.*, maximize intra-regional flow in each cluster and when the clusters are small, since the number of city decreases, it directly affects the flow in each region.

We observe that when the time bound is large enough, the objective value increases. However, if the aim is also to decrease the transportation time as much as possible, the time bounds can be decreased approximately by 30 minutes for fixed number of RCCs which is a significant value for the organ transplantation process.

5.1.2.3 Model 1 with Equity Constraints

For both fixed ischemia time case and fixed number of RCC case, some of the results represent unbalanced clusters in terms of population in a region. These numbers directly affect the number of potential donors and number of patients in the waiting lists in these clusters which creates unfairness in the regions. Some regions can reach the organ easily due to high number of potential donor in their region. Therefore, to get more balanced regions, as we stated in Chapter 4, we add equity constraints into model 1. During the calculations, we did not add Istanbul's potential number of donor and patient number to the model since Istanbul is an overly populated city and always deteriorates the balance.

Defining the threshold values for each case is one of the important parts to balance regions. Therefore, first, the threshold values are found for fixed ischemia time case and given number of p and are represented at Tables 5-5 and 5-6, respectively. This value should be between 0 and 1, 0 representing no equity relation between regions and 1 representing the regions can be clustered equable. C1, C2 and C3 represent the threshold values for equity 1, equity 2 and equity 3 cases, respectively.

Table 5-5 Threshold Values for Equity1, Equity 2 and Equity 3 for Fixed Ischemia Time Bounds

Organ	Fixed T	Min. Best p	C1	C2	C3
HEART	220	-	Infeasible	Infeasible	Infeasible
LIVER	405	6	0.2	0.05	0.01
KIDNEY	570	4	0.35	0.15	0.01

Table 5-6 Threshold Values for Equity1, Equity 2 and Equity 3 for fixed p Values

Fixed p	Min T	C1	C2	C3
9	314	0.15	0.01	0.01
6	374	0.2	0.05	0.01
4	537	0.2	0.15	0.01

For both of the tables, a complete enumeration is conducted to find the largest C value which gives feasible outputs. Both Tables 5-5 and 5-6 represent that the threshold values are not high enough to balance the regions. The maximum threshold value is 0.35 for kidney ischemia time with 4RCCs. Especially for equity 2 and equity 3 cases, regions cannot be balanced due to number of patients in the waiting lists are not homogenously distributed in 19 cities. In order to observe the best equity levels, we fix highest T value (for kidney ischemia time) with different p values. We obtained the threshold values as stated in Table 5-7.

Table 5-7 T=570 minutes with Different p Values for the Threshold Values for Equity 1, Equity 2 and Equity 3.

T	570		
P	C1	C2	C3
5	0.6	≤0,04	≤0,04
7	0.9	≤0,04	≤0,04
9	0.9	≤0,04	≤0,04

At Table 5-7, only the threshold values greater than 0.4 are presented. For equity 1, we can obtain 0.9 with 9 RCCs. For equity 2 and equity 3, these values are less than 0.4 therefore we omitted these values. We cannot state that there is a relation between number of p and threshold values since the distribution of the number of patients and donors is not homogeneous in nationwide.

We next represent the objective values for the models with equity constraints for fixed p. We face that the objective values decrease since equity constraints are binding constraints restricting the feasible region. The objective values for given number of p values case with the threshold values are presented at Table 5-6 are represented in Table 5-8.

Table 5-8 Objective Values x 10^8 for Equity1, Equity 2 and Equity 3 for given number of p

p	T	Eq1 Obj. Val.	Eq2 Obj. Val.	Eq3 Obj. Val.
9	314	7.13	11.10	11.70
6	374	9.86	10.50	16.00
4	537	15.40	13.30	18.40

When the objective values are compared within equity constraints, we see that when the threshold value decreases, the objective value increases. Therefore, equity 1 objective values are the lowest and equity 3 objective values are the highest values in the table. Since we focus on more equitable regions in this case, the equity 1 solutions are found and stated as follows:

When p equals to 9, with the transportation time bound is 314 minutes, the RCC locations are Ankara, Bursa, Denizli, Diyarbakir, Erzurum, Istanbul, Konya, Malatya and Trabzon. Figure 5.8 depicts this case.

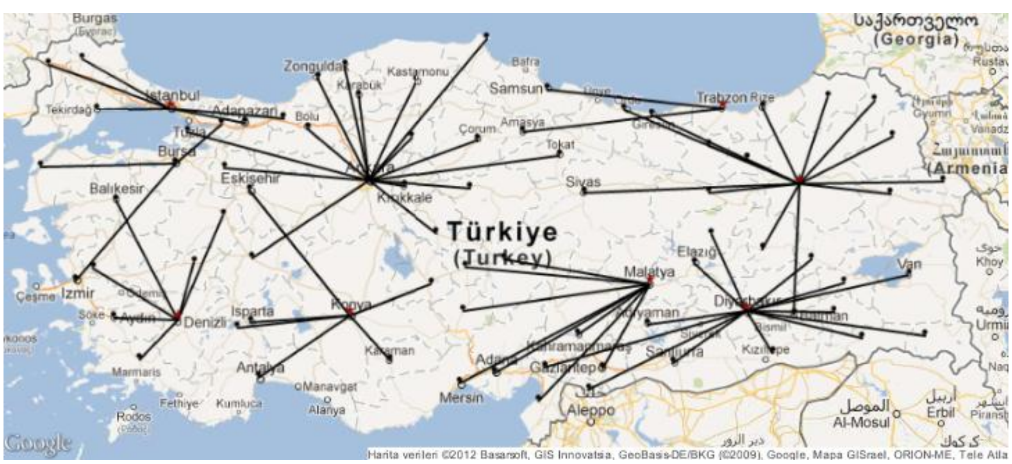

Figure 5.8 Equity 1 Solution for given p is 9 with T is 314 minutes

The results with model 1 with no equity constraint and model 1 with equity 1 constraint are depicted at Table 5-9. The objective value decreases by 61.95 % from no equity objective value case.

Table 5-9 Objective Values x 10^8 and RCC Location for given number of RCC Case when p=9 and T=314 minutes

	Model 1 No equity	Model 1 with equity 1 constraint
Objective Values	18.7	7.13
RCC Locations	7,16,21,22,27,33,55,61	6,16,20,21,25,34,42,44,61

For p=6 case (as in liver case), the RCCs are found as Ankara, Diyarbakir, Eskisehir, Konya, Kahramanmaras and Samsun where T=374 minutes. Figure 5.9 illustrates this case.

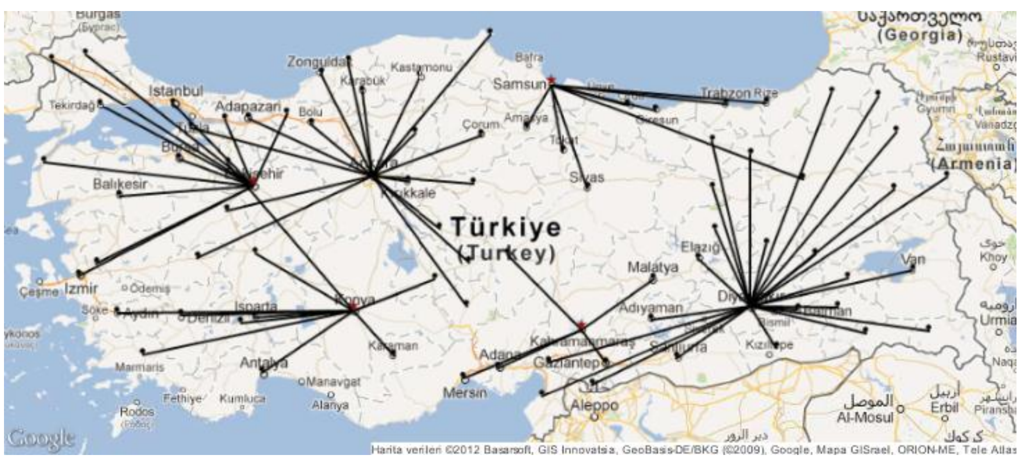

Figure 5.9 Equity 1 Solution for given number of RCC Value, 6, in 374 minutes

The results with model 1 with no equity constraint and model 1 with equity 1 constraint for p=6 case, we obtain the results at Table 5-10. The objective value decreases 49 % from no equity objective value case.

Table 5-10 Objective Values x 10^8 and RCC Location for given number of RCC Case when p=6 and T=374 minutes

	Model 1 No equity	Model 1 with equity 1 constraint
Objective Values	19.4	9.86
RCC Locations	6,21,33,26,25,41	6,21,26,42,46,55

For the last case of the fixed number of p= 4, with the T=537 minutes, the optimal RCC locations are Izmir, Malatya, Kahramanmaras and Samsun. The clusters are represented at Figure 5.10.

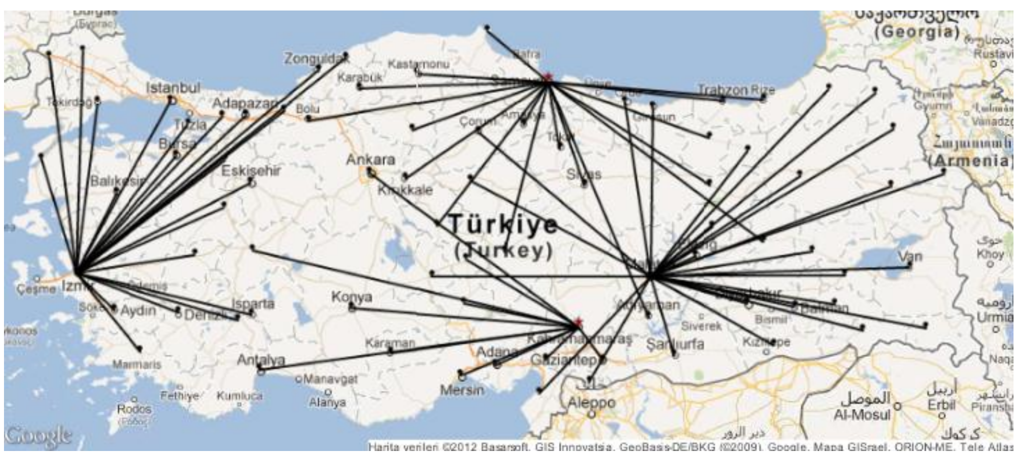

Figure 5.10 Equity 1 Solution for given number of p=4 in 537 minutes

When the equity 1 solutions are compared with the solutions, in general we can state that, in east side regions, many cities are allocated to one RCC due to low number of population (donor) in these regions. That is also the explanation of why the west side regions consist of less number of cities.

Table 5-11 presents the RCC locations and objective function values with and without equity constraint for p=4 and T=570. We observe from Table 5-11 that the objective value decreases by 53 % from no equity objective value case.

Table 5-11 Objective Values x 10^8 and RCC Location for given number of RCC Case when p=4 and T=537 minutes

	Model 1 No equity	Model 1 with equity 1 constraint
Objective Values	33	15.4
RCC Locations	21,25,26,38	25,44,46,55

The remaining results about equity 2 and equity 3 are represented at Appendix 6 to Appendix 11.

5.1.2.4 Model 2 Results

In this part, the outcomes of the model 2 will be discussed. Since model 1 cannot find a feasible solution for heart case, in this model the purpose is to find feasible solutions for heart case by adding required number of helicopters to the model.

There are only 5 heart transplantation capable cities in Turkey. Therefore; initially we set the solution for 5 RCC with the current heart transplantation. However, the problem results with infeasibility since there does not exist any city capable with heart transplantation in the east side of Turkey. Therefore, we constructed two problem scenarios for this case. Initially, we will consider again current 5 of these RCC locations and we add one RCC from the candidate set of eastern cities (Diyarbakir, Erzurum, Gaziantep and Malatya) that maximizes the objective function. In the second perspective, we consider to locate 9 RCCs 5 of which are current RCC locations having heart transplantation centers.

When model 2 is run for the first scenario, the minimum required number of helicopter is 17, with the given RCC locations Adana, Ankara, Antalya, Istanbul, Izmir and eastern city Erzurum.

The result of the first problem structure is given in Figure 5.11 and the objective value is in Table 5-12.

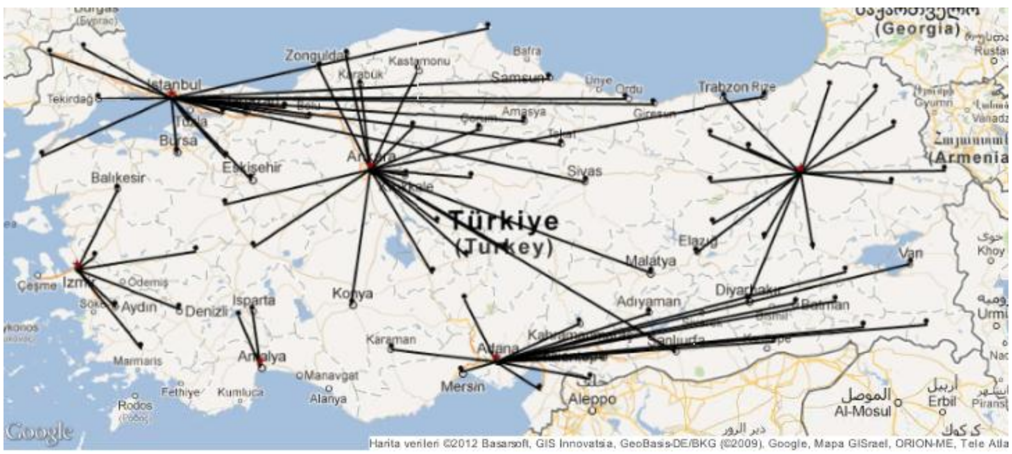

Figure 5.11 Model 2 Solution for T=220, p=6 and number of helicopters is 17

In Figure 5.11 the long allocation links represent the helicopter assignments of that city to RCCs. For example Van is allocated Adana with a helicopter. Due to the objective function, which is the maximization of the intra-regional flow for each region, many cities have allocations with far cities. For instance, many cities are allocated to Istanbul RCC to increase the organ flow in that region. Sanliurfa cannot be allocated to Adana by highway distance. Then, the helicopter opportunity enables Sanliurfa to be allocated to Ankara.

Next the problem is solved for 9 RCC where 5 of them are given (current locations). This time the required number of helicopter is only 3, the solution is given at Table 5-12 and at Figure 5.12.

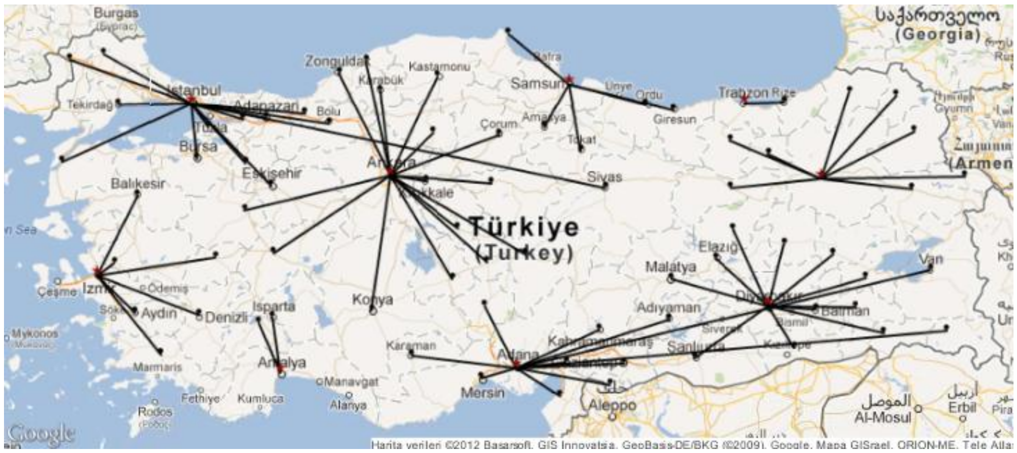

Figure5.12 Model T=220, p=9 and number of helicopters is 3

When the RCC numbers are increased to 9 where 5 of them are still current locations for the heart case, only 3 helicopters are required to obtain feasible solutions where helicopters are assigned to Sivas, Van and Hakkari. When the number of RCCs increases the required helicopter decreases and as we discussed before, when p increases, the objective value decreases.

Table 5-12 Model 2, T=220, p=6 and 9

T	H	p	Model 2 Obj. Val. x 10^8
220	17	6	14.1
220	3	9	12.8

5.1.2.5 Current Organ Transplantation System Results

After all cases and models with equity constraints are analyzed, the comparison between proposed models and current RCC locations in Turkey with their allocated city performance is studied. The current system outputs are obtained from our models by fixing the current RCC locations and allocations and calculating the intra-regional flow. The outputs are stated at Table 5-13 with our proposed solutions.

The current system allocations are presented at Figure 5.13.

Table 5-13 Current System vs. Proposed System Solutions for Fixed Time Bound (Ischemia Time Based)

Organ	T	p	Current System Obj.Val. x 10^8	Proposed p	Proposed System Obj. Val. x 10^8
HEART	220	-	Infeasible	-	Infeasible
LIVER	405	9	Infeasible	6	19.9
KIDNEY	570	9	10.9	4	33.5

As in our proposed models, current clusters cannot satisfy heart ischemia time bound in the regions. However, the current system cannot result with a feasible solution even for the liver ischemia time bound. We want to remark here that for T=570 and p=9, the clustering based on our models nearly triples the objective function value. Next, we compare the minimum T bound coverage as depicted in Table 5-14.

Table 5-14 Current System vs. Proposed System Solutions for p=9

	Current System Solution		Proposed Solution	
p	T	Objective Value x 10^8	T	Objective Value x 10^8
9	481	10.9	314	18.7

When the RCC number of RCCs is fixed to 9, the minimum time bound between the donor city and the recipient city is 481 minutes with the current system and can be decreased by more than 2,5 hours with the proposed solution. Moreover, the objective function value representing intra region flow still increases with less T bound.

The threshold values for equity 1, equity2 and equity 3 are also calculated for the current system as shown in Table 5-15.

Table 5-15 Threshold Values for Equity Constraints for Current System and Proposed System

	Equity 1	Equity 2	Equity 3
C for 9 RCCs of current locations	0.01	0.01	0.01
C for proposed 4 RCC	0.35	0.15	0.01

The current system regions represent that, they are not clustered with respect to the equity base.

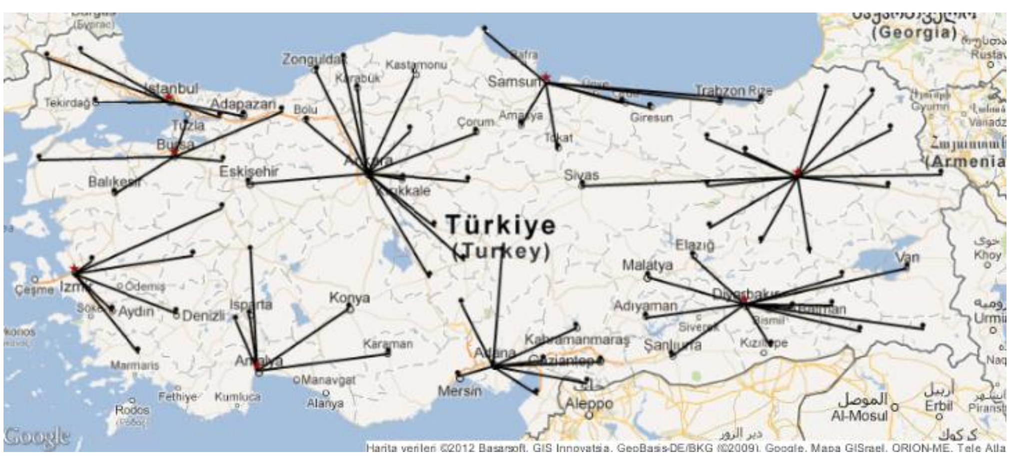

Figure 5.13 The Current Turkish RCC Locations and Allocations of the Cities

Next we compare the current and proposed systems with the helicopter option. If we assume all hospitals can perform heart transplantation we obtain the results given in Table 5-16. We obtained that; the minimum number of helicopters is 8 with current clustering.

Table 5-16 Current System vs. Proposed System Solutions for Model 2 where 9 RCCs are Capable with Heart Transplantation System, T is 220 minutes

T	p	Helicopter	Obj. Val.
Current	9	8	10.9
Proposed	9	3	12.8

Table 5-16 presents that current system needs 8 helicopters to find a feasible solution and proposed system needs 3 helicopters. Even if current system has more helicopters than proposed system, still the objective value of proposed system is approximately 15 % higher than current system.

5.2. Results of the Simulation Model

5.2.1. Parameter Settings

In the simulation model, the inter arrival of donors is calculated as follows: in the system there are 3,335 donors with the summation of 3,001 living donors and 334 cadavers in 2011(Ankara Numune Egitim ve Arastirma Hastanesi, 2012). We divided this number to 365 days and we found that the mean of inter-arrival of the donors is 2.01 hours. Therefore, inter-arrival of donors is distributed with exponential distribution with a mean of 2.01. The donor's city is assigned with empirical distribution such that the probability of each donor's city is related with the potential number of donor of that city which is the same number used for Oi in the mathematical model.

The percentage of organs for 2011 donations and emergency case are given in Table 5-17. The percentage of emergent cases is another important parameter, which is based on our data (Appendix 12).

Table 5-17 Percentages of Donated Organs and Emergent Cases in the System

Donated Organ	Donation Percentage	Emergency Cases
Kidney	76.5 %	1%
Liver	20.2 %	13%
Heart	3.3 %	86%

For emergent cases, the transportation is always by plane.

In the regular case, the destination city of the donated organ is found with the probability that we defined at Chapter 4. At both local search and regional search cases, we assumed that the matching probability of donated organ with any recipient at the same city (considering the donor city has also a transplantation center) or different city is same with the percentage 15 %. We considered this number by taking the average of matching ratio of donated organ with a recipient between 10% and 20% in Turkey (AKSIYON, 2012). Recall that the matching is coordinated hierarchically over ranked lists of RCCs and NCC. The initial order of cities in RCCs and RCCs in NCC are randomly given to the simulation model.

If matching is successful at regional level, then the rank of selected city is updated to the bottom order and if it is at national level, then both the rank of RCC and the city in its list is updated. These lists and orders are organ based and changes for each type of organ.

We used Arena Simulation Software version 13.5 for the simulation modeling (Rockwell Automation, 2010). Since we have many cases during our study, for the sake of clearness, we considered model 1 with transportation time fixed cases (liver and kidney case), special case for T=314 and p=9, model 2 heart ischemia time bound case and current system (kidney ischemia time case and helicopter case) simulations for the analysis and comparisons. In the simulation runs, the run length is set to 365 days and the replication length is fitted to 500 to have sufficiently large sample size for trustable statistics.

5.2.2. Solutions of the Simulation Model

To observe the performance of the mathematical model solutions in real life application, we also simulated the organ transplantation system in general. Therefore, we can see the effect of hierarchical method on RCC locations and their allocations in the system. The performance measures with their half widths are stated in average values at Table 5-18 and Table 5-19 with half width obtained from simulation.

Table 5-18 Simulation Model Outcomes Based on Model 1 Solutions

Clustering Based on		Simulation Outcomes										
p	T	Average Organ Travel Time	Half Width	Total Number of Donated Organs	Half Width	Total Number of Wasted Organ	Matching Within Same Region (%)	Half Width	Matching at Different Regions (%)	Half Width	Number of Plane usage to carry donated organ	Half Width
4	570	134	<0.23	4084	<6.48	0	98.00	<6.43	2.00	<0.78	61.00	<0.66
6	405	106	< 0.2	4087	<6.32	0	96.40	<6.17	3.50	<1.2	41.00	<0.59
9	314	104	<0.18	4089	<6.21	1	87.00	<5.69	12.50	<2.19	121.00	<1.02
9 (current system)	570	89	<0.17	4084	<6.14	0	89.50	<5.6	10.50	<1.93	99.00	<0.89

Table 5-19 Simulation Model Outcomes Based on Model 2 Solutions

System	Case		Simulation Outcomes											
	p	T	Required number of Helicopters	Average Organ Travel Time	Half Width	Total Organ Output	Half Width	Matching Within Same Region	Half Width	Matching at Different Regions	Half Width	Used number of Helicopters	Half Width	Used number of Planes	Half Width
Proposed System	9	220	3	88	<0.16	4086	<6.26	3761	<5.86	325	<1.71	17	<0.41	86	<0.41
Current System	9	220	8	82	<0.15	4088	<6.36	3662	<5.89	441	<1.92	211	<1.45	85	<0.8

Model 1 for Kidney Ischemia Time Bound: Proposed solution with T=570 and p=4

In this case, we took the possible minimum number of RCC value which is 4 to operate the system. The performance of this case states that, the organ travel time is 134 minutes in average. Total number of organ output is 4084. In 2011 this number is 3930 which is near to real life number. 4003 of those organs are matched with a recipient in the same RCC. Only 80 organs are matched in different RCC. Moreover, 61 times the plane is used to transfer the organ.

Model 1 for Liver Ischemia Time Bound: Proposed solution with T=405 and p=6

For this case, the minimum number of RCC in the system is found as 6. The outcomes of the system presents that the organ travel time is averagely 106 minutes on average. The total number of organ is 4087 in the system. 3941 of the organs are matched with a patient in the same RCC and the remaining organs are matched at different RCC. In this time, the number of plane usage is 41.

Model 1 Proposed Solution with T=314 and p=9

The outcomes of this case states that the average organ travel time in the system is 104 minutes. There exist 4089 donated organs, but, there is one organ which cannot be matched with a candidate recipient. This case is one of the possible situations in the system. Here, there exists a heart donation in Hakkari and there is no airport there. Moreover, the nearest transplantation center to Hakkari is Diyarbakir and the distance between these cities is 314 minutes which exceeds heart ischemia time bound. Therefore, it is impossible to transplant heart from Hakkari without helicopter. This case is one of the rare but possible cases in the system. The number of matching within the same region is 3576 and 513 of matching are done at different RCCs. The number of plane usage is found as 121 times in a year.

Model 1 Current System (Kidney Ischemia Time with T=570 and p=9)

When the current RCC locations and their allocated cities are added in simulation model for kidney ischemia time bound, we see that the average travel time of the organ is 89 minutes. Total organ output in the system is 4084 and 3651 of them are in the same RCC. The remaining organs are matched at different RCCs. The number of plane usage is 99 times.

Model 2 Heart Ischemia Time Bound (T=220 and p=9): Proposed System vs. Current System

In this case, from model 2 outcomes, helicopters are also used. With the helicopter opportunity, the results indicate that the average travel time of the organ is 88 minutes and 82 minutes for proposed system and current system, respectively. In the proposed system case the total number of organ output is 4084 and only 17 organs more for current system. Donated organs staying in the same RCC is 3759 organs for proposed system and 3648 organs for current system. In the proposed system, 17 times the helicopter opportunity is used with 3 helicopters and 86 times plane option is selected in the system. For the current system, the number of helicopter usage is 211 with 8 helicopters and the number of plane usage is 84.

Summary of the Outcomes stated in this Chapter

When the outcomes of proposed models and current system are analyzed, we can state that, our proposed model is feasible for liver ischemia time with 6 RCCs. Even if, we strict the RCC values for liver and kidney ischemia time cases, our models results with 54 % and 32 % improvement over current system respectively with respect to objective values. Furthermore, for fixed number of RCCs our model results the minimum duration time between donor city to recipient city with 314 minutes. However, in the current system, this number is 481 minutes which is approximately more than 3 hours from our solution. When T is 570 with 9 RCCs, the current system cannot provide balanced regions, but for our model, we can catch 0.9 threshold value for T=570 and p=9 which approximately equalizes each region. For the Model 2, the current system needs 8 helicopters to satisfy heart ischemia time case. Whereas with the proposed clustering, we require only 3 helicopters. Moreover, we are able to cover all Turkey with 6 RCCs with 17 helicopters where 5 of them are the cities with actual transplantation centers.

From the simulation outcomes, we can conclude that when the number of RCCs is low, it leads long time bounds between donor city and recipient city due to the increase of the boundaries in the region *i.e.* the average organ travel time increases in general. However, the number of plane usage also affects the average organ travel time as in the case for current system performance for T=570 and p=9. Also, the number of plane usage is also based on number of transplantation centers at each RCC as in the case for p=9 and T=314 where some clusters have only one transplantation center which is RCC. In general, for all observed cases, the total organ output is approximately same but the matching number in same RCC changes. The percentages of the matching in the same RCC is 98% for T=570 with p=4, 96% for T=405 with p=6, 87 % for T=314 and p=9, 92% for T=570 and p=9. For helicopter cases 92% for proposed solution and 89% for current system.

When the percentages are compared for T=314 and p=9 the matching in the same RCC percentage is the lowest due to wasted organ exists in that case. The reason of wasted organs is due to both short travel time bound that does not enable to add many cities having transplantation centers and cities having airline case. Therefore, especially for the RCCs where only one city having transplantation center is selected as RCC and remaining cities are potential donor cites such that the potential donor cities do not have airlines could not send the donated organ to other cities. To illustrate; for the Diyarbakir RCC case, when the heart donation exists at Hakkari, since there is not any airline at Hakkari and this case also does not consider helicopter opportunity, the nearest transplantation center is Diyarbakir with 314 minutes that does not send the heart within 220 minutes. Therefore the donated organ is wasted.

When we compare the helicopter cases, our proposed solution requires less number of helicopters. Moreover, the organ travel times in the system is almost same which means that highway transportation is well structured within our solution. Also, in the proposed model, the donated organs are matched with the candidate recipients at different regions 26% less than current system which is also a success with less number of helicopters within a binding ischemia time. Moreover, even if the number of helicopters at current system is 2.5 times higher than proposed system, the helicopter usage of current system is 12 times higher than proposed system. We can state that current system depends on helicopter transportation greatly to operate the processes in the system. The proposed system supports to decrease the dependence on airway due to unavailability of air transportation for any time.

When the kidney ischemia time case is compared with the current case, we can state that, the number of RCCs directly affects the number of matching in the same RCC which supports the idea to spend less time for transportation of the organ.

When the number of plane usage in the simulation is considered, we can state that liver case performs all system with the least number of plane usages. This number also supports the highway transportation usage is highly possible when the liver ischemia time based system is considered.

Detailed simulation outcomes are represented at Appendix between Appendix 13 and 18.

Chapter 6

Conclusion

Organ transplantation is the most special and effective treatment for the patients whose organs need to be changed with a healthy organ from another person. When the numbers of donations and patients waiting for an organ are compared, there exists a huge gap between these numbers. This condition adds more sensitivity to prevent the mistakes during the processes. By this motivation, we developed mathematical models and a simulation model to improve the performance and analyze the organ transplantation system considering the actual organ transplantation processes in Turkey.

In the proposed mathematical models, our main objective is to maximize the inter regional flow from donor cities to recipient cities at each regional coordination center. While maximizing the flow, the ischemia time for the organs is added to the model to control the time spent between donor city and recipient city. We also added a helicopter option not only to decrease the time bound between donor city and recipient city, but also to increase the organ flow in the regions by assigning cities with high number of potential donors to the regional coordination centers.

Since we could not represent the hierarchical nature of the organ transplantation system via the mathematical models and developed a simulation model of the organ transplantation system. By this approach, we can compare the proposed model with the current system not only by the mathematical model outputs, but also with simulation model which represent the real life in a more detailed way. When we obtained the computational results of both mathematical model and simulation model, we were able to compare the current system with both regional level and national level respectively.

In the mathematical models, even if we restrict the problem an either number of RCC locations or transportation time bound, we can state that, at both cases, proposed models improve the organ flow at different regions. Moreover, many RCC locations are matching with actual system. Only the change of the allocated cities will increase the flow in each RCC. In the current system, liver transplantation cannot be supported by highway. However, at proposed solutions, all regions support liver transplantation with highway distance not only with nine RCCs but also with six RCCs. For the kidney case, the required number of RCC regions is four. When the number of RCC is fixed to nine regions, the maximum travel time bound from donor city to recipient city can be decreased to 314 minutes. This number satisfies both liver and kidney transplantations. To find a feasible solution for the heart case and to increase the organ flow in the RCCs, the proposed solution for nine RCC regions requires three helicopters instead of eight of the current system. Also, as in the liver case, six RCCs are sufficient with 17 helicopters to cover all cities within heart ischemia time. Moreover, for the first equity measure, we can create balanced regions (approximately same) in terms of potential number of donors at each RCC, however, in the current system, the regions are not constructed with the consideration of equity measures.

With the simulation model outcomes, we were able to observe the performance of our proposed models in real life case; *i.e.*, multi hierarchical system with organ specified waiting lists. We observed that less number of RCC directly affects the number of matching at the same RCC due to the increase in the number of potential donors in the region. When the percentage of donated organ is matched with a recipient at the same RCC, the proposed systems result better than current system for kidney, liver and helicopter cases. Moreover, the plane usage in proposed systems is much less than current system. Just for the tightened case (p=9, T=314) the plane usage gets almost same number with current system where T is 570 minutes.

When the number of helicopter usage is compared with current system, the solutions represent also how the current system needs improvements compared to proposed helicopter solution. Current system needs 12 times more helicopter usage than proposed model for the system.

When the travel time bound is tightened while number of RCCs is increased, there can be dispose of organ due to the region structure. While cluster becomes smaller, it may have only one transplantation center located at RCC. In that kind regions especially for no helicopter case, when the donated organ is heart and when there is not any airline at that city, the organ cannot be used due to lack of transportation.

In this study, we obtained very successful results for the organ transplantation system in Turkey. Initially, the infeasible solution for liver case by highway distances is solved optimally with our proposed model with 6 RCCs. The current system was designed without any methodology. Therefore, this study enables to observe the structure of the system with the objective and mathematical basis. Furthermore, the equity constraints improve fairness between regions rather than current system regions. This study considers not only city allocation to the regions but also vehicle allocation (helicopter) to the cities. This option improves both system performance by maximizing inter regional flow in the system and points out critical cities in Turkey. Moreover, with the motivation of decreasing transportation time bound from donor city to recipient city, we enable to increase time spent for the operation times. This contribution indirectly improves the operation performances due to increase of time bound. To the best of authors' knowledge, the simulation modeling is used first time to observe the performance of mathematical model outcomes in the hierarchical matching method.

For the future study of this problem, different equity measures can be developed such as minimum number of transplantation centers at each RCC which can be a significant measure to balance the number of matching at same RCCs. Moreover, the helicopter based model can be enhanced more with the consideration of helicopter assignments. Furthermore, the simulation model can be detailed more to represent the real life with different data sets.

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APPENDIX

Appendix 1 Territorial Distances between Donor City (rows) and Recipient City (columns) in Turkey

Erzurum RCC	
Tranpslantation Center / Donor City	Erzurum
Erzurum	0
Sivas	290
Gumushane	135
Bayburt	83
Erzincan	126
Tunceli	162
Bingol	120
Mus	177
Agri	123
Igdir	196
Kars	135
Ardahan	155
Artvin	151

Antalya RCC		
Tranpslantation Center / Donor City	Antalya	Konya
Burdur	81	210
Isparta	87	176
Afyon	195	149
Konya	215	0
Antalya	0	215
Karaman	250	79

Bursa RCC	
Tranpslantation Center / Donor City	Bursa
Canakkale	181
Balikesir	101
Bursa	0
Bilecik	63
Yalova	46
Duzce	152

Izmir RCC		
Tranpslantation Center / Donor City	Izmir	Denizli
Izmir	0	149
Manisa	24	137
Kutahya	223	191
Usak	141	101
Denizli	149	0
Aydin	84	84
Mugla	150	97

Samsun RCC		
Tranpslantation Center / Donor City	Samsun	Trabzon
Samsun	0	222
Sinop	109	331
Amasya	87	307
Tokat	153	267
Ordu	101	121
Giresun	131	91
Trabzon	222	0
Rize	271	49

Adana RCC					
Tranpslantation Center / Donor City	Adana	Icel	Kayseri	Kahramanmaras	Gaziantep
Adana	0	46	222	123	137
Nigde	137	132	85	260	273
Icel	46	0	217	169	183
Osmaniye	57	103	249	67	80
Kayseri	222	217	0	182	235
Kahramanmaras	123	169	182	0	53
Gaziantep	137	183	235	53	0
Kilis	161	207	275	93	42
Hatay	127	173	299	117	131

Appendix 2 Population in the Regions

	Istanbul	13255685	Canakkale	490397	Ankara	4771716	Diyarbakir	1528958	Erzurum	769085	Samsun	1252693	Izmir	3948848	Burdur	258868	Adana	2085225
	Edirne	390428	Balikesir	1152323	Eskisehir	764584	Malatya	740643	Sivas	642224	Sinop	202740	Manisa	1379484	Isparta	448298	Nigde	337931
	Kirklareli	332791	Bursa	2605495	Bolu	271208	Adiyaman	590935	Gumushane	129618	Amasya	334786	Kutahya	590496	Afyon	698626	Icel	1647899
	Tekirdag	798109	Bilecik	225381	Zonguldak	619703	Elazig	552646	Bayburt	74412	Tokat	617802	Usak	338019	Konya	2013845	Osmaniye	479221
	Kocaeli	1560138	Yalova	203741	Bartin	187758	Sanliurfa	1663371	Erzincan	224949	Ordu	719183	Denizli	931823	Antalya	1978333	Kayseri	1234651
	Sakarya	872872	Duzce	338188	Karabuk	22761	Mardin	744606	Tunceli	76699	Giresun	419256	Aydin	989862	Karaman	232633	Maras	1044816
					Kastamonu	361222	Batman	510200	Bingol	255170	Trabozn	763714	Mugla	817503			Antep	1700763
					Cankiri	179067	Bitlis	328767	Mus	406886	Rize	319637					Kilis	123135
					Corum	535405	Siirt	300695	Agri	542022							Hatay	1480571
					Kirikkale	276647	Van	1035418	Igdir	184418								
					Kirsehir	221876	Sirnak	430109	Kars	301766								
					Yozgat	476096	Hakkari	251302	Ardahan	105454								
					Nevsehir	282337			Artvin	164759								
					Aksaray	377505												
RCC		ISTANBUL		BURSA		ANKARA		DIYARBAKIR		ERZURUM		SAMSUN		IZMIR		ANTALYA		ADANA
Total Population		17210023		5015525		9347885		8677650		3877462		4629811		8996035		5630603		10134212

Appendix 3 Total Transplantation Ratio for each RCC

RCC	Transplantation Ratio
ISTANBUL	29.56
BURSA	1.87
IZMIR	20.72
ANKARA	16.31
ANTALYA	21.83
SAMSUN	1.05
ERZURUM	0.64
DIYARBAKIR	3.81
ADANA	4.21

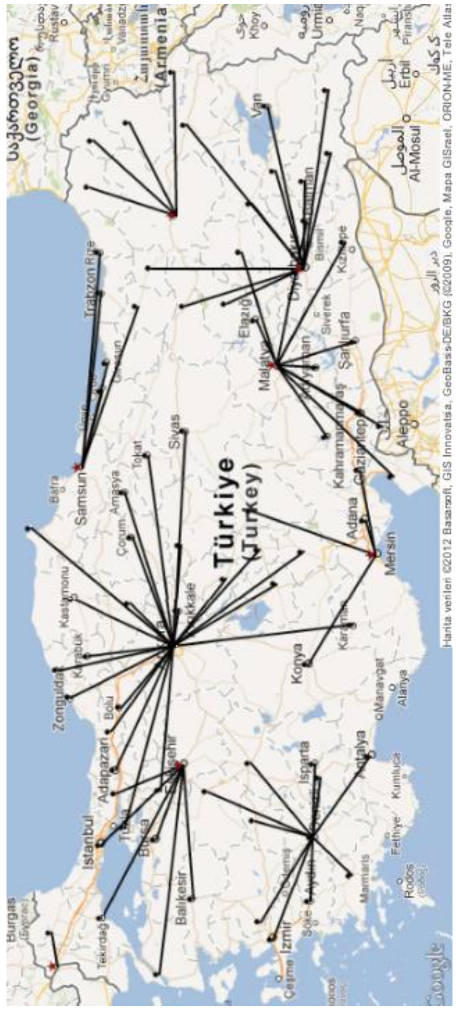
Appendix 4 dj (Organ Demand of Nodes) Values used in Mathematical Models for j $\in$ N

Recipient City	dj
1	502.687
6	3047.421
7	3176.756
16	362.8361
20	309.254
21	369.6272
22	155.0142
25	124.1792
26	117.2085
27	125.6717
33	62.83587
34	5270.484
35	3711.048
38	62.83587
41	310.0285
42	1058.919
44	369.6272
46	62.83587
55	135.821
61	67.9105

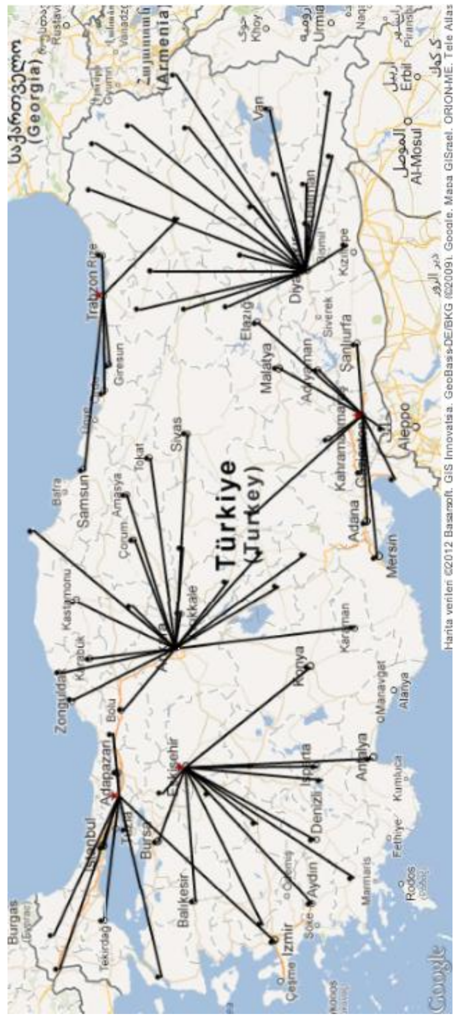
Appendix 5 O_i Values (Supply of Total Number of Donated Organs) used in the Mathematical Models, $i \in M$

Donor City	O_i	Donor City	O_i
1	8953.045	41	5140.748
2	413.0353	42	19706.14
3	6836.285	43	5188.586
4	432.9685	44	517.674
5	1169.997	45	12121.29
6	25728.69	46	4485.983
7	19358.64	47	520.4439
8	131.6099	48	7183.257
9	8697.746	49	325.0215
10	5292.751	50	1522.337
11	1035.201	51	1450.928
12	203.8304	52	2513.372
13	229.7924	53	1117.055
14	1462.331	54	2876.166
15	2533.109	55	4377.862
16	11967.33	56	210.1714
17	2252.449	57	708.5277
18	965.5143	58	513.0101
19	2886.859	59	2629.817
20	8187.767	60	2159.07
21	1068.668	61	2668.998
22	1286.484	62	61.26734
23	386.2731	63	1162.617
24	179.6898	64	2970.114
25	614.3469	65	723.7076
26	4122.573	66	2567.07
27	7302.333	67	3341.387
28	1465.199	68	2035.475
29	103.5392	69	59.44048
30	175.6481	70	2276.391
31	6356.925	71	1491.657
32	4386.744	72	356.6054
33	7075.358	73	300.6256
34	43678.28	74	1012.375
35	34697.84	75	84.23691
36	241.0514	76	147.3135
37	1947.679	77	935.8056
38	5301.052	78	122.7254
39	1096.566	79	528.6879
40	1196.337	80	2057.565
		81	1553.336

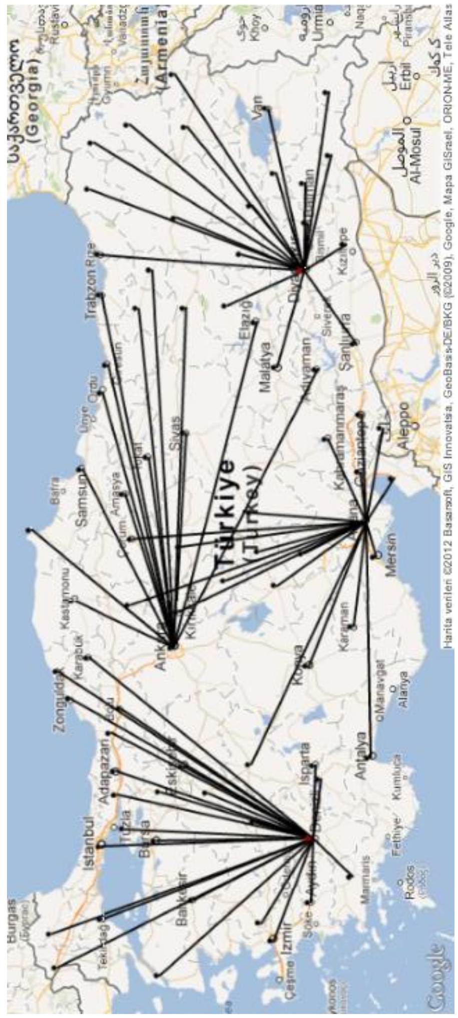
Appendix 6 Equity 2 Solution for given number of p is 9 in 314 minutes



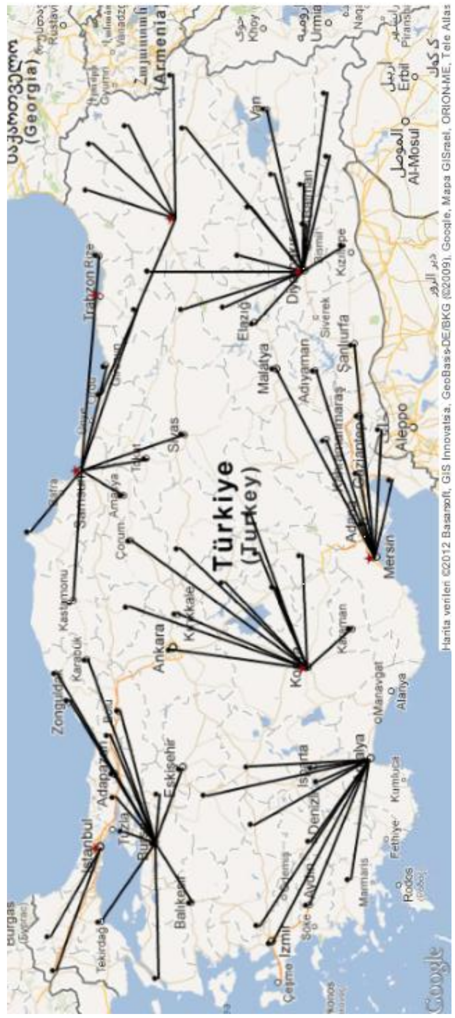
Appendix 7 Equity 2 Solution for given number of p is 6 in 374 minutes



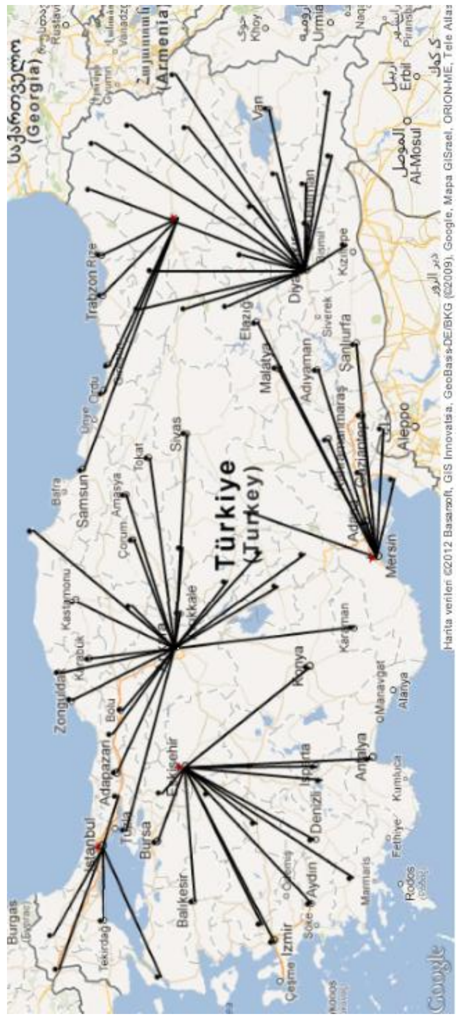
Appendix 8 Equity 2 Solution for given number of p is 4 in 537 minutes



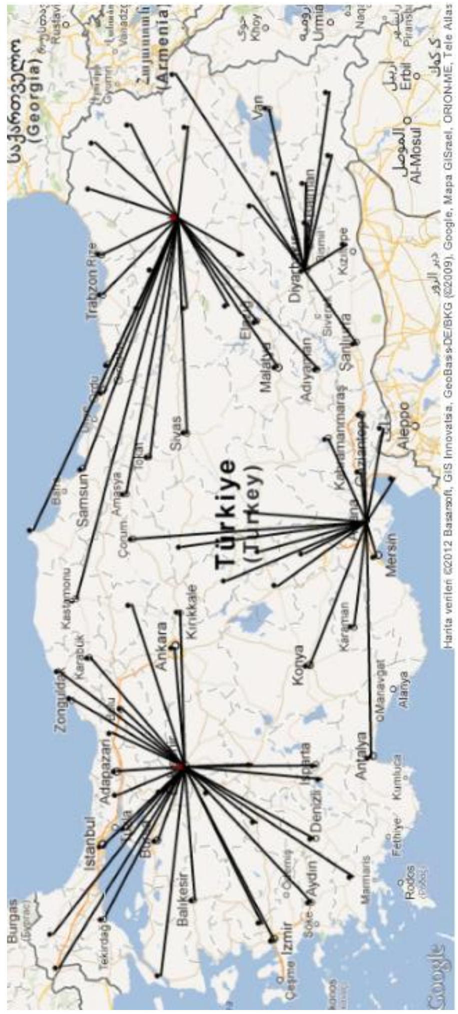
Appendix 9 Equity 3 Solution for given number of p is 9 in 314 minutes



Appendix 10 Equity 3 Solution for given number of p is 6 in 374 minutes



Appendix 11 Equity 3 Solution for given number of p is 4 in 537 minutes



Appendix 12 Number of Patients from each RCC for Heart, Liver and Kidney Cases and Emergent Cases

CENTER	NORMAL PATIENT	EMERGENTPATIENT
ORGAN: KIDNEY		
ADANA RCC	403	0
ANKARA RCC	230	1
ANTALYA RCC	284	7
BURSA RCC	81	0
DİYARBAKIR RCC	42	0
ERZURUM RCC	31	0
İSTANBUL RCC	609	2
İZMİR RCC	234	0
SAMSUN RCC	34	0
TOTAL	**1948**	**10**
ORGAN: HEART		
ADANA RCC	6	4
ANKARA RCC	16	25
ANTALYA RCC	28	10
BURSA RCC	0	0
DİYARBAKIR RCC	0	0
ERZURUM RCC	0	0
İSTANBUL RCC	18	19
İZMİR RCC	17	17
SAMSUN RCC	0	0
TOTAL	**85**	**75**
ORGAN: LIVER		
ADANA RCC	30	2
ANKARA RCC	87	12
ANTALYA RCC	42	4
BURSA RCC	13	1
DİYARBAKIR RCC	58	21
ERZURUM RCC	11	1
İSTANBUL RCC	111	14
İZMİR RCC	76	7
SAMSUN RCC	12	1
TOTAL	**440**	**63**

Appendix 13 Simulation Outcomes of p=4 and T=570 minutes

9:01:49PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	17,420

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_t570\model Page 1 of 3

9:01:49PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.5267	< 0.00	0.4854	0.5573	0.00	9.5000

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.5267	< 0.00	0.4854	0.5573	0.00	9.5000

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17421.26	23.68	16396.00	18404.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17420.13	23.69	16394.00	18404.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	1.0478	< 0.00	0.9608	1.1279	0.00	15.0000

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_t570\model Page 2 of 3

Unnamed Project

Replications: 500 Time Units: Hours

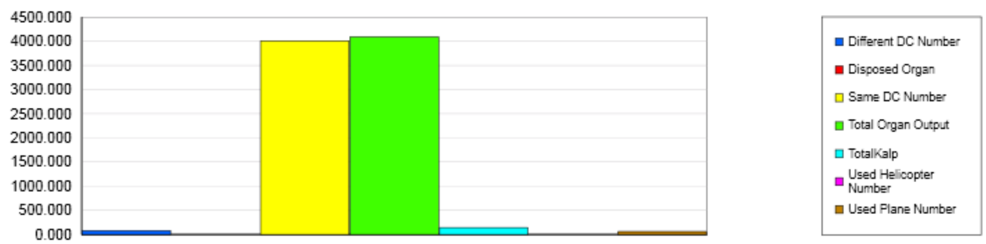
User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Organ Travel	134.79	< 0.23	125.11	143.06	0.00	570.00

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Different DC Number	80.9180	< 0.78	57.0000	108.00
Disposed Organ	0.00400000	< 0.01	0.00	1.0000
Same DC Number	4003.60	< 6.43	3753.00	4198.00
Total Organ Output	4084.52	< 6.48	3837.00	4279.00
TotalKalp	144.27	< 1.07	106.00	177.00
Used Helicopter Number	0.00	< 0.00	0.00	0.00
Used Plane Number	61.6620	< 0.66	32.0000	80.0000



Appendix 14 Simulation Outcomes of p=6 and T=405 minutes

9:15:40PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	17,423

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_t405\model Page 1 of 3

9:15:40PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.4157	< 0.00	0.3830	0.4456	0.00	9.5000

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.4157	< 0.00	0.3830	0.4456	0.00	9.5000

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17424.06	23.72	16680.00	18104.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17423.32	23.73	16676.00	18103.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.8271	< 0.00	0.7613	0.9071	0.00	14.0000

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_t405\model Page 2 of 3

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

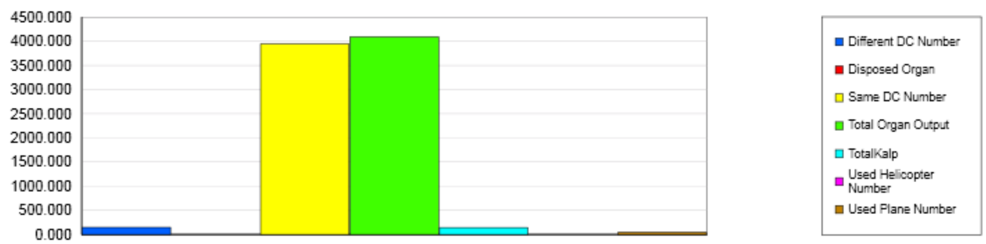
User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Organ Travel	106.33	< 0.20	98.8830	114.50	0.00	570.00

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Different DC Number	146.16	< 1.20	111.00	196.00
Disposed Organ	0.01800000	< 0.01	0.00	1.0000
Same DC Number	3941.14	< 6.17	3705.00	4172.00
Total Organ Output	4087.30	< 6.32	3850.00	4328.00
TotalKalp	143.91	< 1.05	114.00	183.00
Used Helicopter Number	0.00	< 0.00	0.00	0.00
Used Plane Number	41.1820	< 0.59	22.0000	62.0000



Appendix 15 Simulation Outcomes of p=9 and T=314 minutes

8:30:59PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	17,448

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_p9\model Page 1 of 3

Unnamed Project

Replications: 500 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.4065	< 0.00	0.3827	0.4304	0.00	9.5000

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.4065	< 0.00	0.3827	0.4304	0.00	9.5000

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17449.22	23.28	16576.00	18136.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17448.46	23.28	16576.00	18136.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.8098	< 0.00	0.7449	0.8688	0.00	15.0000

Unnamed Project

Replications: 500 Time Units: Hours

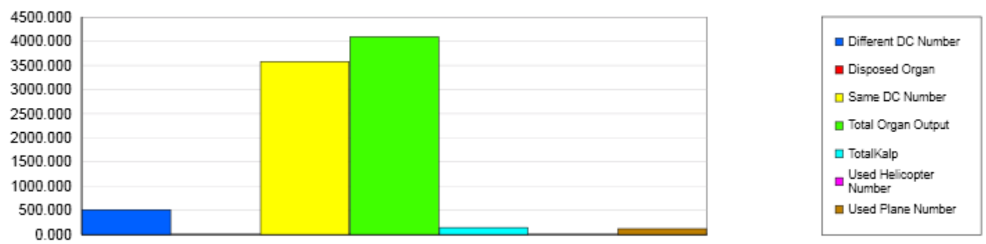
User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Organ Travel	104.05	< 0.18	98.4448	110.49	0.00	570.00

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Different DC Number	513.59	< 2.19	443.00	595.00
Disposed Organ	0.01600000	< 0.01	0.00	1.0000
Same DC Number	3576.07	< 5.69	3381.00	3764.00
Total Organ Output	4089.66	< 6.21	3886.00	4295.00
TotalKalp	144.83	< 1.06	103.00	178.00
Used Helicopter Number	0.00	< 0.00	0.00	0.00
Used Plane Number	121.50	< 1.02	92.0000	155.00



Appendix 16 Simulation Outcomes of Current System for p=9 and T=570 minutes

8:45:30PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	17,420

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_p9current\model Page 1 of 3

Unnamed Project

Replications: 500 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.3512	< 0.00	0.3249	0.3795	0.00	9.5000

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.3512	< 0.00	0.3249	0.3795	0.00	9.5000

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17420.26	23.14	16580.00	18220.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17419.59	23.14	16580.00	18220.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.6985	< 0.00	0.6382	0.7615	0.00	13.0000

Unnamed Project

Replications: 500 Time Units: Hours

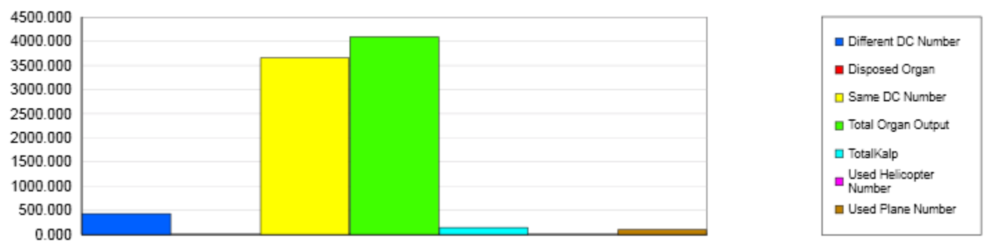
User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Organ Travel	89.8658	< 0.17	83.3300	95.6367	0.00	570.00

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Different DC Number	432.56	< 1.93	371.00	489.00
Disposed Organ	0.00400000	< 0.01	0.00	1.0000
Same DC Number	3651.72	< 5.60	3424.00	3849.00
Total Organ Output	4084.28	< 6.14	3876.00	4304.00
TotalKalp	144.05	< 1.02	107.00	185.00
Used Helicopter Number	0.00	< 0.00	0.00	0.00
Used Plane Number	99.37	< 0.89	68.0000	126.00



Appendix 17 Simulation Outcomes of Model 2 for p=9, T=220 minutes and h=3

9:50:53PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	17,426

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_helipro\model Page 1 of 3

Unnamed Project

Replications: 500 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.3453	< 0.00	0.3241	0.3658	0.00	9.5000

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.3453	< 0.00	0.3241	0.3658	0.00	9.5000

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17426.35	22.87	16620.00	18236.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17425.66	22.87	16620.00	18235.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.6871	< 0.00	0.6362	0.7399	0.00	13.0000

Unnamed Project

Replications: 500 Time Units: Hours

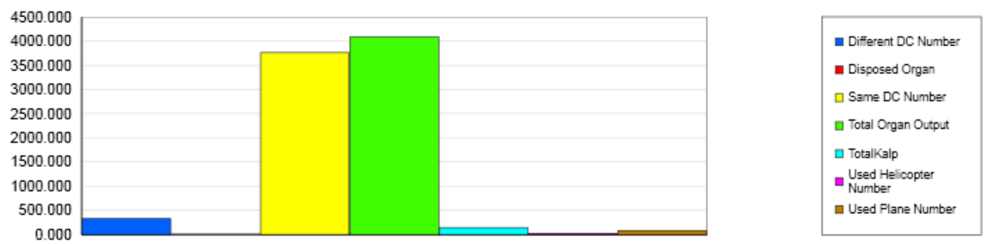
User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Organ Travel	88.4016	< 0.16	83.0580	93.9011	0.00	570.00

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Different DC Number	324.47	< 1.71	277.00	373.00
Disposed Organ	0.00	< 0.00	0.00	0.00
Same DC Number	3759.60	< 5.86	3560.00	3919.00
Total Organ Output	4084.07	< 6.26	3883.00	4268.00
TotalKalp	144.18	< 1.01	107.00	183.00
Used Helicopter Number	17.5720	< 0.41	7.0000	33.0000
Used Plane Number	84.4600	< 0.75	58.0000	115.00



Appendix 18 Simulation Outcomes of Model 2 for Current system with p=9, T=220 and h=8

9:41:32PM **Category Overview** July 3, 2012

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	17,432

Model Filename: C:\Users\Pelin\Desktop\DataSimu\DATA_helicur\model Page 1 of 3

Unnamed Project

Replications: 500 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.3237	< 0.00	0.2992	0.3443	0.00	9.5000

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.00	< 0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.3237	< 0.00	0.2992	0.3443	0.00	9.5000

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17432.26	23.69	16692.00	18180.00

Number Out	Average	Half Width	Minimum Average	Maximum Average
Entity 1	17431.65	23.69	16690.00	18180.00

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Entity 1	0.6443	< 0.00	0.5854	0.6977	0.00	15.0000

Category Overview

Values Across All Replications

Unnamed Project

Replications: 500 Time Units: Hours

User Specified

Tally

Expression	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Organ Travel	82.8126	< 0.15	77.2824	87.7202	0.00	570.00

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Different DC Number	440.51	< 1.92	364.00	503.00
Disposed Organ	0.00	< 0.00	0.00	0.00
Same DC Number	3648.27	< 5.89	3478.00	3854.00
Total Organ Output	4088.77	< 6.36	3874.00	4315.00
TotalKalp	144.50	< 1.03	101.00	176.00
Used Helicopter Number	211.16	< 1.45	174.00	269.00
Used Plane Number	84.7040	< 0.80	57.0000	110.00