MOBILE BLOOD DONATION LOGISTICS:
CASE FOR TURKISH RED CRESCENT

A THESIS

SUBMITTED TO THE DEPARTMENT OF INDUSTRIAL

ENGINEERING

AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE OF

BILKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

by

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July 2012

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ABSTRACT

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July, 2012

Blood transfusion is one of the most critical operations in various medical interventions. Currently, the only authorized way of securing the required blood for transfusion is through voluntary donations. For this reason, reorganizing blood donation operations to create an operable and efficient system is of utmost importance. In this study, a mobile blood collection system is designed for Turkish Red Crescent (TRC) to increase blood collection levels. This design also takes into account operational costs as a second objective so as to aim the collection of large amounts of blood at reasonable cost. In the current system, TRC has bloodmobiles that perform independent direct tours to certain activities (fairs, college fests etc.), but at the end of each day, they bring the collected blood to a designated depot to prevent its spoilage. Considering blood's considerably short shelf-life of 24 hrs, these direct tours may seem justifiable yet they are not efficient in terms of logistics costs. The proposed system consists of classic bloodmobiles and a new vehicle – called the shuttle – which visits the bloodmobiles in the field and transfers the collected blood to the blood centers, so that bloodmobiles can continue their tours without having to make daily returns to the depot.

A mathematical model is developed to determine the stops of bloodmobiles, the duration of each visit as well as the tours of the bloodmobiles and the shuttle. In the literature, a study that covers all these decisions does not exist. Therefore, a new extension of Selective Vehicle Routing Problem (SVRP) is defined, called SVRP with Integrated Tours. Also, a 2-stage IP based heuristic algorithm is developed for the same problem. The performances of these methodologies are tested on the data set obtained from past blood donation activities in Ankara. In addition, GIS data of the European part of Istanbul is used as a constructed test case. The Pareto set of optimum solutions is generated based on blood amounts and logistics costs, and finally a sensitivity analysis on some important design parameters is conducted.

Keywords: Mobile blood collection, Healthcare logistics, Selective Vehicle Routing Problem

ÖZET

GEZİCİ KAN BAĞIŞI LOJİSTİĞİ: TÜRK KIZILAYI UYGULAMASI

Feyza Güliz Şahinyazan
Endüstri Mühendisliği Yüksek Lisans
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Temmuz, 2012

Kan nakli birçok tıbbi işlemin en önemli kısımlarından biridir. Mevcut durumda, nakil için ihtiyaç duyulan kan ancak gönüllü bağışlarla sağlanabilmektedir. Dolayısıyla, kan bağışı sistemini verimli bir şekilde işleyebilecek şekilde yeniden tasarlamak büyük önem arz etmektedir. Bu çalışmada, Türk Kızılayı için, toplanan kan miktarını artırmak amacını güden bir kan toplama sistemi tasarlanmıştır. Tasarlanan sistem ayrıca operasyon maliyetlerini de ikincil bir amaç olarak değerlendirerek büyük miktarda kanın makul maliyetlerle toplanabilmesini sağlamayı hedeflemektedir.

Mevcut sistemde Türk Kızılayı belirli aktivitelere(fuarlar, üniversite festivalleri vb.) kan toplama araçlarını göndermekte, bu araçlar ilgili günün sonunda, toplanan kanın bozulmaması için, topladıkları kanı belirli bir depoya götürmektedir. Kanın 24 saatlik dayanma süresini göz önünde bulundurarak bu şekilde tek bir noktaya günlük turlar düzenlenmesi sistemin yapısının bir gereği olarak görülebilir, fakat lojistik maliyetleri açısından bakınca verimli değildir. Önerilen sistem, var olan kan toplama araçlarının yanı sıra bir transfer aracının da sisteme eklenmesi ile her günün sonunda mobil kan toplama araçlarını ziyaret edip toplanan kanı kan merkezlerine taşımasını, böylece kan toplama araçlarının turlarına depoya günlük geri dönüşler olmaksızın devam edebilmelerini sağlamaktadır. Kan toplama araçlarının duraklarına, her durakta beklenecek süreye kan toplama araçlarının ve transfer araçlarının rotalarına karar veren bir matematiksel model geliştirilmiştir. Literatürde bütün bu kararları beraber kapsayan bir çalışma bulunmamaktadır. Dolayısıyla, Seçici Araç Rotalama Problemi(SARP) için, Girişik Turlu SARP adında yeni bir version tanımlanmıştır. Ayrıca, aynı problem için 2 aşamalı, tamsayılı programlama tabanlı bir sezgisel algoritma geliştirilmiştir. Bu yöntemlerin performansları, Ankara'da geçmiş kan toplama verileri kullanılarak test edilmiştir. Ek olarak, İstanbul Avrupa Yakası'nın Coğrafi Bilgi Sistemi verisi kullanılarak bir test problemi daha yaratılmıştır. Eniyi çözümlerin, toplanan kan miktarı ve lojistik maliyetine bağlı Pareto Kümesi hesaplanmış ve son olarak da bazı önemli parametreler üzerinde duyarlılık analizi gerçekleştirilmiştir.

Anahtar Kelimeler: Mobil kan toplama, Sağlık Lojistiği, Seçici Araç Rotalama Problemi

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere gratitude to Assoc. Prof. Bahar Yetiş Kara and Assoc. Prof. Mehmet Rüştü Taner for their supervision and encouragement throughout the last three years. I am grateful to them for not only their perfect guidance for my thesis, but also their support for my future academic endeavors. Their patience and understanding helped me to overcome every struggle that I had faced during this period.

I am grateful to Assoc. Prof. Oya Ekin Karaşan and Assoc. Prof. Haldun Süral for accepting to read this thesis and for their valuable comments and helpful suggestions.

I am most thankful to my mom Melda, dad Halil and sister Esra, for their unconditional love and support. Every single day with them is a blessing since 1988.

I am grateful to my dearest friends Fırat Kılcı, A. İrfan Mahmutoğulları and Serasu Duran for their help and courage in my most desperate times and for the laughters we shared in unforgattable moments. I also would like to thank to my officemates Pelin Çay, Bilal Çay, Haşim Özlü, Başak Yazar, Okan Dükkancı, Bengisu Sert and all my friends I failed to mention for their kindness and morale support.

I am thankful to Yeşim Karadeniz and Yeşim Erdoğan as well. Without their trust and help this thesis would not to come an end this easily. I will never forget their support.

I would like to acknowledge financial support of the Scientific and Technological Research Council of Turkey(TUBITAK) for their Graduate Study Scholarship Fund.

Finally, I would like to express my deepest gratitude to Görkem Özdemir for his endless love and support. But mostly, I want to thank him for bearing me even the times when I lost my control and for teaching me that 2=1.

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Chapter 1

Introduction

Healthcare logistics is an emerging area of research with numerous studies that focus on important questions in different areas. In particular, the main subjects of healthcare related problems are ER room and doctor utilization, health care center location and medical supply transportation. These problems can be considered as trending topics because of the effects on people's lives as well as the computational challenges involved in their solutions.

Blood donation logistics can be classified under the medical supply transportation problems as a healthcare logistics problem. Although blood transfusion is one of the most critical operations in various medical interventions, blood is a very limited resource. Since blood cannot be produced synthetically, the only source of it is donations. Annual demand on blood is 50 million units whereas the regular blood donors consist only 5% of the population. However, volunteer blood donations barely satisfy world-wide blood demands. Thus, people give blood in exchange of money which increases the risk of transfusion-related-infections. The reason is that people, who sell their money, tend to lie about their medical conditions. In order to raise the number of donors and their donation frequencies, effective use of bloodmobiles may be successful. Bloodmobiles can reach more people than those at fixed donation points, even the people with limited time and limited means of transportation.

In this study, we propose a new mobile blood collection system for Turkish Red Crescent (TRC). The main motivation of this problem is that TRC faces shortage of blood regularly. Yet, the bloodmobiles are utilized as re-locatable fixed points not as a part of a mobile blood collections system. Therefore, this study focuses on designing a cost efficient and easy-to-implement bloodmobile system for TRC.

In the current system, bloodmobiles visit some pre-determined activities such as fairs, college fests, and at the end of the day they return the depot to transfer the blood before spoilage. Blood needs to be delivered to an analysis and storage system (depot) in 24 hours after the donation. However, this requirement causes the blood-mobiles to perform direct tours between the donation points and the depot. For activities that last more than one day, this application causes extra logistics costs. Because of the high costs, TRC does not consider to visit other points with relatively high donation potentials. With these shortcomings in mind, a new mobile blood collection system is proposed that consists of a transporter vehicle, called the shuttle, along the regular bloodmobiles. The main purpose of shuttle is to visit all the bloodmobiles in field at the end of a collection day and bring the collected blood to the depot. This approach enables the bloodmobiles to continue their tours without visiting the depot. The problem is determining the stops of bloodmobiles, the duration of each visit as well as the tours of the bloodmobiles and the shuttle.

To the best knowledge of the authors', there does not exist a study in the literature that considers all the issues listed above. Doerner et al. propose the use of shuttles to bring the collected blood to the depot, however, their model assumes the stops of bloodmobiles as fixed locations that are know a priori. Selective Vehicle Routing Problem (a.k.a Team Orienteering Problem) suggested by Chao et al. defines a way to select the stops of bloodmobiles and the routes of bloodmobiles, but the shuttle tours would be excluded with that approach. Therefore, a new problem called Selective Vehicle Routing Problem with Integrated Tours is defined in this study.

In Chapter 2, blood donation and transfusion basics are summarized. Also, the evolution of blood donation operations is described shortly. Chapter 3, gives details on the bloodmobile systems all around the world and compares these systems with TRC. Basically, the shortcomings of TRC are listed and discusses.

In Chapter 4, the problem that is discussed in this study is defined, related literature is addressed consecutively. This problem is related with different areas of the literature. First of all, the healthcare logistics literature is reviewed. Secondly, blood related logistics and supply chain papers are examined in order to understand the logistics dynamics that lies behind blood transportation processes. Finally, the selective vehicle routing problem and its extensions are discussed which inspires our solution methodology for this problem.

Chapter 5 describes the mathematical model that is developed for this problem. Network design, cost and blood potential functions are also explained in detail. Also, the valid inequalities designed for the mathematical model are supplied.

In Chapter 6, the performance of the mathematical model is tested on the data set obtained from past blood donation activities in Ankara. In addition, GIS data of the European part of Istanbul is used as a constructed test case. Also, some alternatives to the current depot location are compared. The efficiency of suggested valid inequalities are also tested. The tradeoff between the amount of blood collected and the total logistics cost is analyzed with the help of the Pareto efficient curves of Ankara and Istanbul instances. Finally a sensitivity analysis on some important design parameters such as the number of bloodmobiles and the blood potential estimation parameters is conducted.

Chapter 7, describes the 2-stage IP based algorithm. Basically, this algorithm chooses the stops of the bloodmobiles according to their blood potentials in the first stage. Then, finds the tours of the bloodmobile and shuttle tours with the help of the MIP model that is described in Chapter 5. Computational times and optimality gap results of this algorithm are compared with the exact solutions that are obtained in Chapter 6. The thesis is concluded with a summary of the study and possible future research directions in Chapter 8.

Chapter 2

Blood Transfusion & Donation

Blood is a very critical component in human life. However, in today's conditions scientists are not able to produce blood synthetically. That is, the only source of blood is other human beings so blood transfusion has a significant role in today's healthcare operations. In United States the need for blood is about 10 million units per year. In Germany and Japan, the annual demand is nearly 4 million units in both countries. Turkish Red Crescent estimates Turkey's blood need to be above 1.5 million units in 2011 [1]. All these demands can be satisfied by successful blood donation & transfusion operations only.

2.1 Basics

Blood is composed of red and white blood cells, plasma, platelets and proteins. The main function of blood is regulating the carbon dioxide-oxygen metabolism. Also, blood transports oxygen, nutritious elements and hormones to the tissues while it brings back the carbon dioxide and toxic elements to the lungs and kidneys for removal [2]. Other than these functions, blood circulation helps to maintain the pH value of the blood in the desired level and controls the body temperature.

These critical functions are performed by the different components of blood. We can summarize the components of the blood as in Figure 2-1.

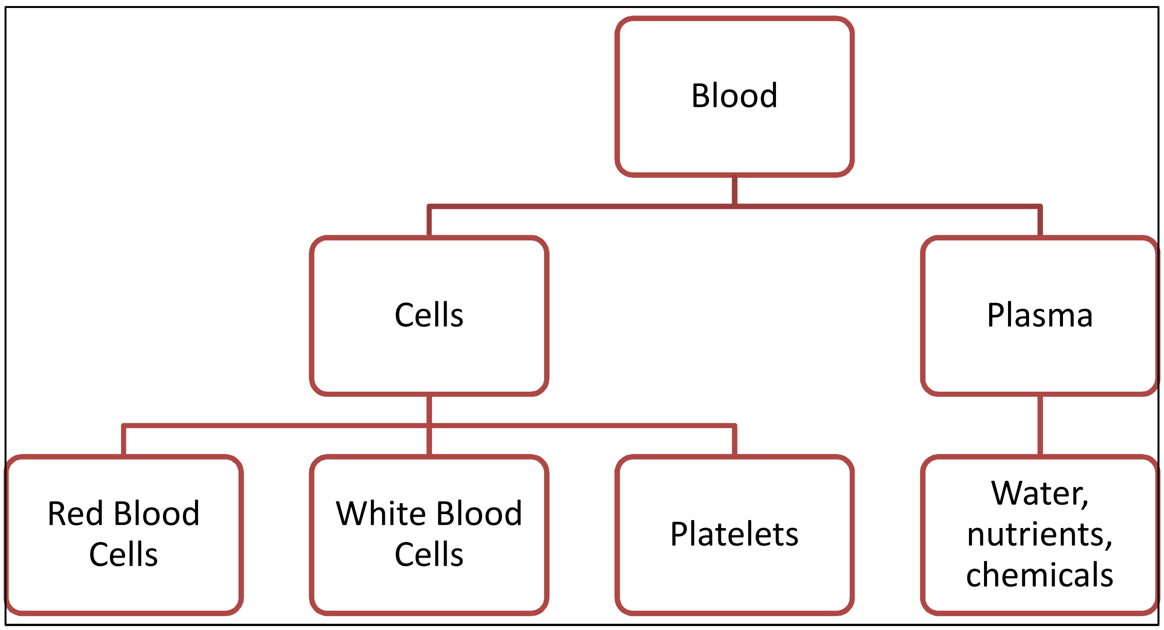


Figure 2-1 Components of blood

Plasma is the liquid part of the blood and constitutes 55% of the blood. The main function of plasma is transportation of water and water-soluble materials such as minerals, hormones, urine and vital proteins.

Remaining %45 of blood is composed of blood cells, mainly, red blood cells (erythrocytes), white blood cells (leukocytes) and platelets (thrombocytes). Figure 2-2 summarizes the basic characteristics of the blood cells:

Element	Diameter (in um)	Number (per mm^3)	Scientific notation (per mm^3)	Main function
red blood cells	7 - 8	4,500,000 - 52500,000	4.5×10^6 5.5×10^6	oxygen transport
white blood cells	9 - 12	7,000 - 10,000	7×10^3 1×10^4	defense against microorganisms
platelets	2 - 4	300,000	3×10^5	blood-clotting

Figure 2-2 Characteristics of blood cells

[http://www.nsbri.org/humanphysspace/focus3/earthphys-frame.html]

A healthy adult carries about 5-6 liters of blood and an average adult can easily handle a loss of 500 ml. of blood without a transfusion. On the other hand, if a person loses between 1000-1500 ml blood in short amount of time or some blood components (platelets, red blood cells) are below the required levels because of a disease (cancer, anemia etc.) or an operation, he needs a transfusion operation.

In most of the cases blood transfusion is used as a temporary therapy. In those cases one patient may require several units of blood, but as soon as the threatening situation (operation, shock etc) disappears, the blood transfusion may be terminated. On the contrary, some patients need blood donation as long as their disease is cured or even as a life-time. The well-known diseases that require a life-time blood support are: Cooley's anemia, anemia, hemophilia and leukemia [3].

Even though, some operations still require whole blood transfusion, most of the donated blood is decomposed after the donation and required blood products are transferred to the patients. With this approach, the patient does not receive unnecessary components and also from a single unit of whole blood more than one person may benefit. Also, the shelf-life of the blood-components are longer than the whole blood. In particular, whole blood can stay without perishing up to 24 hours whereas red blood cells, plasma and platelets remain fresh up to 42, 60 and 5 days respectively [3]. For this reason, making use of blood components is more preferable that storing whole blood units. There are two main process that is used to obtain blood components. First one is **centrifuge,** which is the process of spinning blood samples around a center so that the components with different density will separate from each other. Centrifuge is applied to the blood units that are collected in classic way. (Figure 2-3) In whole blood donation, the donor's vessel is connected to a plastic bag and with his blood pressure the blood is collected in a plastic bag. In one donation session one person can give up to 500 ml.(1 unit) of whole blood.

Figure 2-3 Standard blood donation via plastic bags

The second way of separating blood components is **apheresis**. (Figure 2-4) In **apheresis** therapy, the donor connects an apparatus, and this apparatus takes his blood, decomposes the required component from the blood and gives the rest of the blood back to the donor.

Figure 2-4 Apheresis donation

This method has some advantages over the classical whole blood donation. First of all the donor receives some parts of his blood back. Also, in one apheresis session one donor can donate platelets that are equivalent to up to 6-8 whole blood donations. In addition to these, apheresis can be applied more frequently than whole blood donation. It is suggested that one gives a break of 6 months between two whole blood donation sessions. However, one can donate platelets with apheresis bi-weekly. On the contrary, apheresis methodology has its shortcomings as well. First of all, apheresis machine is not a portable design, and so it is not possible to utilize such a device in bloodmobile tours. This is an important problem because mobile blood donation constitutes a very significant part of the overall blood donation amount. Also, apheresis procedure lasts around 2 and a half hours where standard whole blood donation takes at most half an hour. Finally, apheresis seems frightening to most of the donors since it requires connecting a large machine and sitting still for about 2 hours. Considering all these reasons, blood collectors mostly prefer to pick up whole blood from the donors and obtain the blood products later with centrifuge.

Once the blood is collected from the donors it is brought to some special center where several tests will be performed on the whole blood. Since the shelf-life of the whole blood is very short the distance between the donors/donation centers and the testing center is an important issue to handle. All around the world the tests that are performed on collected blood are more or less the same. First the blood is tested for infectious diseases such as: anti-HIV test, anti-HCV (Hepatitis C) test, HBsAg test (Hepatitis B), syphilis test etc. Then, blood type test are performed and blood units are labeled accordingly.

The main blood groups are A, B, 0 and AB. The A and B is the name of two different proteins that is carried in red blood cells. If a person carries both of them in his red blood cells his blood type is AB and carries none of them, then his blood type is classified as 0. One person's plasma contains the antibodies of the proteins that he does not carry. Therefore, a person with 0 blood type carries antibodies for both A and B proteins and if he receives a blood type other that 0, the plasma in his body will react to the proteins in donors blood. In addition to this classification bloods are also categorized as Rh positive or Rh negative whether or not they carry Rhesus factor. The same logic with the blood type proteins is applicable to Rh factor. A person with Rh- blood type cannot receive blood cells from a Rh+ donor. Table 2-1 shows the red blood cell compatibility chart of the blood types.

Table 2-1 Red blood cell compatibility chart

Red blood cell compatibility table

Recipient	Donor							
	O-	O+	A−	A+	B−	B+	AB−	AB+
O−	✓	✗	✗	✗	✗	✗	✗	✗
O+	✓	✓	✗	✗	✗	✗	✗	✗
A−	✓	✗	✓	✗	✗	✗	✗	✗
A+	✓	✓	✓	✓	✗	✗	✗	✗
B−	✓	✗	✗	✗	✓	✗	✗	✗
B+	✓	✓	✗	✗	✓	✓	✗	✗
AB−	✓	✗	✓	✗	✓	✗	✓	✗
AB+	✓	✓	✓	✓	✓	✓	✓	✓

On the other hand, the plasma transfusion has the opposite rules since the antibodies are carried in the plasma. For instance, a 0 blood type patient can receive plasma from A, B and AB blood type donors since a person's plasma with 0 blood type contains antibodies of both A protein and B protein. The plasma compatibility among blood types is as in Table 2-2.

Table 2-2 Plasma compatibility chart

Plasma compatibility table

Recipient	Donor			
	O	A	B	AB
O	✓	✓	✓	✓
A	✗	✓	✗	✓
B	✗	✗	✓	✓
AB	✗	✗	✗	✓

The distribution of these blood units are not even among people, some blood types are rarer than the others. However, the ratios vary from nation to nation or region to region. For instance the distributions among the blood types in Turkey and UK are as in Figure 2-5.

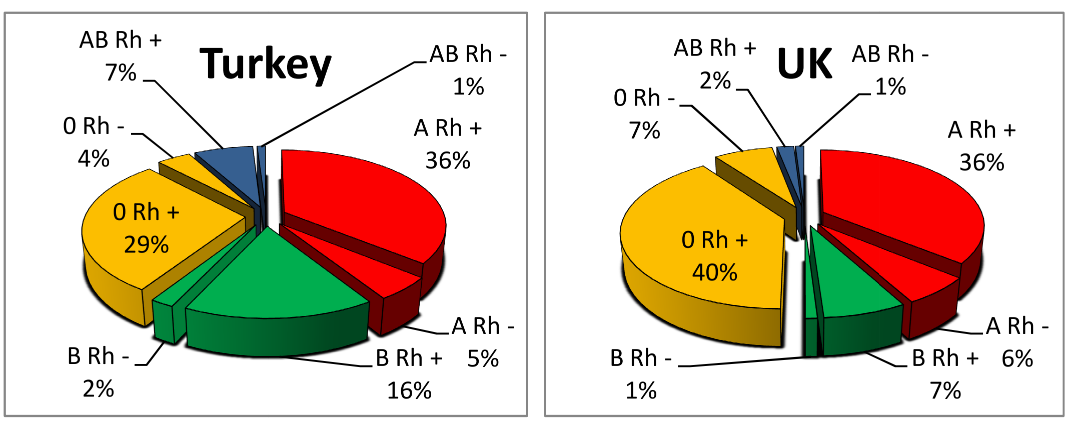


Figure 2-5 Population distribution among blood types in Turkey and UK

After all the disease and blood type testing are completed, the centrifuge phase starts. The centrifuge process may or may not take place at the same facility that the testing phase is performed. However, in many systems the storage of the centrifuged blood is handled in the same facility that centrifuging takes place.

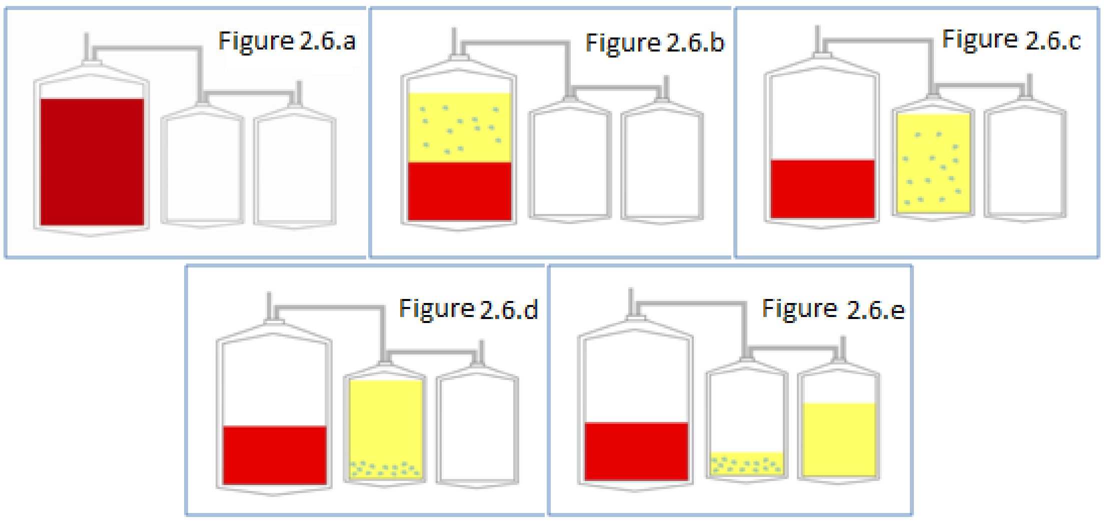


Figure 2-6 Phases of centrifuge operation

In this stage, one unit of whole blood (Figure 2.6.a) is first mildly centrifuged in order to distinguish the plasma from the blood cells (Figure 2.6.b). In this stage, plasma contains platelets. This plasma and platelet mixture is taken to another bag (Figure 2.6.c). The remaining part constitutes of red blood cells and called red blood cell suspension. This suspension is mixed with a protective solution and kept in special fridges between +2℃ - +6℃. The shelf life of this red blood solution is 42 days. The plasma with platelets is centrifuged again and the platelets subsides (Figure 2.6.d).

After this second centrifuge, the obtained plasma is taken to another bag and frozen (Figure 2.6.e). Plasma remains fresh up to 3 months, if it is kept between -18℃ - -25℃. The bag that contains the platelets is kept between +20℃ - +24℃ in a special machine which gives a continuous vibration. Under these conditions, the platelets will not perish before 5 days.

2.2 Evolution of Blood Transfusion & Donation

Blood donation operations evolved in 17th century and up until now, this concept preserves its importance in healthcare operations. With technological developments and improved equipments the blood donation and transfusion operations progressed significantly.

Before the first successful blood transfusion between humans, there were many successful and failed attempts between animals, from animals to humans and from humans to humans. In 1667, the first successful transfusion from sheep to human is performed by Jean Baptiste Denis in France. However, many unsuccessful attempts and resulting deaths caused Paris Society of Physicians to outlaw any kind of blood transfusion.

Dr. James Blundell is known for the first successful human-to-human blood transfusion in 1818. Many scientists try to figure out what goes wrong in some transfusions which are performed in very similar conditions with the successful ones. In 1901, Karl Landsteiner came up with a very critical answer to this question when he discovered the first three main blood types (A, B and O). One year later, AB blood group is found by Decastrello and Sturli.

During the World War I, the importance of blood transfusion grew dramatically. As a result, related scientific studies became more crucial. The main problem, that the scientists focused on was to keep blood fresh during the transportation to the battlefield and maintain it in field hospitals a little bit longer. Scientists suggested a breakthrough methodology, mixing the collected blood with sodium citrate, to prevent blood to perish quickly. With this new approach, the old blood transfusion methodology that requires the donor and the receiver to be in the same room simultaneously is vanished and also pioneered the technologic improvements that make blood-banking possible. Another important discovery belongs to WWI era is frozen blood. Scientists found that refrigerated blood stays longer.

As well as the technological developments, management of the blood donation and transfusion processes become more organized after WWI. Blood transfusion operations performed more commonly for patients other than war victims as well. British Red Crescent founded the first human blood transfusion center in 1921. In 1932, the first facility that can be classified as a blood bank started to operate in Leningrad Hospital, Russia. Dr. Bernard Fantus established the first blood bank of United States in 1937.

During the years 1939-1940, the RH blood system was discovered and recognized as the major reason of the complications that occur the blood transfusion operations after the discovery of major blood types. As a result, ABO and RH identification tests were applied each unit of blood until 1947. Also, syphilis tests performed to the transfused blood and this test pioneered many similar disease tests that are performed today.

In 1950, Carl Walter and W.P. Murphy suggested to use plastic bags instead of the glass bottles to carry collected blood. This development yielded easier and safer transportation of the collected blood and enabled today's bloodmobile technology. Additionally, plastic bags are easier to handle in centrifuge processes so, with the use of plastic bags obtaining multiple blood products from a single unit of blood came into the picture.

After 1954, blood transfusion started to be used for different disease therapies other than hemorrhage such as hemophilia, chicken pox, cancer etc. With the widespread use of blood transfusion, the disease detection tests gained importance. Starting from 1971 many disease tests such as Hepatitis B-C, HIV 1-2, anti-HLTV-1, etc, are added to the list.

Chapter 3

Blood Donation Logistics

3.1 Blood Donation Logistics in the World

There are 187 Red Cross and Red Crescent societies all around the world and these societies are the main blood suppliers and disaster response coordinators in their respective countries of operation. All these organizations are united under the International Federation of Red Cross and Red Crescent Societies (IFRC) [4]. This federation aims to help people in need at time of wars, terrorist attacks, natural disasters etc. This federation also facilitates communication among these societies and in turns enables quick and effective response respond to the large-scale incidents when the national society falls short of doing so. For instance, IFRC was one of the first and most effective respondents of 2005 Pakistani Earthquake, in which many Red Cross/Crescent societies all over the world prepared and delivered the medical supplies, shelters and other urgent needs very quickly in a very well organized manner.

Although, the IFRC members act as a team in major incidents, their organization structures are slightly different when it comes to national problems. Yet, their missions and visions are basically the same. In general, they are main disaster response organizations and blood collectors in their country.

World Health Organization (WHO) states that blood transfusion from volunteer blood donors to patients is the safest way. For this reason there are many European countries that forbid giving blood in exchange of money. If a person sells his blood for monetary gain, he may have reason to lie in respond to the questions regarding his medical history, sexual habits and other critical medical issues. Infection tests are performed for every unit of blood that is received but these tests have error factors, hence the answers of these questions may be as important as the test results. Since Red Crescent and Red Cross receive blood only from volunteer donors, they are considered to be not only the largest but also the safest national blood suppliers in the countries of operation.

On the other hand, there are still many countries where sale of blood and blood products is legal. According to WHO's report, 42 countries can supply only up to 25% of their blood needs from unpaid volunteer donors. [5]

As one can deduce from Figure 3-1, most of the countries in South America, Africa and Asia have unpaid blood donation rates below 90%. When it comes to blood products such as plasma, the picture is even worse. For instance, in the US selling plasma is legal even though blood needs of the country are satisfied entirely by volunteer blood donation. In China, many people sold their blood for cash in mid-90's and there was a large scale HIV spread observed back then. [6]

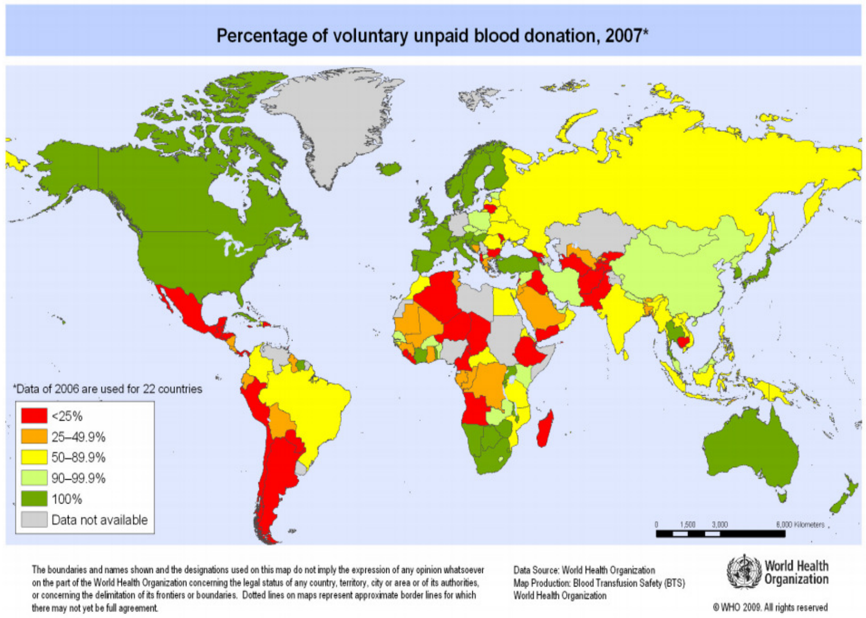


Figure 3-1 Percentage of voluntary blood donation

American Red Cross itself, supplies nearly 40% of the national blood supply (12 out of 30 million units of blood products annually). [7] The rest of the demand is covered by the hospitals' blood transfusion units/banks, and the third parties which take blood products from blood-sellers and convey them to the patients.

Red Crescent and Red Cross Societies all over the world share the same organization structure for their blood collection units. These units consist of mainly fixed points (such as blood centers, hospitals and cliniques) and bloodmobiles. A **bloodmobile** is a vehicle (usually a bus or a large van) containing necessary equipment for the blood donation procedure. Blood drives involving bloodmobiles usually happen in public places such as colleges and churches. These drives aim to reach at numerous donors that may not be planning to make a blood donation otherwise.

In a well developed blood collection system, the majority of the collection procedure is performed by the bloodmobiles. The fixed locations mainly focus on testing and storage of the blood and also serve as a depot until the transportation of the blood to the demand points. In addition, fixed locations serve as a base for the apheresis type procedures which are too complicated to be performed in a bloodmobile. About 80% of the donations collected by American Red Cross are performed in bloodmobiles, whereas only the remaining smaller part takes place in fixed points. ARC completed 200.000 bloodmobile tours annually where 50.000 of them are sponsored by companies, schools and organizations.[7] An individual donor can find the nearest bloodmobile tour in the proximity of a selected location on a given date by providing the ZIP code to the website of ARC. It is possible to make an appointment for a bloodmobile tour through the interface shown in Figure 3-2.

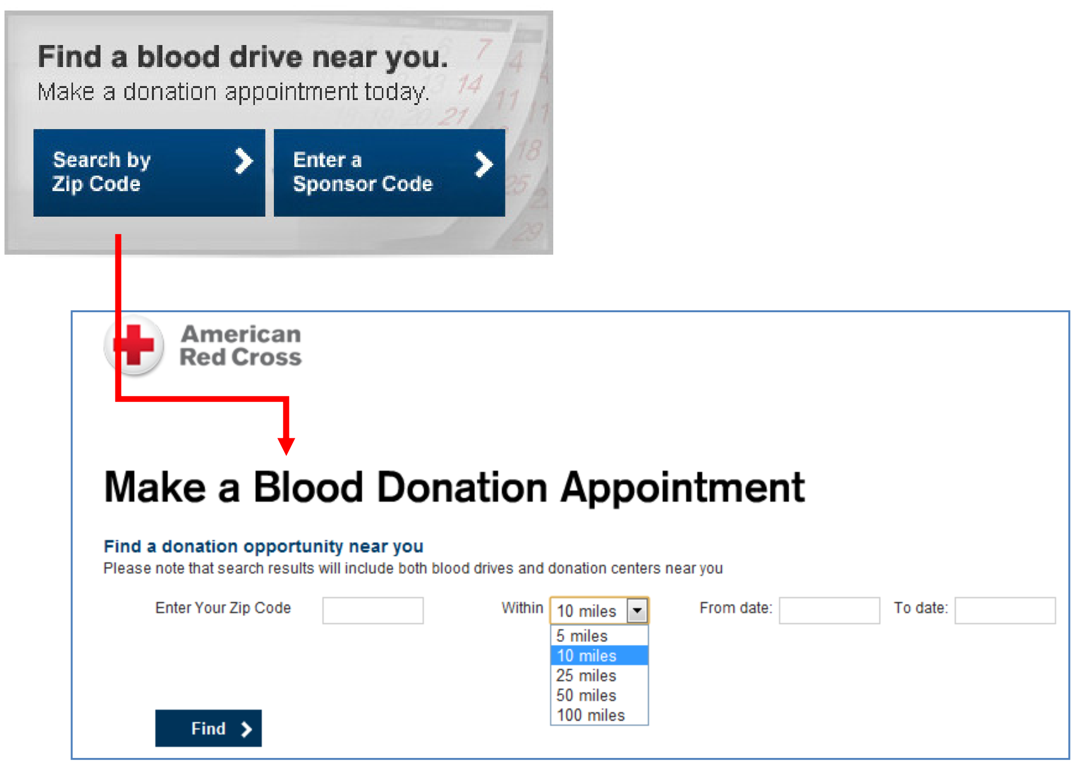


Figure 3-2 Blood drive appointment interface in the website of ARC

Instead of attending an independent bloodmobile tour, one can arrange a specific bloodmobile tour for his school or company as well. That is called sponsored blood drive. It is very easy to host a blood drive as a sponsor. All the sponsor needs to do is to arrange a suitable place (a school garden, a parking lot etc.), recruit donors by announcing the organization and complete a simple form.

The US has a very well designed bloodmobile system. Similarly, Canada, United Kingdom and Singapore has significantly well-designed blood collection systems with well-operating bloodmobile components. In the next section, we will take a look at blood collection units of Turkish Red Crescent (TRC) and explain the similarities and the differences of TRC with other similar societies.

3.2 Blood Donation Logistics in Turkey

In Turkey, blood collection operations are mainly performed by Turkish Red Crescent which is also a member of IFRC. TRC operates 55 blood collection centers in 51 cities around Turkey and provides nearly seventy per cent of the national blood supply. The organization is responsible for collecting blood from voluntary blood donors, analyzing the collected blood and transporting it to the demand points such as hospitals. On the other hand, TRC provides services not related to blood transfusion/donation such as disaster management, humanitarian help and education on disaster response.

After the Istanbul earthquake in 1999, TRC started a nationwide blood donation campaign, since the stocks in blood banks fell below the critical levels. The goal was collecting 1.5 million units of blood and the target was achieved with the help of community sense. Since then, the campaign repeated periodically to keep the stocks ready for a potential disaster as well as the satisfaction of the regular demand. After the announcements of the campaign, mobile units become significantly important since they can reach at even those with limited means of transportation. Still, the mobile blood collection is not the major part of blood collection in Turkey unlike the other countries in the world. TRC performs blood collection operations via fixed locations and with the help of a mobile system. Their structures and operational mechanisms can be summarized as follows:

- *Fixed Locations:* Regional Blood Centers (RBC), less developed Blood Centers (BC) and supporting facilities known as Blood Stations (BS) are the three types of fixed locations. RBCs are capable of performing every blood related action such as collection, analysis, storage, distribution etc. The coordination of activities in BCs and BSs are also among the responsibilities of RBCs. BCs, which are more common, can also perform basic analysis and storage as RBCs. BSs support only the collection and temporary storage of blood that is brought by the mobile units. Disease and blood type analysis needs to be performed at RBCs or BCs. The demand points are fed from these centers in the desired amounts only after the analysis process is completed. Each mobile unit is assigned to either a BS or BC, thus mobile blood tours are originated from these centers. In the system that is described by Şahin et al. [8] there are 7 RBCs, 23 BCs and 34 BSs. The proposed hierarchy in Şahin's study can be seen in Figure 3.3.

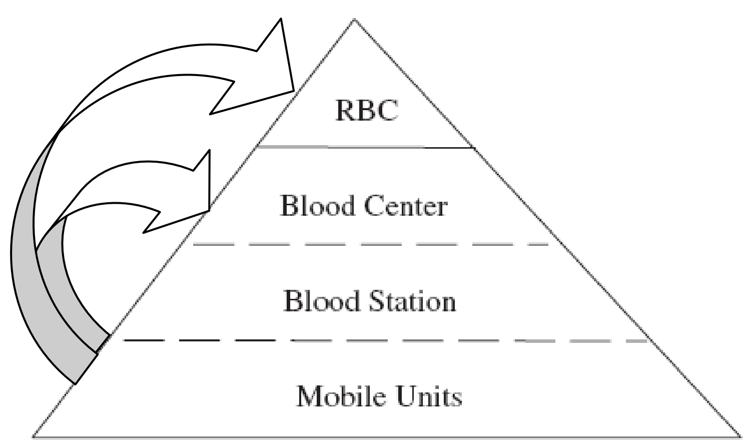


Figure 3-3 Hierarchy of TRC

- Bloodmobiles: Mobile Systems provide an effective way to contact with volunteers by arranging their tours according to social events or company calls. In Turkey, bloodmobiles provide service at pre-arranged temporary locations such as governmental organizations, municipalities and certain public events, where the potential number of donors is large. Pre-determined locations are visited by bloodmobiles according to a yearly prepared scheduled. However, they do not perform regular tours to distant locations. In the current system, bloodmobiles perform independent direct tours to the locations where public events take place or company campaigns. In Figure 3.4, one of the bloodmobiles during a collection activity can be seen.

Figure 3-4 A bloodmobile of TRC

Locations and dates for mobile blood collection are usually determined by the host organizations and TRC. TRC assigns collector teams to these host organizations on the designated days. After the collection process the collected blood needs to be sent to the closest RBC/BC for analysis and storage at the end of each day due to the perishable nature of whole blood because shelf life of whole blood is 24 hours. Although, the whole blood deteriorates very quickly, the blood components can be stored significantly long terms with the help of chemicals and special storing conditions as described in the previous chapter. At the end of each day, bloodmobiles return to the RBC/BC (depot) to which they are assigned to for preventing early blood spoilage. If the activity or campaign is a 2 or 3 day one, the bloodmobile comes to this point in the morning and goes back to depot at the end of each day. One good example of 3 day long blood donation activities is college fests. If there is not a pre-arranged donation activity the bloodmobiles stay idle in the depot (corresponding blood center/ blood station).

Chapter 4

Problem Definition & Related Literature

4.1 Problem Definition

Observations on the blood donation systems of those countries which cover their blood donation needs entirely by voluntary blood donation suggest that a successful mobile blood donation system may significantly increase the donation volumes.

TRC aims to improve blood donation volumes considering the annual demand increase. As an NGO that has a limited budget, it needs to do so while keeping operational costs in a reasonable level. Fixed blood collection units are utilized considerably well in Turkey. However, the mobile units are not utilized well. They show up only in very large public events which are rather rare. Other than that, they wait in the depot or in front of malls and serve as temporary fixed points. Even though, their visits to malls seem as reasonable choices, people are usually too busy to take time for donation. Also, the potential donors realize that there is a bloodmobile only after they reach that point. Hence, they do not have time to prepare themselves to make a successful donation. If a person intends to donate blood, he needs to stop smoking temporarily and taking drugs and alcohol 24 hours before the donation. In addition, he should not do sports on the donation day. However, a person who comes up a bloodmobile incidentally may not satisfy these conditions. Despite the fact that visiting crowded places in weekends carry a high potential, this arrangements do not yield high donation rates.

Another problem of the current blood collection system is the fact that bloodmobiles performing independent direct tours to activities which last longer than one day. Also they sometimes omit the second or the third day of the activity. There are two problems with this application. If a bloodmobile performs a direct tour instead of simply waiting for 2 days in that place, the transportation cost is doubled. Yet, if the crew chooses to skip the second or third day of the activity, they lose the opportunity to collect a significant amount of blood donation because most of the people focus on the ongoing activity on the very first day. It is also more likely that they hear about a bloodmobile after the first day. These are the shortcomings of direct blood mobile tours. However, the collected blood needs to be carried to a blood center at the end of each day before the blood perishes as explained in Chapter 2.

Instead of improving the current blood mobile system, we design a new mobile blood collection system for TRC that overcomes all symptoms that are described above. The new system basically allows 2 or even 3 day stay-overs, while conveying the collected blood to the depot still on time. The new system also proposes more frequent and utilized bloodmobile tours with a weekly schedule. The routes are not completely based on special, large-scale events but instead; smaller towns and suburban places will be visited as well.

The proposed system consists of current blood mobiles and an additional shuttle per depot. The bloodmobiles start their tours at the beginning of the planning horizon and they may not come back until the last day. They will visit several potential locations once they leave the depot and spend at least one day for each stop. If the estimated blood potential of a location is significantly high, the bloodmobile can stay overnight in there without returning to the depot. With the help of the new shuttle service the redundant tours between the location and the depot are eliminated, since the shuttle will visit every bloodmobile in the field at the end of each day and transport the collected blood to the depot. In this case, the crew of the bloodmobile needs to go their houses themselves. Yet, this is not a problem since potential stops of bloodmobiles are easy to reach for people. The only exception is the end of a bloodmobile tour because bloodmobile also comes back to the center and for this reason; shuttle's visiting that bloodmobile at the end of the planning horizon is redundant. An example of shuttle and bloodmobile tours can be seen in Figure 4.1. Figure 4.1.a represents the potential stops of the bloodmobiles and the depot. In Figure 4.1.b, the tours of 3 bloodmobiles are given, the self loops correspond to stay-overs. In Figure 4.1.c, the labels of the bloodmobiles correspond to days that they are visited by a bloodmobile. The Figures 4.1.d, 4.1.e and 4.1.f show a set of potential shuttle tours belonging to the first, second and third days of the planning horizon.

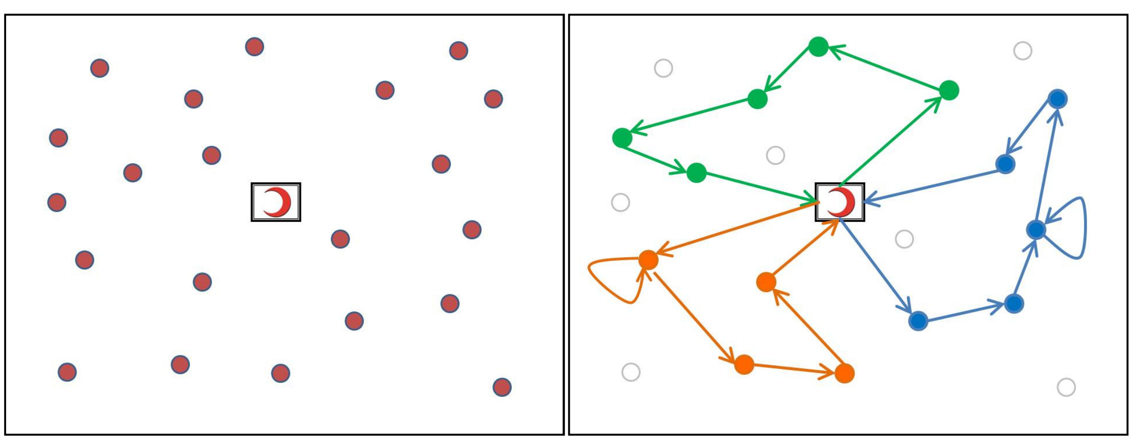
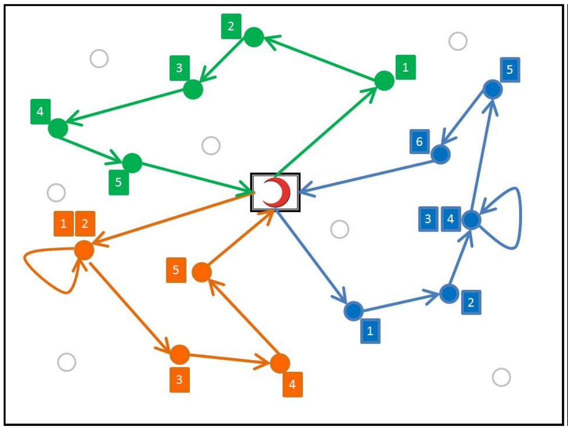


Figure 4.1.a Figure 4.1.b



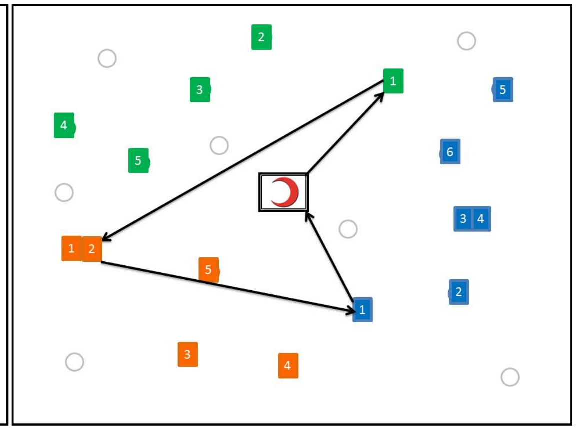
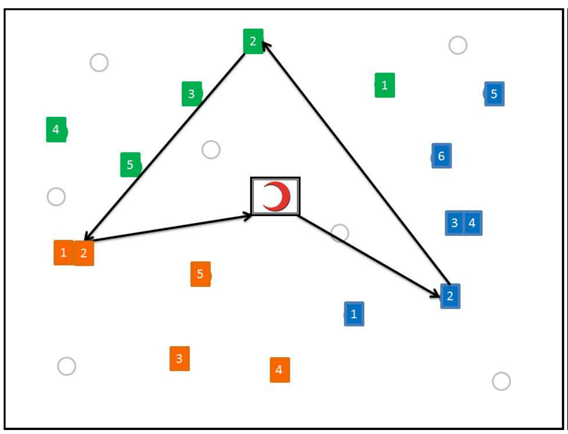


Figure 4.1.c Figure 4.1.d



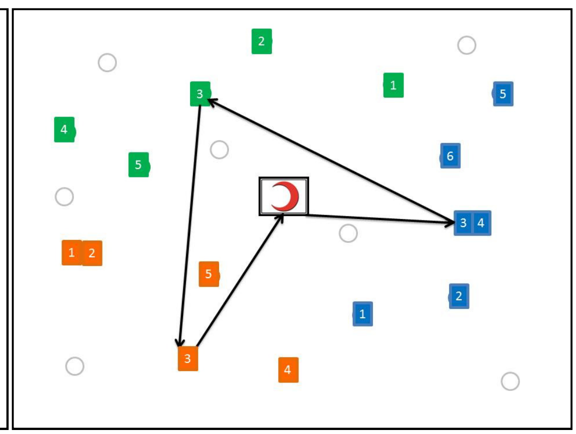


Figure 4.1.e Figure 4.1.f

Figure 4-1 An example of bloodmobile and shuttle tours in the proposed system

With this new system we aim to utilize unused bloodmobiles, increase the frequency of bloodmobile tours, reduce the operational costs of mobile blood collection system and gain regular donors. Our approach that will be discussed in the next chapter aims to:

- choose the locations that bloodmobiles visit among possible candidates,
- determine the length of the stay on a visited location by bloodmobiles,
- sequence the chosen locations in tours of bloodmobiles and

- build the shuttle tours based on stops of bloodmobiles in the field for each day of the planning horizon,

while maximizing the collected blood amount and minimizing the transportation costs of the vehicles. Since the stops are not known a priori and we need to define the tours between stops that are chosen among potential places, our problem can be classified as a variant of Selective Vehicle Routing Problem, which will be detailed in the following section. The stops of shuttle tours are determined according to bloodmobile stops and at the same time we need to come up with the least cost shuttle tour as well. This setup yields considering interdependent bloodmobile and shuttle tours. Hence, we named our problem as Selective Vehicle Routing Problem with Interdependent Tours (SVRPwIT). To the best of the authors' knowledge this variant of Vehicle Routing Problem has not been defined in the literature.

4.2 Related Literature

OR Applications in health care logistics operations has an increasing trend in recent years. Several OR practitioners focus on health related problems such as emergency room and doctor utilization, health care center location and medical supply transportation. Health related transportation problems are deeply investigated because of their complicated nature brought by the simultaneous consideration of medical constraints and challenging transportation dynamics.

In his analysis Jarrett [9] summarizes these new trends in international healthcare logistics and makes comparisons in a global scope. The author gives details on several implementations of just-in-time (JIT) approach in health-logistical environment. Since these methods are already adopted in industry for a long time-period, he also compares these two application areas in terms of advantages and disadvantages. He summarizes several real-life examples both from the industry and the healthcare sector and points out the differences between the JIT implementations in these two areas.

Brandeu et al. [10] covers a set of different operations applications in different areas. While doing so, they attach these issues to current health care problems and possible future challenges. As a result of limited resources today's major healthcare delivery problems occur in low and middle-income countries. Malnutrition and related infectious diseases, insufficient vaccination, absence of affordable essential medication are at the top of the list. Surprisingly, on the other hand, health care delivery systems are not perfect in most of the high-income countries. The main reason for this is ineffective usage of resources. It is also indicated that the health care accessibility will still remain limited in the future even though many improvements are achieved. The book covers the relevant studies under three main sections: namely, healthcare operations management, public policy analysis and clinical applications.

Problems that are based on healthcare logistics consider equity as one of the major objectives besides the operational costs and as Brandeu's projections point majority of the healthcare problems will occur on low income countries. There are different studies on providing healthcare services to the poor and unhealthy people in developing countries. Considering the healthcare infrastructures and geographical conditions in low-income countries, especially in Africa, scientists develop different approaches of providing health services while respecting to equity. In their study, Hodgson et al. [11] search for ways of increasing the accessibility of primary health care resources in Suhum District of Ghana and in order to do so, they decide to utilize mobile healthcare facilities. In their study, they solve a Covering Tour Problem (CTP) to find the 'best' tour for the mobile healthcare facility. In particular, they find the shortest tour which has at least one stop in a certain radius of each population center. They also consider the rainy and dry seasons while determining parameters. The paper suggests an exact algorithm for small instances and an insertion based heuristic for larger ones. The accessibility of primal health care increased up to 99%, where it was only 30% before this study.

Doerner et al [12] focus on a similar problem in Senegal. However, instead of solving a CTP they come up with a different model which combines three objectives: tour cost, average distance a member of the population to the nearest stop and coverage of population. They suggest three solution strategies. One is to compute the Pareto-optimum solution sets and the other two are variations of genetic algorithms for multi-objective problems.

Since blood is hard to obtain and it easily perishes, blood product management is one of the very interesting and challenging healthcare problems. There are many studies conducted in this subject. Belien and Force [13] classify blood supply management studies in their survey. One can easily observe the increasing attention on this subject after year 2000 by examining the charts on this paper. In their survey, the authors solely focus on inventory management studies of blood products. This paper is a very up-to-date study, which summarizes what kind of problems are faced in blood banking and during blood transportation from blood storages to the demand points etc.

For instance, Pierskalla's [14] study is a comprehensive analysis on the supply chain operations of blood banking. In this paper, the author starts with stating the major decisions in a blood bank environment such as the number and locations of blood centers in a region, the supply and demand coordination and the assignment of donor areas to transfusion centers. The transshipment operations of the blood between blood centers or even depots in the demand points are considered in details. Consequently, the paper contains a good analysis on inventory management of the collected blood. As a real-life aspect of the study, it provides significant statistics on supply chain management of blood banks and analyzes currently-in-use blood banking models in US.

Similarly, Hemmelmayr et al. [15] discuss delivery and storage strategies for Austrian Red Cross and they investigate whether a vendee (hospitals) or a vendor (blood bank) based inventory setting is better. Satisfying demand in transfusion centers with minimum amount of blood perished is the main objective(s) of the logistics department of Austrian Red Cross. They seek the best delivery strategy in order to meet the needed blood. Their first strategy consists of a bunch of fixed tours with an MIP model that chooses the schedule of the tours. Their second option combines flexible tours with a regular schedule for visits.

Delivering blood products from blood banks or suppliers to hospitals is only one aspect of this problem. In many cases, redistributing the blood between the hospitals is also necessary for preventing outdating. If there is an urgent need of a specific blood type in a hospital, they may want to use the blood with closer spoilage date from another hospital. The reason is even one unit of blood spoilage is not tolerable, especially if it is a rare blood type. However, this approach requires a well planned and dynamic storage management. In their study, Kendall and Lee [16] concentrate on this redistribution problem. Their model has different objectives, such as prevention blood shortages and overages in hospitals, minimization of the number of outdated units, maintaining the average age of blood products at an acceptable level and minimization of the operating costs. The authors use goal programming to solve this problem with conflicting objectives.

These four studies are interested in the operations after arrival of the donated blood at the blood banks and/or hospitals. However, blood donation supply chain is much longer if we consider all the steps from the first supplier (donor) to the last customer (receiver). If the blood donation takes place in a fixed location, then there will not be extra operations to consider in the supply chain context because these fixed points are generally part of either a blood bank or a hospital. However, blood may be collected by a bloodmobile. As a result, many questions about rotations, tour durations and other logistic issues come into the picture.

Despite many countries' major blood donations are performed via mobile points, there are few studies on bloodmobile operations in the literature. In Turkey, using bloodmobiles in a systematic way is first suggested in Sahin et al.[8]'s study. This study is one of the very few studies that help the re-building process of Turkish Red Crescent after the 1999 Golcuk and Duzce earthquakes. In this study, the authors propose a new hierarchy for TRC's blood services. The suggested hierarchy consists of small but widely distributed blood stations, high-tech equipped blood centers and regional blood centers and finally mobile units. As a second stage of the study they determine the locations of these components of the suggested system with a help of *pq-median* location model, which is an extension to the classical *p-median* problem. This model includes two integrated p-median problems; it first chooses locations of p (regional) blood centers and then locates q blood stations and assigns them to the opened blood centers.

Using bloodmobiles effectively is also very important. Launching a bloodmobile station is not enough; every step should be designed carefully. If the ongoing processes in a bloodmobile are slow and unorganized, it may miss the opportunity to fully serve a point with high blood potential in the allotted time window and in turn may result in the loss of many future potential regular donors. With this motivation, Brennan et al. [17] and Alfonso et al. [18] focus on reducing operational times in a bloodmobile. They both test their suggested layouts and strategies using simulation with different customer arrival patterns and behaviors.

Doerner and Hartl [19], [20] focus on health care logistics problems in a disaster relief context. They describe routing problem issues that arise in emergency preparedness and give several models for ambulance location and routing problems, disaster response problems as well as blood transportation. They keep the main focus on Austrian Red

Cross (ARC) healthcare operations and use real data obtained from ARC. In particular, their research focuses on blood collection with the utilization of mobile blood collectors as one aspect and transportation of the collected blood to the demand points as another. The suggested system includes extra transporters to take the blood from the mobile campaign teams in addition to regular bloodmobiles of the campaign. The extra transporters are added to the system in order to carry the blood from the bloodmobiles to the analysis center before it perishes. The locations of bloodmobiles are assumed known and fixed. They define a time window based on the lifespan of the collected blood from the donors and so, define ARC's problem as a Vehicle Routing Problem (VRP) with multiple interdependent Time Windows. Finally, the paper concludes with a periodic VRP problem defined for periodic blood supply to demand points (hospitals).

While designing bloodmobile tours, the planner should consider the amount of potential locations as well as the operational costs. Since the number of potential locations can be excessive and planning horizon or estimated budget is limited, visiting all these stops is not practical in real life. Therefore, choosing a subset of these locations as tour stops is very reasonable. These kinds of routing problems are classified as the Selective Travelling Salesperson Problem in the literature. These types of problems have two major objectives: minimizing the tour cost and maximizing the profit that is obtained visiting those nodes. Although, the main motivation is determining the subset that is to be visited, what varies in general is the selection of the objective function and the constraint with a desired achievement level of the other consideration. If these two objectives are combined in the objective function then the problem is called the Profitable Tour Problem (Dell'Amico et al. [21]). On the other hand, if the objective is defined as maximization of the collected profit (blood) and a pre-determined cost level is given as a constraint, then it is classified as Orienteering Problem (a.k.a TSP with profits - Laporte and Martello [22] or maximum collection problem Katoka and Morito [23]). Finally, if a problem is defined with a cost minimization objective and a pre-determined profit lower bound in the constraints, it is considered as a Prize Collecting Travelling Salesman problem, which is defined by Balas [24]. In their study Feillet et al. [25] compares all these three approaches in detail. They also give real life applications related to this problem and summarize exact and heuristic solution procedures of them.

These three approaches assume that the profit is ready to be picked up, once the vehicle visits that location. However, the real situation might not be this simple. The profit may depend on surrounding districts of the stop and the distance between the stop and the districts may affect the value of that stop. Also, customers may want to choose the stop at which they get service. In their study, Erdogan et al [26] consider these new constraints and define a new problem called the Attractive Travelling Salesperson Problem. Their problem has two different vertex sets customers and potential stops. The value of each stop is determined by a function that depends on population and distance of the surrounding customers. The developed model decides which customers will be assigned to which stops while determining the subset of stops that are visited by salesperson. The authors develop a branch and cut procedure for this problem as well as a tabu search algorithm.

Vansteenwegen et al [27] is a very recent survey on the orienteering problem. In this paper, the authors classify all variations of the orienteering problem with a deep insight on new exact and heuristic solution procedures. The study also considers team orienteering problems, which have the same definition with the exception of using multiple vehicles instead of a single one. The team orienteering problem is an important concept especially in the context of our study because using only one vehicle may not be an effective approach to model bloodmobiles especially in a metropolis.

Team orienteering problem is defined by Chao et al. [28]. In this study they model the orienteering problem, which is defined previously, for the multiple vehicle case. In general, this problem is referred to the Selective Vehicle Routing Problem from now on.

Combining multi-objective approach with multi vehicle routing problems is important and there are several studies on this subject. Jozefowiez et al. [29], [30] concentrate on this problem. In particular, the second paper gives a detailed taxonomy on multi-objective vehicle routing problems. However, the studies that are discussed in these two papers have classical vehicle routing approaches, in which the vehicles need to visit all vertices in a given problem. This is not applicable to the case that is discussed in our study.

In their study Archetti et al. [31] considers capacitated selective VRP problems. They develop models for both Capacitated Profitable Tour Problem with multi-vehicle (maximizing profit with a given cost upper bound) and Capacitated Team Orienteering Problem (both the cost and the profit component is combined in the objective). Then, they develop tabu search meta-heuristics for these two problems.

Another variation of the Capacitated Selective Vehicle Routing Problem (CVRP) is defined by Aksen and Aras [32]. The authors also add a time deadline for each customer, and if the vehicle visits that customer after the deadline, it gains no profit. The paper provides a MIP formulation for this problem as well as a 2-stage iterative heuristic methodology. In the first stage a simulated annealing algorithm is adopted to find tours for the classical CVRP problem on the instance. In the second stage, the algorithm decides on the nodes that are to be discarded according to their profit and deadline values. Basically, the second stage transforms a CVRP solution to a Selective CVRP solution with time deadlines.

Valle et al. [33] come up with an interesting variant of the Selective VRP problem. They define their problem with a pre-specified profit constraint, but instead of minimizing all tour lengths, they minimize the length of the maximum tour. The authors propose a branch and cut algorithm (BC) and a local branching (LB) algorithm for the instances with a small number of vehicles. For large instances, they develop a GRASP (Greedy

Randomized Adaptive Search Procedure) based algorithm to improve the bounds that are obtained by BC and LB.

Sural and Bookbinder[34] define a variant of Vehicle Routing Problem with backhauls where the backhauls can be performed for a subset of the demand nodes according to their profits. Therefore, the backhaul tours of this problem can be classified as Selective VRP tours. They develop an MILP for the problem and lift the Miller-Tucker-Zemlin subtour elimination constraints accordingly.

The selective VRP approach is very suitable for determining the bloodmobile tours. It takes into account unvisited potential stops and multi-objective nature of the problem. However, once a bloodmobile visits a location it should stay there for at least one whole day because of the set up costs and blood donation campaign's features. Also, independent direct tours are not favorable as described in Section 4.1. Yet, the blood is perishable and needs to be in a testing center/storage within 24 hrs after donation. Therefore, using a variant of Selective VRP will not be sufficient. Doerner and Hartl [19], [20] suggests collecting blood from the bloodmobiles in the field with the help of a collector vehicle where they take the locations of bloodmobiles as fixed points. However, we need to develop a whole bloodmobile system for TRC and tours of blood locations need to be decided as well. As a result, we will adopt a selective VRP approach and combine it with the collector vehicle idea where the bloodmobiles perform Selective VRP tours and the shuttle's (collector vehicle) tours will be determined by the stops of blood mobiles by the developed model as described in the next section.

Chapter 5

Model Development

Although TRC owns bloodmobiles, it does not systematically perform blood collection via bloodmobiles. In order to develop a good and operable system for TRC we adopt some useful ideas from literature and develop a complete mobile blood collection system. In the proposed system bloodmobiles perform regular tours to points with blood potential. Also, the new system will utilize a single shuttle for each Blood Center or Regional Blood Center. This shuttle collects the blood from the bloodmobiles in the field that are assigned to that particular BC/RBC. Thus, this problem is to be solved for each BC/RBC in isolation at the beginning of each week.

5.1 IP Models

The proposed mobile blood collection system entails a complex problem with several considerations. First of all, the problem has two major objectives: achieving high blood collection amounts and keeping logistics costs low. Also, the decision maker needs to select the nodes to be visited, the duration of the visits and the routes of the bloodmobiles and the shuttle among the selected nodes. We model the decision maker's problem as a Selective Vehicle Routing Problem with Integrated Tours. Considerations that are taken into account within this problem are as follows:

1. Each tour starts and ends at an RBC/BC which will be referred as depot here on.
2. Bloodmobiles may visit a proper subset of the nodes.
3. A bloodmobile can visit any given node at most for once. The stay-over period of a bloodmobile at a given node is restricted between 1 – 3 days.
4. If a bloodmobile visits a node, it should stay at that node for at least one day.
5. The blood collected at a node should be transferred to the depot in the evening either by the shuttle or the bloodmobile itself on its return at the end of its tour.

Let $G = (N, A)$ be a geographical network, where N is the set of potential stops of the bloodmobile and the depot. Set A represents the roads between these nodes. In order to model the possible stay-overs of bloodmobiles, we will use an extended version of G. Let G' be the extended version of the geographical network for modeling the stay-overs on nodes. For each actual potential location, G' has three nodes, the first one is the original node (v) and the other two are the artificial nodes (v') and (v'') corresponding to two-day and three-day stay-overs, respectively. The model takes into account stay over periods of up to three days. If the solution reveals that a blood mobile visits v' (v''), it means the bloodmobile stays in v for 2 (3) days. G is designed in a way that v' (v'') cannot be visited unless a bloodmobile visits v (v'). With this set-up, an original node (v) is accessible from an artificial node, but an artificial node can be reached only from its original node.

Formally, $G' = (N', A')$, where $|N'| = 3|N|$ and $v_{i+|N|}$, $v_{i+2|N|}$ represents 2 and 3 day stay-overs respectively $\forall\, v_i \in N$. Let c_{ij} represents the arc distance between node i and node j in G. In G', the arc distances are defined as follows:

$$c'_{i'j'} = c_{ij} \;, \qquad \forall i \equiv i'(mod_{\;|N|}), \forall j \equiv j'(mod_{\;|N|}) \qquad (*)$$

As a result, $c_{i',i+|N|} = c_{i',i+2|N|} = 0$, since $c_{ii} = 0\; \forall i \in N$. Despite the stay overs are described as separate nodes, the travel between an actual node and the copy node has 0 cost with the help of this cost function.

The blood potentials of the artificial nodes are also defined as a function. The past blood collection activities of TRC shows that the blood potential of a node in the second or third day of the activity is less than the first day. In order to model this behavior we develop a decreasing function that represents the blood potentials for artificial nodes. Let b_j , be the blood potential of an original node $j \in N$ on the first day of visit. Then, the blood potential of a node $j \in N'$ is defined as follows:

$$b_j = \begin{cases} b_j, & if\ j \le |N| \\ b_j\beta, & if\ |N| < j \le 2|N| \\ b_j\beta^2, & if\ j > 2|N| \end{cases} \qquad (**)$$

β is a parameter that belongs to [0,1] interval, so that this function can model the decrease of blood potential during the stay-over period. The estimation process of β will be described in Chapter 6. Also, a detailed sensitivity analysis on the value of β is conducted in that chapter.

Let D represent the days in the planning horizon of the problem and consider m identical bloodmobiles. The output model will be m tours for the bloodmobiles and up to $|D| - 1$ tours for the shuttle. The tours of the bloodmobiles start on the first day and end at or before end of the planning horizon. On the other hand, each tour of a shuttle starts and ends on the same day. Since the bloodmobiles transfer the collected blood themselves on their return to the depot; the shuttle does not need to work on the last day of their respective tours. Incidentally, as all bloodmobiles will have returned to the depot by the end of the planning horizon the shuttles do not need to be in service on this last day.

Problem parameters are defined as follows:

$c'_{ij} = The\ travelling\ cost\ from\ node\ i\ and\ to\ node\ j,\ \ where\ (i,j) \in A'$

$b_j\ = The\ blood\ potential\ of\ node\ j, \qquad where\ j \in N'$

$B = Desired\ value\ for\ the\ amount\ of\ blood\ to\ be\ collected$

$m = Number\ of\ bloodmobiles$

Decision variables are defined as follows:

$$x_{ijd} = \begin{cases} 1, if\ a\ bloodmobile\ travels\ to\ node\ j \in N' directly\ from\ node\ i\ \in N'\ on\ day\ d \in D \\ 0, ow \end{cases}$$

$$y_{ijd} = \begin{cases} 1, if\ the\ shuttle\ travels\ to\ node\ j\ \in N'\ directly\ from\ node\ i\ \in N' on\ day\ d \in D \\ 0, ow \end{cases}$$

$$z_{id} = \begin{cases} 1, if\ node\ i\ \in N'\ requires\ a\ shuttle\ on\ day\ d \in D \\ 0, ow \end{cases}$$

$V_i = dummy\ continuous\ variable\ that\ represents\ the\ order\ of\ node\ i \in N'\ in\ a\ shuttle\ tour$

The proposed model (*MinCost-B**-*Blood*) is as follows:

$$minimize \quad \sum_{j \in N'} \sum_{i \in N'} c'_{ij} \sum_{d \in D} X_{ijd} + \sum_{j \in N'} \sum_{i \in N'} c'_{ij} \sum_{d \in D} Y_{ijd} \qquad (O1)$$

subject to

$$\sum_{i \in N'} X_{ijd} = Z_{jd} + X_{j1d+1}, \qquad \forall j \in \{2, \dots, N'\}, \forall d \in \{1, \dots, D-1\} \tag{1}$$

$$\sum_{d \in \{1,\dots,D-1\}} (X_{j1d+1} + Z_{jd}) \leq 1, \qquad \forall j \in \{2, \dots, N'\} \tag{2}$$

$$\sum_{i \in N'} X_{ijd} = \sum_{k \in N'} X_{jkd+1}, \qquad \forall j \in \{2, \dots, N'\}, \forall d \in \{1, \dots, D-1\} \tag{3}$$

$$\sum_{j \in N'} X_{1j1} = m \tag{4}$$

$$\sum_{j \in N'} \sum_{i \in \{2,\dots,N'\}} X_{ij1} = 0 \tag{5}$$

$$\sum_{j \in N'} \sum_{d \in D} X_{1jd} = m \tag{6}$$

$$\sum_{j \in N'} \sum_{d \in D} X_{j1d} = m \tag{7}$$

$$\sum_{i \in N'} X_{ijd} \geq X_{j(j+|N|)(d+1)}, \forall j \in \{1, \dots, 2|N|\}, \forall d \in \{1, \dots, D-1\} \tag{8}$$

$$X_{(j-N)jd} \geq Z_{jd} + X_{j1d+1}, \forall j \in \{|N|+1, \dots 3|N|\}, \forall d \in \{1, \dots, D-1\} \tag{9}$$

$$\sum_{i \in N'} Y_{ijd} = Z_{jd}, \qquad \forall j \in N', \forall d \in \{1, \dots, D-1\} \tag{10}$$

$$\sum_{i \in N'} Y_{j1d} = Z_{jd}, \qquad \forall j \in N', \forall d \in \{1, \dots, D-1\} \tag{11}$$

$$\sum_{j\in\{2,\ldots,N\}} Z_{jd} \leq m \sum_{j\in\{2,\ldots,N\}} Y_{1jd}\,, \qquad \forall d \in \{1,\ldots,D-1\} \tag{12}$$

$$\sum_{j\in\{2,\ldots,N\}} Z_{jd} \leq m \sum_{j\in\{2,\ldots,N\}} Y_{j1d}\,, \qquad \forall d \in \{1,\ldots,D-1\} \tag{13}$$

$$V_i - V_j + mY_{ijd} \leq m-1, \forall j \in \{2,\ldots,N'\}, \forall i \in \{1,\ldots,N'\}, \forall d \in \{1,\ldots,D\} \tag{14}$$

$$V_i \geq 0, \qquad \forall j \in \{2,\ldots,N'\}, \tag{15}$$

$$\sum_{j\in N'} b_j \sum_{i\in N'} \sum_{d\in D} X_{ijd} \geq B^* \tag{16}$$

$$X_{ijd}, Y_{ijd,} Z_{jd} \in \{0,1\} \quad \forall d \in \{1,\ldots,D\}, \forall j \in \{1,\ldots,N'\}, \forall i \in \{1,\ldots,N'\} \tag{17}$$

Constraint set (1) ensures that if a bloodmobile visits node *j* on day *d*, then node j should either be visited by the shuttle also on day d or the bloodmobile returns directly to the depot immediately after node *j* on day *d+1*. Constraint set (2) restricts a node to be visited at most once. Constraint set (3) specifies the flow balance conditions such that if there is a bloodmobile coming to node *j* on day *d* there should be also an outgoing one from node *j* on day *d+1*. Constraint (4) forces all bloodmobile tours to start on day 1. Constraint (5) prevents tours starting from any node other than the depot. Constraints (6) restrict the number of vehicles leaving the depot. Constraint (7) ensures all bloodmobiles turn to the depot. Both constraints (6) and (7) allow self tours for depot. Therefore, if a bloodmobile is not needed, then a self tour of depot is used. Constraint set (8) satisfies that if a node is visited for longer than one day, the bloodmobile should stay on that node consecutively. Constraint set (9) forces that if an expanded node ($j+|N|$) is visited on day *d+1*, then the original node *j* should have been visited on day *d*. Constraint sets (10) and (11) ensure that the shuttle picks up the collected blood from the nodes that are require shuttle service. Constraint sets (12) and (13) initiate and finalize shuttle tours even if there is a single node requiring the shuttle service on day *d*. Constraint sets (14) - (15) represent Miller- Tucker- Zemlin (MTZ) sub-tour elimination constraints for shuttle tours. Constraint set (16) ensures blood-collectors to achieve a desired blood level B^* that is determined by the decision maker. Finally, constraint set (17) is integrality definition of the decision variables. The model contains MTZ constraints for only shuttle tours. Since, for each day a shuttle tour is performed, these constraints together with the constraint set (3) also prevents subtours in bloodmobiles.

The desired blood level *B* could be determined by considering the current inventory levels or the decision maker may consider the collected blood amount as a second objective. Hence, we also need to find the maximum amount of blood for a given district while respecting the system constraints such as the number of vehicles and tour lengths in days. One way of doing this is simply moving the LHS of constraint set 16 to the objective function and solving *MinCost-B*-Blood* as a maximization problem but, this model considers the shuttle tours as well. Obviously, the shuttle tours do not affect the amount of blood collected by bloodmobiles. Because of this reason, *MinCost-B*-Blood* has redundancies such as the shuttle tours and their connection with the bloodmobile tours. Since the maximum amount of blood that can be collected from a given instance is not determined by the shuttles, a smaller IP which focuses only on the blood-collector-vehicles is developed.

Constraints (10) - (15) in *MinCost-B*-Blood* build shuttle tours, so our new model will not include them. In addition to that, variable Z_{jd}connects the collector tours to the shuttle tours via constraint (1) so we can eliminate these variables in our new model. We can replace Z_{jd} with $\sum_{i=1}^{3N} X_{ijd} - X_{j1d+1}$ by constraint (1) in the constraint sets (2) and (9). With these substitutions we obtain constraint sets (18) and (19) instead of (2) and (9) respectively:

$$\sum_{i \in N'} \sum_{d \in \{1,\dots,|D|-1\}} X_{ijd} \leq 1, \qquad \forall j \in \{2, \dots, N'\} \tag{18}$$

$$X_{(j-N)jd} \geq \sum_{k=1}^{3N} X_{jkd+1}, \qquad \forall j \in \{|N|+1, \dots 3|N|\}, \forall d \in \{1, \dots, D-1\} \tag{19}$$

The projected model (*MaxBlood*) is as follows:

$$maximize \sum_{j \in N'} b_j \sum_{i \in N'} \sum_{d \in \{1,\dots,|D|-1\}} \left(X_{ijd}\right) \tag{O2}$$

$subject\ to$

(3),(4),(5),(6),(7),(8),(17),(18),(19)

$$U_i - U_j + |D| X_{ijd} \leq |D| - 1, \;\; \forall d \in \{1, \dots, D\}, \forall j \in \{2, \dots, N'\}, \forall i \in \{2, \dots, N'\} \tag{20}$$

$$U_i \geq 0, \;\; \forall j \in \{2, \dots, N'\} \tag{21}$$

Recall that sub-tours of blood collectors are prevented by the shuttle sub-tour elimination constraints in the previous model. Since those constraints are not included in the second model, we add Miller-Tucker-Zemlin constraints (20)-(21) for blood collectors.

After the maximum amount of blood that can be collected is determined by *MaxBlood*, that amount can be given to *MinCost-B***-Blood* as an aspiration level as B and the model is solved with the objective of minimizing the total cost. Obviously, there exists a feasible collector and shuttle tour that can obtain the blood amount that is found in *MaxBlood*, since there are no distance limitations on the shuttle tours.

5.2 Valid Inequalities

A set of logical valid inequalities are developed to improve the performance of *MinCost-B*-Blood*. First of all, since we know that any artificial nodes cannot be visited before the corresponding original node, we know that on the very first day of the planning horizon no artificial nodes will be visited by a bloodmobile. Therefore, the shuttle will not visit any artificial node on the first day, either. Since, this information is known a priori, it can also be considered as a pre-processing operation. This argument yields the valid inequality 1:

$$\sum_{j \in \{|N|+1,\ldots,3|N|\}} z_{j1} = 0 \qquad (22)$$

Secondly, we design our constraints so that, a two day stay over node is accessible only from its original node and a three day stay over node is accessible from its two day stay over node. Thus, the flow of the bloodmobile is in this forward direction and no flow is allowed in the backward direction. For this reason, we know that any artificial node succeeds a three-day stay-over node on a blood mobile tour. The mathematical expression for this valid inequality 2 is as follows:

$$\sum_{d \in \{1,\ldots,D-1\}} \sum_{j \in \{|N|+1,\ldots,3|N|\}} x_{ijd} = 0, \quad \forall i \in \{2|N|+1,\ldots,3|N|\} \qquad (23)$$

Finally, we know that if a bloodmobile returns to the depot before the end of the planning horizon, we will have one less bloodmobile in the field than the previous day. Of course, it is not true for the last day of the planning horizon, so we rule out the last day. We can express this statement as a valid inequality as follows:

$$\sum_{i \in \{2,\dots N'\}} X_{i1d} = \sum_{i \in N'} \sum_{j \in N'} X_{ijd} - \sum_{i \in N'} \sum_{j \in N'} X_{ijd+1}, \qquad \forall d \in \{1, \dots, |D| - 1\} \tag{24}$$

The next chapter will present the computational results on the performances of *MinCost-B***-Blood* and *MaxBlood* as well as the combinations of the valid inequalities described above. Also, the results of the sensitivity analysis on the problem parameters can be found in Chapter 6.

Chapter 6

Computational Analysis

In order to test the performance of developed methodologies and obtain theoretical and managerial insights, a series of experiments are conducted on several data sets. In this chapter, data sets and results of experiments will be explained in detail.

6.1. Data Sets

In this study, computational experiments are based on two different data sets. This problem is inspired by the bloodmobile collection problem of TRC Ankara. Therefore, real donation data of past blood collection activities in Ankara is gathered. Secondly, GIS data belonging to the districts in the European Part of Istanbul is collected and each district is considered as a potential point while the blood potential is assumed to be proportional with the population of districts.

Headquarters of TRC in Ankara has blood collection activity data of the past years containing the date, location and the collected amount of blood. TRC supplied the blood collection data that is obtained in 2009-2010. Since0 TRC keeps track of every donation activity; it is not realistic to use all of this information. Some of the activities can be a one-time donation campaign, while some others may be traditional ones that repeat after a certain time interval. For instance, some companies or colleges have an annual donation campaigns whereas some other companies decide to improve their image and organize a blood donation activity. After a series of meetings, these cases are eliminated and we focus on the activities that may repeat and so can be considered as a potential stop of bloodmobiles. In addition to that, some of the points closer than 1 km are aggregated. After these eliminations, we end up with 38 potential points in Ankara with known blood potentials. TRC’s headquarter in Kızılay is the ultimate stop of current blood mobiles, which is also a RBC that serves Middle Anatolian Region of Turkey. For this reason, we consider that building as the depot in our analysis. These 38 points and the depot are pinned in Figure 6.1.

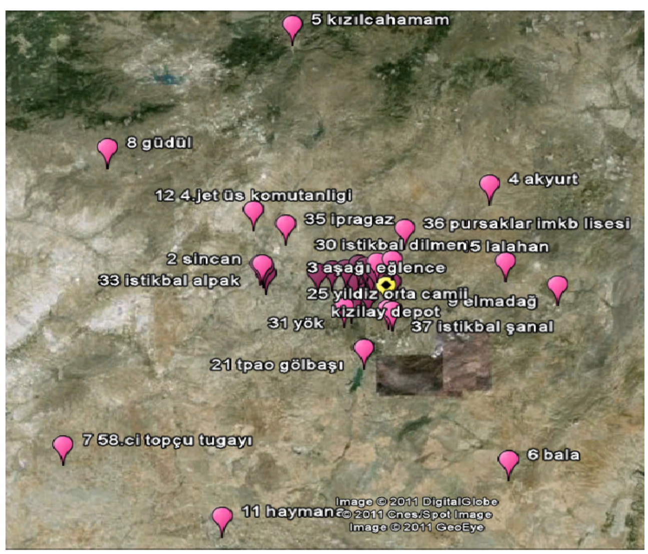


Figure 6-1 Potential points of Ankara(Yellow point represents the depot)

After deciding the potential points in Ankara, we constructed the distance matrix between these points. Instead of Euclidean distances, using actual road distances yields more realistic solutions. For this construction, we use TomTom Online Route Planner (http://routes.tomtom.com/) with the shortest route option. Utilization of TomTom Route Planner gives us the actual road distances between the points under consideration. The selected points, their blood potentials and the original distance matrix can be seen in Appendix 1.

Unlike Ankara, Istanbul data is not based on past activities, but instead is considered as an a priori analysis for future blood collection activities. For this reason, all the districts in the European part of Istanbul have been taken into account. Again, closer districts and their populations are aggregated and the actual center of TRC in Fatih, which is a BC, is considered as depot. After this aggregation, 97 points including depot. These 96 district centers and the depot are pinned in Figure 6.2.

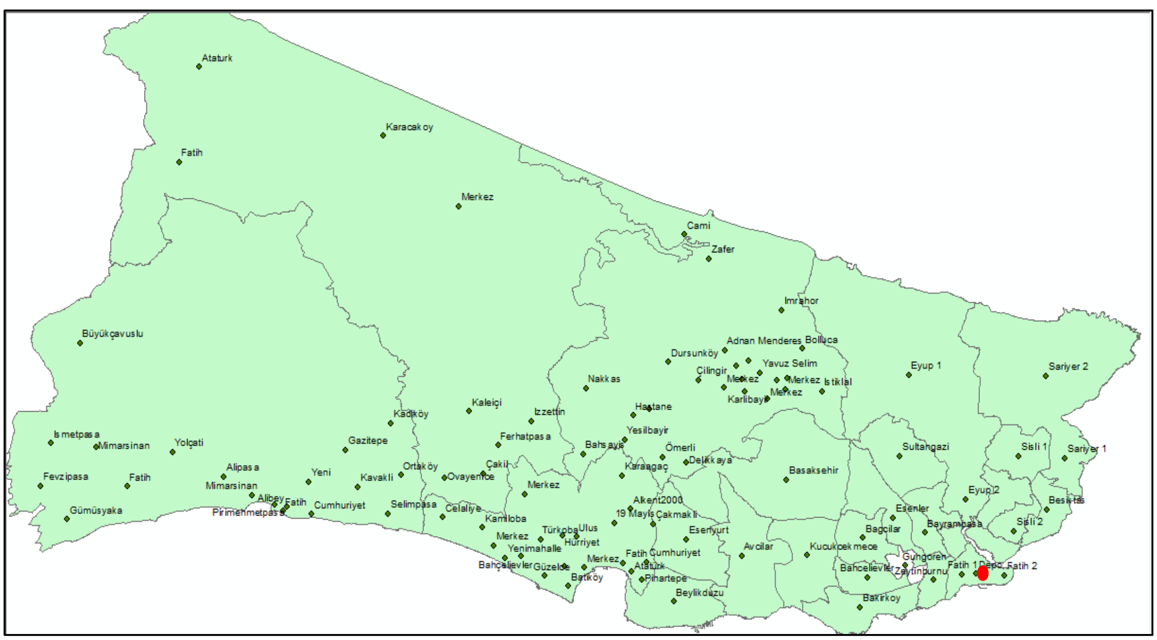


Figure 6-2 Potential points of Istanbul (Red point represents the depot)

After this aggregation, the distances between these districts are calculated via Geographical Information System software as an approximation of the actual road distances. Also, the populations are considered as the blood potentials of the districts.

As it is described in Chapter 5, the maximum length of a visit by a bloodmobile is determined as three days. We triplicate the original cost matrix with the cost function (*) as described in Chapter 5. At the end of this process, we have three new nodes for each original node. For node i in the original matrix, node i ,$i + |N|$, $i + 2|N|$ corresponds to original node, 2-day-stay-over node and 3-day-stay-over node respectively. Also, we need to define the blood potentials of these artificial nodes. We assume that, blood potential decreases as the bloodmobile continues to stay in a given node, with a pre-determined coefficient β. If a node's original blood potential is b_j, then second day's and third day's potentials are $b_j * \beta$ and $b_j * \beta^2$, respectively (**). In our calculations, we estimated the value of β as 0.8. We consider our planning horizon as seven days. We know that TRC Ankara has three bloodmobiles, and we conduct our experiments accordingly. Finally, all these computations are performed on an Intel Core i7 2.20GHz PC with 8 GB RAM. Gurobi version 5.0.0 is used to solve these models.

6.2. Base Case Analysis for Ankara and Istanbul Instances

With the data sets described in previous section we test the proposed system for Ankara and Istanbul cases and compare results with the current system. For both instances, we first solve the *MaxBlood* to calculate the maximum amount of blood that can be obtained in 7 days with 3 vehicles. After that, we feed the optimal solution of *MaxBlood* to *MinCost-B^*-Blood*, as B^* in constraint (15) to minimize the total logistics costs of collecting that amount.

Firstly, we focus on the Ankara instance since it is constructed based on real blood collection data. The optimal solutions and CPU times can be seen in Table 6.1.

Table 6-1 MaxBlood and MinCost-B-Blood results for Ankara*

	objective	cpu	node	iteration	shuttle dist	bloodmobile dist
MaxBlood	1420(units)	34 sec	0	27852		
MinCost-B^*-Blood	912.5 (km)	212 sec	410	63266	456.6 (km)	455.9 (km)

From 38 candidate stops the bloodmobiles choose to visit only 11 of them. At the end of the planning horizon bloodmobiles collect 1420 units of blood and traverse 912.5 km.s. If these points were visited with dedicated tours, as it is in the current system, the total distance travelled would be 1011 km.s. Thus, for Ankara case, it can be claimed that the proposed system performs better than the current system. The overall tours of bloodmobiles and the shuttle tours in different days are as in the Appendix 2.

Secondly, Istanbul case is analyzed for a future possible implementation. After an approximation of Istanbul network is constructed, we solve *MaxBlood* and *MinCost-B^*-Blood* for this instance as well. The results for 3 vehicles and 7 days are given in Table 6.2.

Table 6-2 MaxBlood and MinCost-B-Blood results for Istanbul*

	objective	cpu	node	iteration	shuttle dist	bloodmobile dist
MaxBlood	9004079(people)	207 sec	0	62551		
MinCost-B^*-Blood	446.613(km)	2083 sec	2228	138757	304.096(km)	142.517(km)

The bloodmobiles visit 9 of 96 candidate stops and reach 9004079 people whereas the vehicles travel for approximately 446 km.s. If bloodmobiles performed dedicated tours to visit these selected nodes, the total distance would be 661.6 km.s. Therefore, the proposed system yields a better solution for Istanbul case as well. The bloodmobile and shuttle tours for Istanbul instance are given in Appendix 3.

6.3 Depot Location Analysis

In order to further test the performance of the proposed models new instances are generated out of the original Ankara network as well. Random subsets with size 35, 30 and 25 (5 instances for each) are chosen, then *MaxBlood* and *MinCost-B***-Blood* solved on these instances. At first, these instances considered with the original depot but then, also for each instance, another random node is chosen as the depot. The objectives, solution times, and the proportion of the bloodmobile and the shuttle in the cost can be seen in Table 6.3. The instances in the left hand side are the original instances. The instances in the right hand side solved for the corresponding LHS instances with a random depot selection. The reason for performing such an analysis is to observe the effect of the depot location on solution times. There are different studies in the literature that conclude solving a VRP problem with a central depot is easier than one with an off-the-center depot instance. The locations of depots of corresponding random instances are shown in Appendix 4.

Contrary to the commonsense, smaller instances may require more time than larger ones on the average. Average time to solve the instances with 25 nodes is 99.4 seconds whereas the average for the instances with 30 nodes is 196.6.

Also, it can be seen from the table that when the depot is central, the bloodmobile and shuttle proportions of the total cost is comparable. On the other hand, the shuttle costs almost always (in all cases except for instance 28) outweigh the bloodmobile costs when the depot is chosen randomly, so that may not be central. The reason is that, the nodes with high potentials are chosen as definite stops, but this time, their distribution around the depot may not be homogenous. Since the shuttle performs daily tours between these distant points, the tour lengths of it increase. Also, it can be deduced from this table that solving the instances with random depot locations requires longer solution times. Again, it can be seen that CPU times of the instances in the right hand side are almost always longer (in all cases except for instances 28 and 30). Yet, these findings cannot be generalized and the performances of the models highly depend on the instances.

Table 6-3 Generated instance results of Ankara

		actual depot				random depot				
Size	ins	MinCost-B*-Blood	shuttle (%)	b.mobile (%)	cpu (sec)	ins	MinCost-B*-Blood	shuttle (%)	b.mobile (%)	cpu (sec)
35x35	ins 1	912.5	50.04	49.96	130	ins16	931.2	54.07	45.93	164
	ins 2	912.5	50.04	49.96	141	ins17	1341.5	54.95	45.05	1764
	ins 3	792.1	42.84	57.16	119	ins18	1095.1	55.79	44.21	8245
	ins 4	912.5	50.04	49.96	131	ins19	1017.8	53.53	46.47	824
	ins 5	972	54.66	45.34	121	ins20	1004	55.29	44.71	362
				AVG	128.4				AVG	2227.1
30x30	ins 6	1151.8	53.13	46.87	118	ins21	1056.5	55.95	44.05	219
	ins 7	1021	56.64	43.36	78	ins22	2120.4	59.55	40.45	300
	ins 8	538.3	48.58	51.42	98	ins23	632.5	52.71	47.29	2056
	ins 9	858.2	61.83	38.17	82	ins24	863.2	62.01	37.99	142
	ins 10	893.4	53.35	46.65	121	ins25	912.1	53.45	46.55	242
				AVG	99.4				AVG	591.8
25x25	ins 11	1015.9	55.72	44.28	57	ins26	1023.8	56.47	43.53	110
	ins 12	929.6	46.07	53.93	105	ins27	1071	50.85	49.15	203
	ins 13	1075.8	45.97	54.03	332	ins28	1094.5	44.98	55.02	245
	ins 14	980.3	50.67	49.33	204	ins29	993	51.03	48.97	232
	ins 15	1137.6	51.36	48.64	285	ins30	1147.8	51.71	48.29	149
				AVG	196.6				AVG	187.8

It can be stated that the location of the depot affects both the total logistics costs and the solution times significantly. This observation yields us another analysis on the depot locations of Ankara and Istanbul. The current locations of each depot might be chosen according to the population density and traffic load. However, there may be better alternatives that may yield decreased logistics costs. As a first alternative, for each point, we calculate the maximum distance to another point, say max_j, and then we choose the point with the minimum max_j value as depot. We also calculate the weighted distances for each point, and choose the one with the lowest value as the depot. For this calculation, the blood potentials (populations) are used as weights. For computational comparison purposes we also, choose a random depot location as another instance. The results of these settings for Ankara and Istanbul cases, the objective values and computational statistics can be seen in Tables 6.4. and 6.5, respectively.

Table 6-4 Depot location analysis results of Ankara

Ankara	obj(km)	cpu (sec)	node	itn ct	shuttle(km)	b.mobile(km)
actual ctr	912.5	212	410	63266	456.6	455.9
random ctr	1037.6	237	2838	145212	640.5	397.1
maxmin ctr	930.9	245	897	69520	474.9	456
weighted ctr	**907.1**	**151**	**363**	**42372**	**465.7**	**441.4**

Table 6-5 Depot location analysis results of Istanbul

Istanbul	obj (km)	cpu (sec)	node	itn ct	shuttle(km)	b.mobile(km)
actual ctr	446613	2083	2228	138757	304096	142517
random ctr	577611	3606	13537	793421	380835	196776
maxmin ctr	899509	5632	68625	3951977	598773	300736
weighted ctr	**391779**	**3234**	**1613**	**101761**	**272183**	**119596**

The best alternatives with respect to the logistics cost are marked in both tables. Expectedly, the best logistics cost for both Ankara and Istanbul are provided by the depot location that is closest to the center of mass of the network. Since, these selections are as close as possible to the points with high blood potentials these results are expected. Also, these results show that the current locations of depots are really chosen well because the objective values between the actual center and weighted center cases are not very high. The *maxmin* center of Istanbul performs even worse than a random selection of depot location because the population of the European side in Istanbul is very dense in the districts that are closer to the Bosphorus. As a result, solely focusing on the distances and neglecting the population may result in poor objective values. We also observe that the shuttle tours dominate the bloodmobiles tours.

With this analysis, we compare several depot location alternatives, in two very different metropolitan structures of Ankara and Istanbul. Ankara has a circular structure around a single geographical city center, and its population is more or less homogenously distributed. On the other hand, the geographical center and the population-center of the European side of the Istanbul are far from each other. The population is accumulated along the Bosphorus shore, which is almost at the boundary of the region. However, the weighted center performs very well in both instances. Yet, it can be suggested that an analysis on the metropolitan structure of the city under consideration must be conducted while deciding on the location of the depot.

6.4 Valid Inequalities

The performance of valid inequalities that are defined in Chapter 5 are tested with different depot alternatives in order to eliminate the effect of depot location. All three valid inequalities are added both individually and in all possible combinations to *MinCost-*B^**-Blood* to solve the Ankara (39 nodes) and Istanbul (97 nodes) instances with the actual, random and min-max depot locations. The results are given in Table 6.6 for Ankara and in Table 6.7 for Istanbul.

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Table 6-6 Valid inequality performances of Ankara instances with different depot locations

Ankara(39x39)	cpu(sec)	node	itn ct		cpu(sec)	node	itn ct
actual center				**maxmin center**			
MinCost-B*-Blood	212	410	63266	**MinCost-B*-Blood**	245 sec	897	69520
VI 1	***174***	***361***	***53721***	**VI 1**	209 sec	422	55972
VI 2	227	1074	77451	**VI 2**	202 sec	1247	65944
VI 3	217	532	63291	**VI 3**	247 sec	760	66329
VI 1 & VI 2	184	393	64705	**VI 1 &VI 2**	192 sec	159	42585
VI 1 & VI 3	186	433	63271	**VI 1 &VI 3**	***176 sec***	***266***	***47414***
VI 2 & VI 3	182	705	66720	**VI 2 & VI 3**	231 sec	1214	76065
VI 1 & VI 2 & VI 3	186	1082	88551	**VI 1 &VI 2 & VI 3**	197 sec	634	49953
random center				**weighted center**			
MinCost-B*-Blood	237	2838	145212	**MinCost-B*-Blood**	151	363	42372
VI 1	***232***	***2567***	***134985***	**VI 1**	218	315	44524
VI 2	380	4807	240119	**VI 2**	***142***	***439***	***45073***
VI 3	335	3358	173624	**VI 3**	212	613	66943
VI 1 & VI 2	415	4538	254072	**VI 1 & VI 2**	183	555	53638
VI 1 & VI 3	272	2445	136882	**VI 1 & VI 3**	194	878	62123
VI 2 & VI 3	373	5113	313165	**VI 2 & VI 3**	189	778	61446
VI 1 & VI 2 & VI 3	360	3482	200249	**VI 1 & VI 2 & VI 3**	227	331	54891

Table 6-7 Valid inequality performances of Istanbul case with different depot locations

Istanbul (97x97)	cpu	node	itn ct		cpu	node	itn ct
actual center				**maxmin center**			
MinCost-B*-Blood	2083 sec	2228	138757	**MinCost-B*-Blood**	5632 sec	68625	3951977
VI 1	3180 sec	1407	115689	**VI 1**	5270 sec	109666	4022727
VI 2	***2062 sec***	***2097***	***134682***	**VI 2**	6898 sec	197546	6980756
VI 3	2968 sec	1528	119483	**VI 3**	6246 sec	130692	5166434
VI 1 & VI 2	4648 sec	3223	190774	**VI 1 & VI 2**	6500 sec	143740	4984827
VI 1 & VI 3	3733 sec	5250	397130	**VI 1 & VI 3**	4137 sec	70392	3376800
VI 2 & VI 3	2277 sec	2982	145964	**VI 2 & VI 3**	3898 sec	63700	2466664
VI 1 & VI 2 & VI 3	2330 sec	1582	118492	**VI 1 & VI 2 & VI 3**	***3783 sec***	***71999***	***3895625***
random center				**weighted center**			
MinCost-B*-Blood	3606 sec	13537	793421	**MinCost-B*-Blood**	3234 sec	1613	101761
VI 1	3943 sec	17673	991983	**VI 1**	3357 sec	1663	125626
VI 2	***3325 sec***	***8962***	***532142***	**VI 2**	2784 sec	1970	151242
VI 3	5087 sec	15954	941116	**VI 3**	2875 sec	1959	142023
VI 1 & VI 2	6196 sec	10763	522922	**VI 1 & VI 2**	4260 sec	4966	288313
VI 1 & VI 3	5704 sec	11715	604073	**VI 1 & VI 3**	***2507 sec***	***1848***	***139581***
VI 2 & VI 3	7188 sec	24549	1364994	**VI 2 & VI 3**	5244 sec	3498	261758
VI 1 & VI 2 & VI 3	4735 sec	9530	510820	**VI 1 & VI 2 & VI 3**	3389 sec	2255	137153

VI 1, VI 2, VI 3 corresponds to the inequality sets (22), (23), (24) that are defined in Chapter 5, respectively. Valid inequality combinations with the best computational times are underlined for all data sets. As it can be seen from these tables, valid inequalities do not perform consistently in terms of computational times. However, in all six instances there exists at least one inequality combination that outperforms the original IP. Therefore, we use all three inequalities in our further analysis.

6.5 Pareto Optimum Analysis of the Original Ankara and Istanbul Cases

Our problem is based on two different objectives: maximizing the amount of collected blood and minimizing the logistics cost of collection. Therefore, the interaction between these two objectives is of interest. Also, such an analysis allows the decision makers in TRC to perform a posteriori deductions. For this reason, the efficient frontier of these two objectives is generated for both the Ankara and Istanbul instances.

For the Ankara case, we decrease the percentage of blood collected with increments of 10, where 100 percent corresponds the objective of *MaxBlood.* The we solve *MinCost-*B^**-Blood* with corresponding blood levels. For Istanbul, we manage to obtain some of the points on the efficient frontier. However, problems corresponding to some of the points were not possible to solve with this methodology. For this reason, we switched constraint 16 and the objective function, so that the model finds the best possible amount of blood with a given level of logistics cost. In both cases, one extremum is defined by the original solution of the problem (cost of collecting maximum amount of blood) and the second one is basically set to zero units of blood and zero cost. Figures 6.3 and 6.4 represent the efficient frontiers of Ankara and Istanbul instances, respectively.

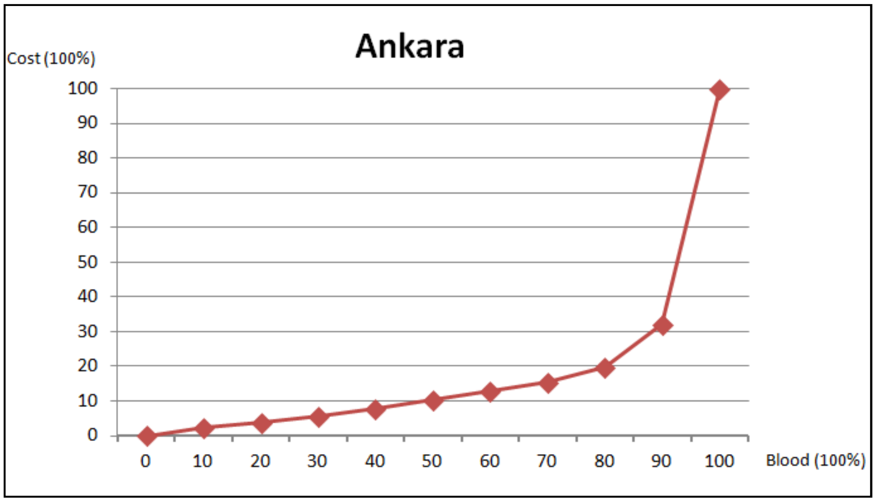

Figure 6-3 Pareto Optimum Curve of Ankara Case

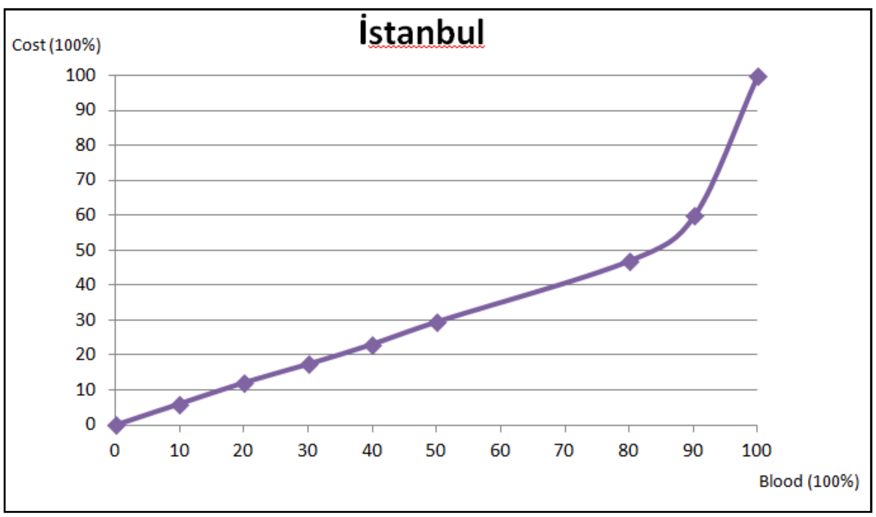

Figure 6-4 Pareto Optimum Curve of Istanbul Case

These two figures show that, if TRC settles for 10% less of the maximum possible blood, they save on logistics costs significantly. The decrease in Ankara case is steeper than the Istanbul case, which can be explained by the location of the depot and the more intense distribution of high blood potential nodes around the depot.

6.6 Sensitivity Analysis on Problem Parameters

Finally, we conduct a sensitivity analysis on two parameters of our problem, which are the number vehicles and the constant β. TRC Ankara has three bloodmobiles currently. Thus, the analysis is conducted for number of 2, 3, 4 and 5 bloodmobiles. The blood constant β, is determined empirically. Thus, in order to model different donor behaviors or reducing estimation biases, we also change the value of β between 0 and 1 in increments of 0.2. By changing, these values we observe the trends on the objectives as well as the number of nodes that are visited for longer than one day. In Table 6.8, the objective function values, number of nodes with 'long' visits and computational times are summarized. The table also shows the percentage marginal increment in both objectives with the change of problem parameters.

Both objectives increase when the number of vehicles increases or when β increases. This is an expected result. On the other hand, the marginal increments of blood are not as large as the cost increments. In other words, the increase in cost is much higher than that in blood. These statistics show that introducing a new bloodmobile to the system may not be easily justified. In particular, when the distance traversed per blood unit (shown in the rightmost column) is considered, 5 vehicles are not justified for β values of 0.2, 0.6, 0.8 and 1 and also in almost all cases 3 vehicles yield very efficient results.

Table 6-8 Sensitivity Analysis Results on Problem Parameters

alpha	# veh	MaxBlood	marg. Inc(%)	MinCost	marg. Inc(%)	# nodes stayed in 2 days	# nodes stayed in 3 days	CPU of MinCost in sec(gap %)	dist/ blood
0.2	2	871	0.00	775.6	0.00	0	0	347	0.89
	3	1114	27.90	1138.7	46.82	1	0	2127	1.02
	4	1289	47.99	1320	70.19	1	0	36000 (5.86%)	1.02
	5	1419	62.92	1663.6	114.49	2	0	36000 (21.32%)	1.17
0.4	2	905	0.00	745	0.00	1	0	300	0.82
	3	1151	27.18	1138.7	52.85	1	0	2436	0.99
	4	1348	48.95	1355.7	81.97	3	1	36000 (4.39%)	1.01
	5	1509	66.74	1399.7	87.88	5	1	36000 (6.92%)	0.93
0.6	2	976	0.00	804.1	0.00	1	1	183	0.82
	3	1253	28.38	855.8	6.43	3	1	894	0.68
	4	1483	51.95	1220.5	51.78	6	1	7947	0.82
	5	1679	72.03	1551.1	92.90	8	3	16711	0.92
0.8	2	1107	0.00	658.2	0.00	2	2	199	0.59
	3	1420	28.27	912.5	38.64	2	4	136	0.64
	4	1698	53.39	1056.1	60.45	3	5	1091	0.62
	5	1945	75.70	1508.5	129.19	4	7	8545	0.78
1	2	1316	0.00	556.1	0.00	0	4	60	0.42
	3	1690	28.42	714.8	28.54	0	6	132	0.42
	4	2025	53.88	1152.5	107.25	0	8	335	0.57
	5	2322	76.44	1209.4	117.48	0	10	503	0.52

When the β value is 1, the bloodmobiles always choose to perform 3-day stay overs when applicable since the blood potential of a node never decreases during a visit. As a result, the nodes with high potentials are visited until the end of the permissible stay-over length, which is 3 days in our calculations. As the β value decreases, the length of the visits gets shorter because visiting a new node becomes more advantageous than waiting in the current node in terms of the available blood potential . When the β value reaches 0.2, bloodmobiles do not wait at any of the nodes for three days. This situation may also explain the long computational times of instances with lower than β values. The problem becomes more difficult to solve when most of the stay over options offer comparable blood potentials with other unvisited nodes, as β decreases. The change in the number of nodes that are visited for 2 and 3 days are represented in Figure 6-5, 6-6, 6-7 and 6-8 for number of vehicles two, three, four, and five respectively.

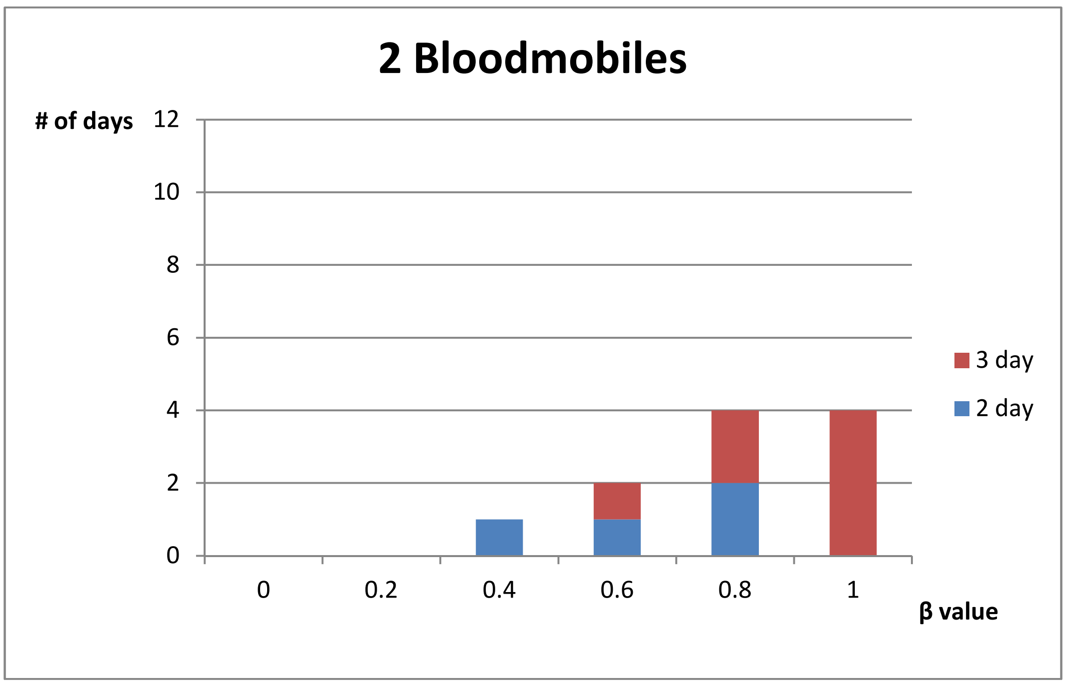

Figure 6-5 Number of nodes visited for 2 and 3 days with number of b.mobiles 2

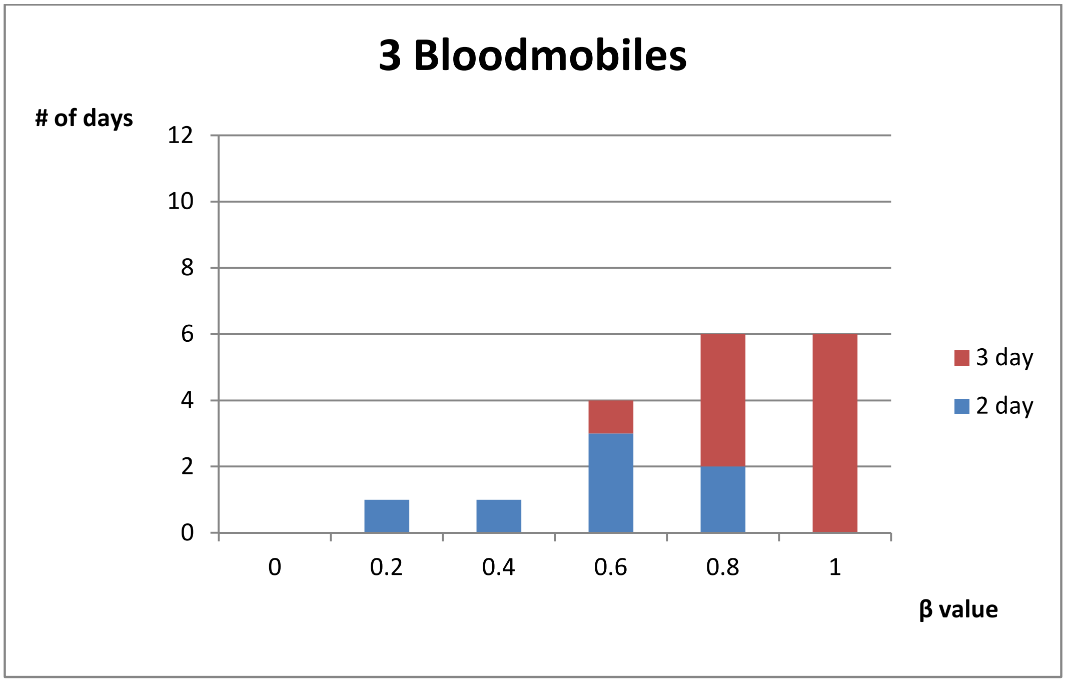

Figure 6-6 Number of nodes visited for 2 and 3 days with number of b.mobiles 3

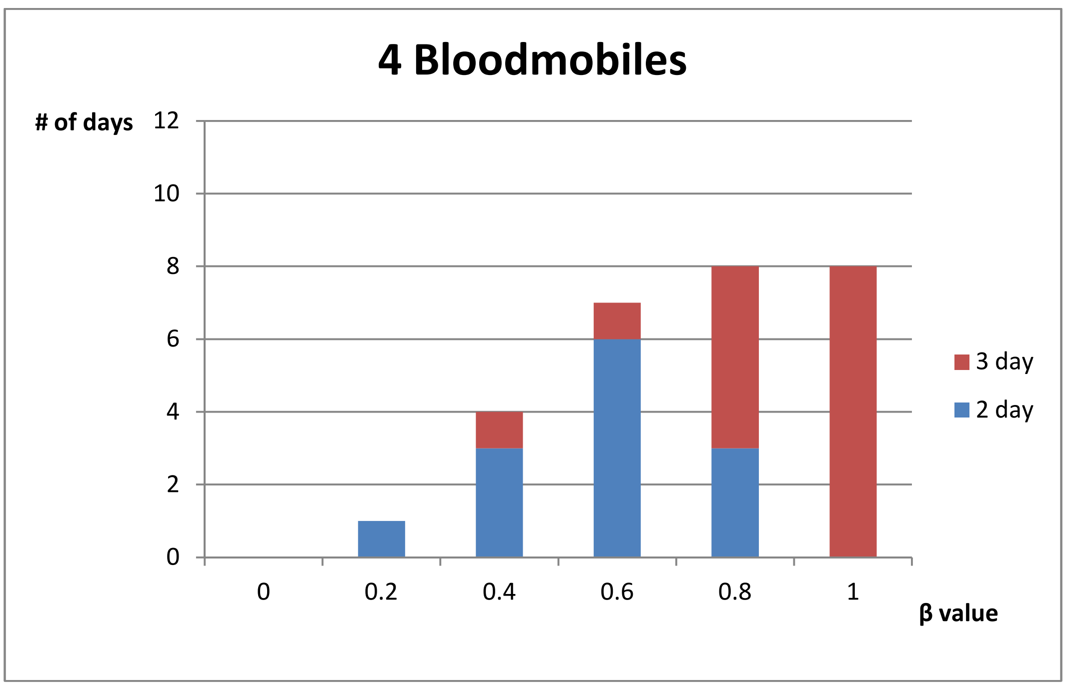

Figure 6-7 Number of nodes visited for 2 and 3 days with number of b.mobiles 4

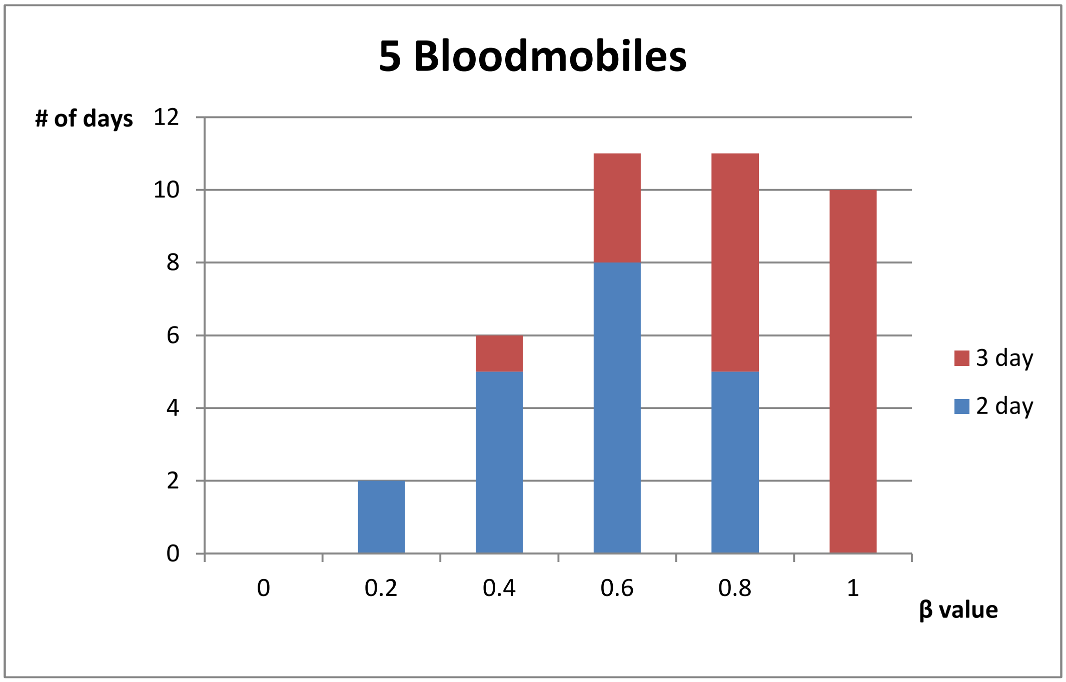

Figure 6-8 Number of nodes visited for 2 and 3 days with number of b.mobiles 5

The stay-over behavior when β increases, is independent of the number of vehicles. In all three alternatives of vehicle count, the number of nodes that are visited for 2 days first increases, and then then drops to 0. Similarly, 3 day stay overs start with 0 and increases until β reaches to 1, for the cases with 2, 3, 4 and 5 vehicles.

To sum up, both the number of bloodmobiles and the β value have significant effects on the objectives. However, increasing the bloodmobiles may not always increase the efficiency of the system as explained before. On the other hand, if β can be controlled, the amount of blood collected can significantly increase. To maintain a higher β value may not be as difficult as it seems. Increasing public's attention to the activity may yield high blood potentials on the second, even the third day of activity. The tours need to be determined long before the collection activity to leave enough time for the announcement of the activity. The target population should be informed about the starting date and the length of the collection activity beforehand, so that they can arrange their schedules accordingly.

Chapter 7

2 Stage IP-based Heuristic Algorithm

Since our problem is defined on a time expanded network and it contains typical VRP-TSP constraints, as the number of potential points or the stay-over period grows, the underlying network gets larger. Especially, the stay-over period markedly affects the number of nodes in the network. Hence, for such instances (with long stay-over periods or many potential points) computational time may be significantly long. This is not a desirable case for decision makers in TRC, since the proposed planning period is 7 days.

With these considerations in mind, we design a 2-stage IP based heuristic approach which yields shorter computational time to obtain good solutions with small optimality gaps.

The proposed heuristic can be summarized in three steps as follows:

1. First we solve model *MaxBlood* to determine the maximum amount of blood that can be obtained from the given instance (B^*). If the decision maker has an a priori knowledge of the blood amount to be collected, this stage can be omitted.

2. Next, we plug in the optimal value of *MaxBlood* (B^*) into the following mathematical model (*NodeSelection*). We solve this mathematical model on the extended network, where the original nodes and the copy ones are treated as individual nodes. The parameters of this model are as defined Chapter 5.

Decision variable:

$$x_i = \begin{cases} 1, if\ node\ i \in N'\ is\ worth\ to\ visit\ by\ a\ bloodmobile, \\ 0, \qquad o.w. \end{cases}$$

<u>*NodeSelection*</u>:

$$\text{minimize} \sum_i x_i c_{1i} \tag{O3}$$

$subject\ to$

$$\sum_{i \in N'} b_i x_i \geq B^* \tag{25}$$

$$\sum_{i \in N'} x_i \leq md \tag{26}$$

$$x_i \in \{0,1\} \qquad \forall i \in N' \tag{27}$$

This mathematical model is developed in order to find out the nodes that the bloodmobiles will visit in order to collect the desired amount of blood. Constraint (25) ensures that the visited nodes have enough blood potential to satisfy the blood need. Constraint (26) enables the chosen nodes to fit in the planning horizon. Binary restrictions on decision variable are given in constraint set (27). Finally, the objective function chooses the nodes that are closer to the depot among the eligible candidates. We develop the objective function in this way because the shuttle tours are performed every day, and so close nodes to the depot may yield shorter shuttle tours.

3. Then we feed only the nodes that are obtained in step 2 and their copies for the stay overs into *MinCost-B***-Blood*. With this approach, the model has to handle a significantly smaller network. For instance for *m* collectors and a *d*-day planning period, the model in step 2 (*NodeSelection*) can result in at most *m* x *d* nodes. Considering the original nodes and their copies, the upper bound on the network size of *MinCost-B***-Blood* is *3m* x *d* with this new approach, whatever the original network is.

NodeSelection consists of two constraints other that binary restrictions and |N'| = n' decision variables. We can conclude that this IP is easier than *MinCost-B***-Blood*, since *NodeSelection* has a very similar structure to the knapsack problem whereas *MinCost-B***-Blood* has a complicated routing problem structure. Also, in step 3 we solve *MinCost-B***-Blood* on a considerably smaller network. Therefore, this IP-based heuristic approach seems more advantageous than solving *MinCost-B***-Blood* on the extended network.

Ankara and Istanbul's original instances and the random instances are used to test the performance of the two stage IP-based heuristic algorithm. Since, the Istanbul instances are larger, heuristic procedure is also applied to the Istanbul instances with different depot locations. Results of heuristic applications for Ankara and Istanbul can be seen in Tables 7.1 and 7.2, respectively.

Table 7-1 Heuristic Algorithm results for Ankara instances

	exact		heuristic			
	objective	cpu	objective	Stg 1	Stg 2	gap
actual ctr	912.5	212 sec	912.5	< 1 sec	10 sec	0%
random ctr	930.9	245 sec	930.9	< 1 sec	11 sec	0%
maxmin ctr	1037.6	237 sec	1037.6	< 1 sec	64 sec	0%
weighted ctr	907.1	151 sec	907.1	< 1 sec	67 sec	0%

Table 7-2 Heuristic Algorithm results for Istanbul instances

	exact		heuristic			
	objective	cpu	objective	Stg 1	Stg 2	gap
actual ctr	446613	2083 sec	446613	< 1 sec	9 sec	0%
random ctr	899509	5632 sec	899509	< 1 sec	113 sec	0%
maxmin ctr	577611	3606 sec	577611	< 1 sec	31 sec	0%
weighted ctr	391779	3234 sec	391779	< 1 sec	6 sec	0%

In these tables, Stg 1 and Stg 2 corresponds the CPU times of *NodeSelection* and *MinCost-*B^**-Blood* model with selected nodes chosen by *NodeSelection* as input, respectively. It can be seen from these tables that, this 2-Stage Algorithm reduces the computational times significantly without losing the optimality. All of the instances are solved optimally, using this approach. It is an expected result because the optimal solution of *MaxBlood* is give as $B*$ to the node selection algorithm and the subset of potential points that yields the maximum amount of blood that can be collected may be very few and even sometimes unique. Therefore, the *NodeSelection* chooses those nodes and when we feed those nodes to *MinCost-*B^**-Blood* we obtain the same results very quickly this time. Yet, since this is an IP-based heuristic, its computational performance might be worse for much larger instances. However, we always know that the maximum size of the input matrix of Stage 2 will be at most mdt, where m, d and t corresponds to the number of bloodmobiles, the length of the planning horizon and maximum allowed length of a stayover, respectively.

Chapter 8

Conclusion & Future Research Directions

Mobile blood collection systems yield dramatic improvements on countries' blood collection processes if applied efficiently. Turkey needs an effective, well-planned blood supply chain, since it suffered many earthquakes in the past and will be in the future. In this research, we focused on the problem of designing a new bloodmobile system for TRC, which is cost efficient and easy-to-implement.

In the current mobile blood collection system of TRC, bloodmobiles perform independent direct tours between the depot and certain activities such as fairs, fests and company blood donation campaigns. Other than that, they usually serve as a fixed point. Even for the activities that last longer than one day, they travel to the donation point at the beginning of the day and return to the depot in the evening to prevent the blood perishing. There are two main problems about this approach. Firstly, the bloodmobiles perform redundant tours for the activities that lasts longer than one day or for the donation points which are very close to each other. As a result, a second problem occurs: the bloodmobiles only visit the points which have a very high expected blood potential in order to keep logistics costs low.

As it is explained in Chapter 4, the proposed system consists of original bloodmobiles in addition to a shuttle. With the implementation of this new system, bloodmobiles do not need to come back to the depot to bring the blood, but instead, the shuttle visits the bloodmobiles on-the-roads and transports the collected blood to the analysis center. The healthcare, blood logistics and selective vehicle routing literature is explored. However no study that covers all the aspects of the described problem is encountered. As a result, the selective vehicle routing approach is extended to consider the shuttle tours as well and a new problem named as the Selective VRP with Integrated Tours is introduced to the literature.

A mathematical model, *Mincost-*B^**-Blood,* is described in Chapter 5 with size of variables $O(n^2d)$, where n and d corresponds to number of nodes in the network and the length of the planning horizon respectively. This model, minimizes the logistics cost that is paid to collect a pre-defined blood level of B^* and decides on the stops and stop-lengths of bloodmobiles and the tours of shuttles and bloodmobiles. B^* can be determined by decision makers according to the inventory level of blood, or they can choose to collect the maximum amount of blood possible with respect to the number of vehicle and planning horizon length. To obtain the maximum amount of blood for a given network and parameters, another mixed integer program, *MaxBlood,* was built. Also, three different valid inequalities are defined to improve the computational performance of *Mincost-*B^**-Blood* in Chapter 5.

In Chapter 6, the data sets that are used to test the performance of developed models are explained. Ankara instance is constructed based on the past blood collection data of TRC, whereas Istanbul instance is created using the centers and populations of the European part of the city. First, *MaxBlood* is solved for these two instances, then the results are fed to *Mincost-B***-Blood.* The optimal solutions showed that the proposed system results in better logistics costs than the current one in both cities. Also, an analysis on depot location is performed, alternative depot locations are suggested and the total logistics costs are compared with the original depot locations. We observed that the best logistics costs is be achieved if the depot is located to the point which minimizes the weighted distances to other nodes. Performances of the valid inequalities defined in Chapter 5 are tested as well. However, the performances of these inequalities are not consistent. In addition, we constructed the Pareto Efficient curves of both instances to see the interaction between the two major objectives under consideration: maximization of the collected blood and minimization of the total logistics costs. We observed that if TRC settles for the 90% of the maximum amount of blood, they can increase the logistic expenses dramatically. Finally, sensitivity analysis conducted on the number of vehicles and the value of the blood potential estimation parameter β. We concluded that increasing the number of bloodmobiles is not effective for most of the cases. We can also suggest that maintaining high β values yields very high blood collection amounts. In order to do so, TRC may need to make early announcements of the date and duration of blood collection activities.

The performance of *Mincost-B***-Blood* is satisfactory for the data sets in hand. However, for larger instances, it is not very promising in terms of computational requirements. Therefore, a 2-stage heuristic algorithm is developed to handle this issue. The main motivation behind the algorithm is to put an upper bound on the network size which is fed to the *Mincost-B***-Blood* model. Thus, we develop another integer program *NodeSelection*, which determines the nodes that have blood potential greater than or equal to B^* and that can be visited in the planning horizon by the bloodmobiles. The *NodeSelection* chooses the points according to their distances to the depot then, only the points that are selected by *NodeSelection* are fed to *MinCost-*B^**-Blood.* This approach guarantees that, the input network of *MinCost-*B^**-Blood* could have at most *mdt* nodes, when the number of bloodmobiles are *m*, the length of planning horizon is *d* and the maximum stay-over-length is *t*. The approach resulted with significant decreases of computational times. All instances are solved optimally and computational times reduced significantly with the use of this approach.

Within the scope of this study, we proposed an efficient way for increasing blood donations in Turkey. To this end, we focused on the mobile blood collection vehicles and designed a new bloodmobile system. We showed that attaining high collection levels is possible with relatively low logistics costs. Also, we introduced a new problem to the literature and tested it on several instances to obtain managerial insights for the decision making process of TRC. Finally, for larger instances we designed an IP-based heuristic algorithm.

As a future direction, one can investigate possible alternative application areas for SVRPwIT. For instance, carrying medical supplements such as serum, antibiotics to mobile healthcare facilities which are described in Hodgson et al. is a possible application since those kind of supplements need to be carried and stored in cold-chains and the technology available in mobile healthcare facilities may not be sufficient to keep those items fresh for days or they may need replenishment. Similarly, a shuttle can collect the blood or urine samples from the mobile healthcare vehicles for testing.

Besides the practical future applications, one can also develop a meta-heuristic for SVRPwIT tours even though generating a feasible solution or defining neighborhoods is much more complicated than the classical SVRP problems. Also, it is possible to define valid inequalities other than that are developed in this study. Finally, since SVRPwIT is a new problem performing the polyhedral analysis of this concept may also be a fruitful avenue of further research.

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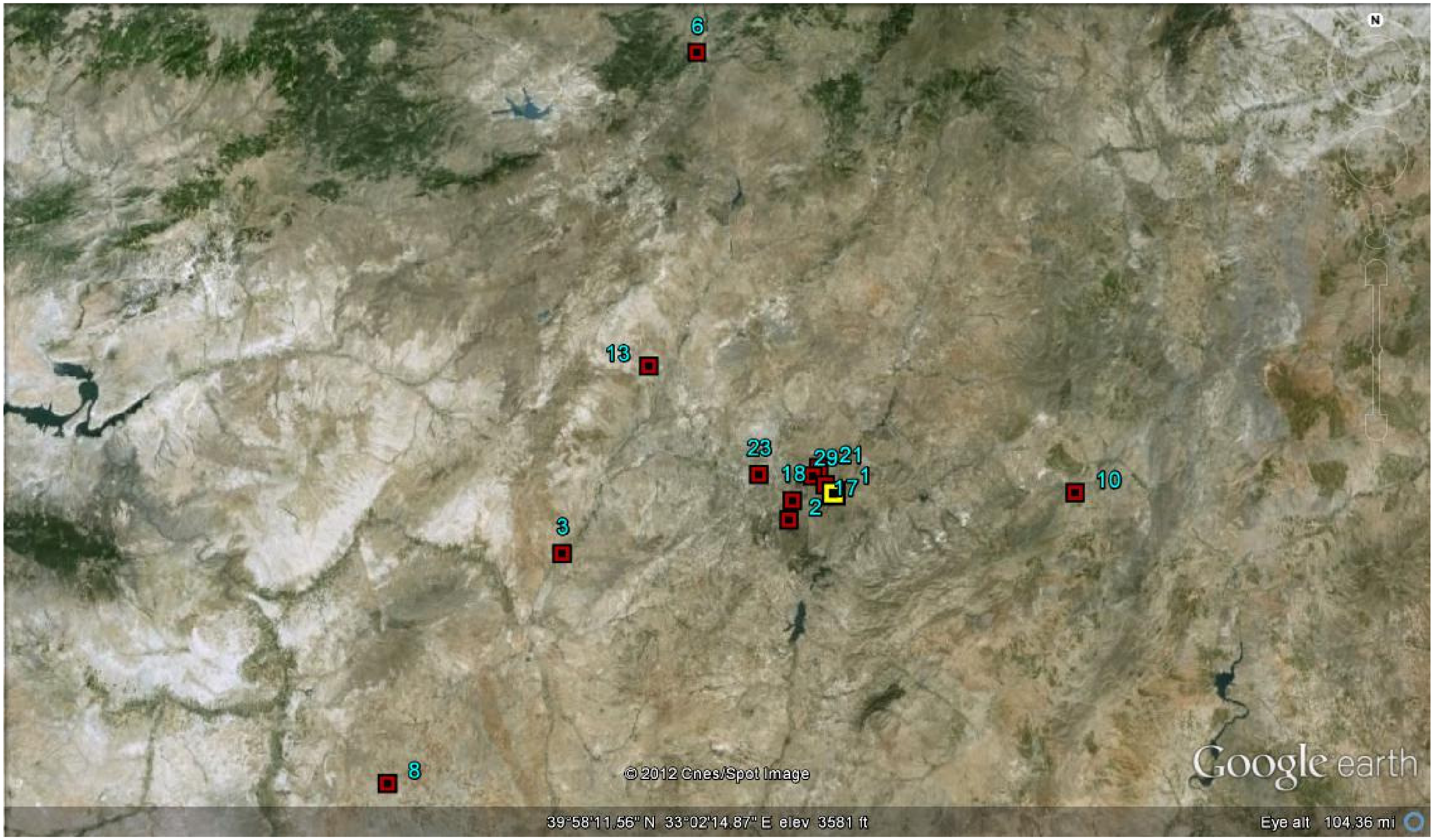
APPENDICES

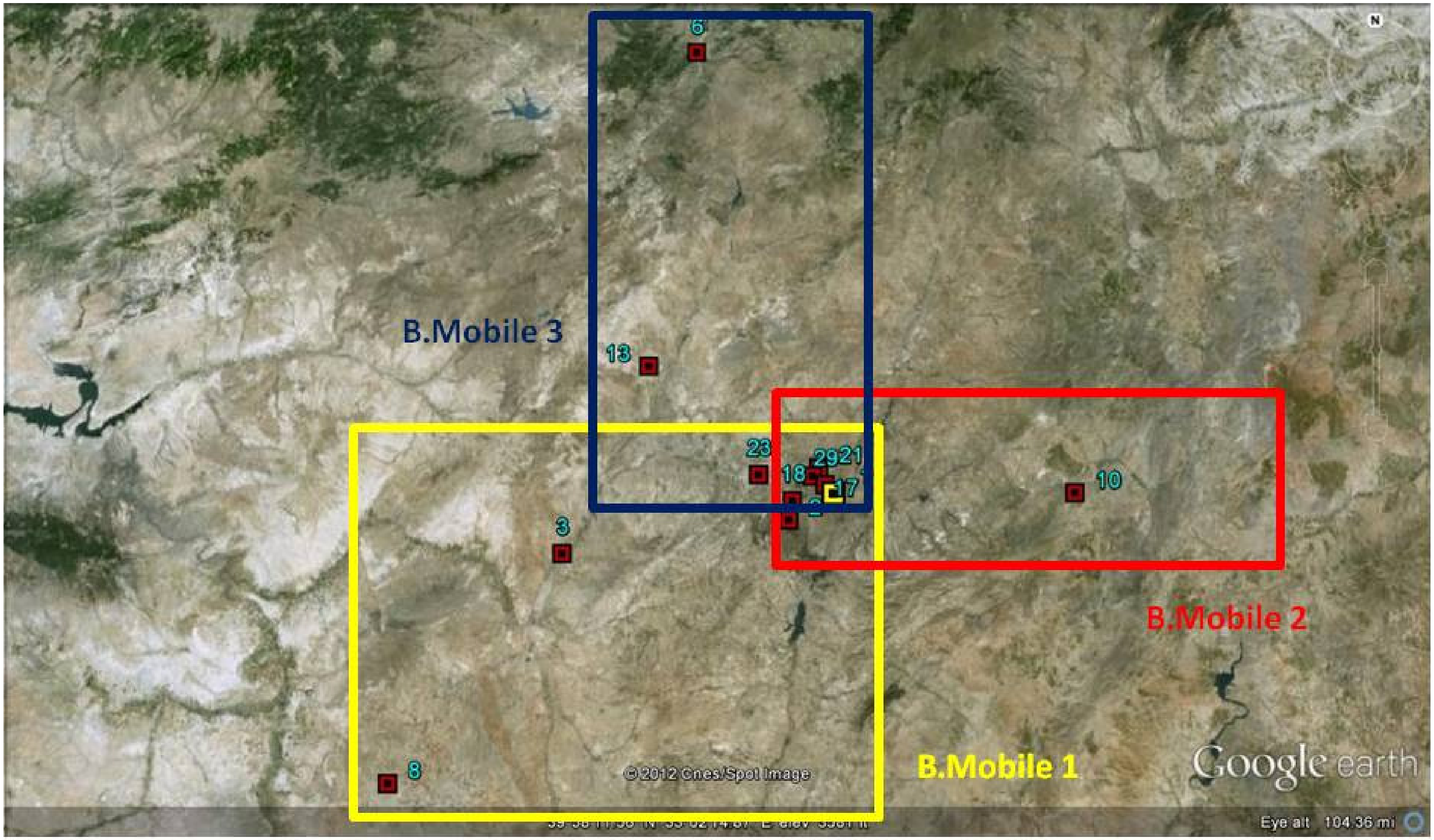
Appendix 1 Potential Stops, Blood Potentials and the Distance Matrix of Ankara Instance

Blood Potential	Node	Point	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
0	0	Kızılay (Depot)	0	10.7	27.3	7.5	37.4	69.6	75.2	75.3	86.3	41.5	3.3	77.8	48	3	6.7	26.5	4.3	6.3	41.5	3.3	4.1	17.9	15.8	4.6	2.5	8.3	14.1	6.7	8.1	3	19	12.3	7.7	28.6	26.6	29.9	15.8	6.5	27.2
186	1	ODTÜ	9.1	0	21.8	13.8	44.6	66.2	78.5	69.6	80.8	48.2	8	77.5	44.6	11.4	10.9	33.1	12.5	6.9	48.2	9.9	12.5	21.3	16.4	9.2	9.7	12.5	14.9	10.4	15.2	7.2	13.5	6.6	8.8	23.1	21.1	26.5	22.2	9.9	21.8
66	2	Sincan	28.2	20.6	0	27	52.7	57.1	95.5	69.7	59.7	65.8	28.6	92.5	22.9	25.2	24	52.6	25	23.3	65.8	29.2	24.2	38.2	13.6	25.7	27	32.2	15.4	23.4	29.7	27.8	8.5	23.1	22	1.3	1	18.7	38.7	30.5	2.8
24	3	A.Eğlence Merkez Camii	6.8	12.8	26.9	0	36.8	67.4	80.1	79	86.3	45.4	8.5	82.7	45.7	6.3	4.8	30.4	5.2	10	45.4	7	4.5	22.7	13.9	10.4	5.7	12.4	11.4	4.8	4.8	8.6	20.3	16	5.8	27.8	26.7	27.7	14.1	12.1	27.4
25	4	Akyurt İlçesi	37.6	43.9	56	36.7	0	91.5	109	111.8	115.7	44.5	39.7	114.2	69.8	38.3	38.7	33.5	37.2	42	44.5	38.5	36.5	54.3	47.3	42.2	36.5	45.7	44.8	38.7	31.2	39.4	53.7	48	40.7	57.3	57	51.8	22.8	42.9	58.8
52	5	Kızılcahamam	72	68.8	56.4	69.4	94.8	0	139.1	118	31.6	108.2	72.7	141	39.9	68.5	66.6	96.2	67.4	66	108.2	73.1	66.6	81.8	56.3	69.7	70.5	75.8	58.2	66.1	72.5	72	56.7	71.3	64.5	57.7	56.2	41.7	72.7	74.1	56.8
34	6	Bala	76.1	74.9	95.7	81.3	101.8	140.4	0	137.7	154.6	64.4	74.9	86	118.6	75.7	79.4	79.4	76.8	74.2	67.4	76.8	76.8	58.7	85.9	71.8	76.2	70.6	84.4	79.4	81.8	74.2	87.3	80.1	80.4	96.9	94.9	100.7	89.5	68.8	95.6
44	7	58.Topçu Tugayı	77.2	68.1	72.2	80.9	112.3	119	138	0	93.2	116.3	75.6	58.6	95.1	75.3	79	101.2	76.4	70.8	116.3	77.9	76.4	80.2	75.3	73.1	77.3	80.6	77.1	78.5	81.3	75.3	69	70.5	76.9	72.9	70.9	80.9	90.3	78	71.6
21	8	Güdül	85.8	78.2	57.6	84.6	110.3	31.6	153.1	94	0	123.4	86.2	128	52.1	82.8	81.6	110.2	82.6	80.9	123.4	86.8	81.8	95.8	71.2	83.3	84.6	89.8	73	81	87.3	85.4	66.1	80.7	79.6	58.9	58.6	71.7	96.3	88.1	60.4
77	9	Elmadağ	40	50.7	66.7	43.6	37.4	108.1	67.9	115.3	126	0	41.6	117.1	86.5	42.9	45.1	15.1	44	46.3	3	37.5	42.8	55.4	54	44.6	39.4	44.3	52.5	45.1	45	43	58.9	52.3	46.2	67.5	66.4	68.4	45.3	46.5	67.1
31	10	Kocatepe Camii	1.8	12.5	28.6	8	37	71.4	75.5	76.7	87.5	41.3	0	78.1	49.8	4.8	8.5	26.3	6.1	7.3	41.3	3	5.9	18.2	17.3	5.6	2.8	5.9	15.9	8.5	8.4	1.4	20.2	13.3	9.5	29.8	27.8	31.7	16	6.8	28.5
35	11	Haymana	79.1	83.4	94.5	84	114.1	141	84.6	51.7	126	118.2	77.9	0	117.4	78.7	82.4	103.1	79.8	77.2	118.2	79.8	79.8	63.3	89.3	74.8	79.2	73.6	87.9	82.4	84.8	77.2	90.6	83.6	83.9	95.2	93.2	103	92.5	71.8	93.8
45	12	4.Ana jet üst komutanlığı	46.9	39.3	18.7	45.6	71.1	40.1	114.2	88.4	52	84.5	47.3	111.2	0	43.9	42.7	71.3	43.7	42	84.5	47.9	42.9	56.9	32.3	44.4	45.7	50.9	34.1	42.1	48.4	46.5	27.2	41.8	40.7	20	19.7	19.6	49.4	49.2	21.5
23	13	Hacettepe Konservatuar	6.3	10.4	24.4	7.5	38.5	68.5	74.7	73.6	83.3	44.5	5.6	77.3	46.9	0	5.6	30	3	4.6	44.5	6.6	2.9	17.3	15	5	5.1	10.1	13	5.6	8.8	5.6	16	10.6	6.6	25.6	23.6	28.8	16.9	9.7	24.3
17	14	Gazi Fişek Fabrikası	6.4	13.7	24	5.1	37.3	65	78.1	77.3	83.4	44.2	7.1	80.6	43.4	4.3	0	30.8	3.2	8	44.2	7.4	2.6	20.7	11.4	8.3	5.2	12	9.9	2.8	7.7	8.1	17.4	13.9	4.9	24.9	23.8	25.3	15.6	12.9	24.5
23	15	Lalahan	26.5	37.2	53.3	30.1	40.7	94.7	77	101.8	112.6	16.7	28.1	102	73.1	29.5	31.7	0	30.6	32.8	16.7	24	29.4	41.9	40.6	31.1	26	30.8	39.1	31.7	31.6	29.5	45.5	38.8	32.8	54.1	53	55	31.8	33	53.7
45	16	Gazi Ü. Eğt.Fklt.	5.5	11.4	25.4	7.1	38.1	66	75.7	74.6	84.4	44.1	5.5	78.3	44.4	1.9	5.2	29.1	0	5.7	44.1	5.7	2.6	18.4	12	6	4.3	10.2	10.5	5.2	8.4	5.7	17.1	11.6	5.6	26.7	24.7	26.4	16.5	10.8	25.3
51	17	TPAO	7.8	6.7	22.1	11.5	42.6	66.2	73.1	69.9	81.1	47	6.7	75.7	44.6	5.9	9.6	31.9	7	0	47	8.6	7	15.8	12.6	3.7	8	9.8	11.1	9.6	12.8	6	13.8	6.9	9.3	23.4	21.4	26.5	20.9	8.1	22.1
21	18	Elmadağ Deniz Kuvt.leri	40	50.7	66.7	43.6	37.4	108.1	67.9	115.3	126	3	41.6	117.1	86.5	42.9	45.1	15.1	44	46.3	0	37.5	42.8	55.4	54	44.6	39.4	44.3	52.5	45.1	45	43	58.9	52.3	46.2	67.5	66.4	68.4	45.3	46.5	67.1
13	19	Deniz İkmal Grp.Kmtn.lğ	3.6	14.3	30.1	7.3	37.1	71.3	78.8	78.9	89	38.4	5.2	81.4	49.7	5.7	8.4	23.4	6.7	9.9	38.4	0	5.8	21.5	17.6	7.8	3.1	10.6	15.8	8.4	7.9	5.6	21.7	15.9	9.4	31.1	29.3	31.6	15.5	10.1	30
59	20	Ankamall	5.7	13.6	25.2	5.6	37.4	66.1	77.9	76.8	84.5	41.6	7	80.5	44.5	4.1	3.3	30.3	3.1	7.8	41.6	6.9	0	20.5	12.5	8.2	4.7	11.3	10.7	3.3	7.7	7.6	18.5	13.8	4.3	26	24.9	26.4	15.8	11.1	25.6
9	21	TPAO Gölbaşı	17.6	21.5	37	22.8	52.6	81.9	61.1	81.2	95.9	56.7	16.4	63.1	59.9	17.2	20.9	41.6	18.3	15.7	56.7	18.3	18.3	0	27.4	13.3	17.7	12.1	25.9	20.9	23.3	15.7	28.6	21.7	21.9	38.2	36.2	42.2	31	10.3	36.9
54	22	İstikbal Yön Mağazacılık	15.9	16.1	14	13.4	47.4	55.1	84.3	75.4	73.4	53.4	17.3	86.9	33.5	13.7	10.4	40.2	12.7	11.2	53.4	16.8	11.8	27	0	14.8	14.6	21	2.5	9.8	16.8	17.1	7.4	15.8	8.4	14.9	13.8	15.4	25.1	19.3	14.5
21	23	Aviva-SA	6.1	8.6	24.1	10	41	68.6	73.2	71.8	83	45.2	4.9	75.7	46.9	4.3	8.1	30.1	5.5	2.9	45.2	6.8	5.4	15.8	14.5	0	6.7	7.6	13.1	8.1	11.2	4.2	15.8	8.8	9.1	25.3	23.3	28.9	19.4	5.9	24
1	24	Ankara İl Müftülüğü	2.9	11.3	27.3	5.3	35	68.7	76.9	77.1	86.6	40.7	4.1	79.5	47.1	3.5	5.7	25.7	4.6	8.1	40.7	3.2	3.4	19.6	14.6	6.2	0	8.5	13.1	5.7	5.6	4.7	19.5	14	6.8	28.1	27	29	13.3	8.2	27.7
24	25	Yıldız Orta Camii	8	15.9	32	13.1	42.9	76.4	71	80.2	90.9	46.9	6.6	73.6	54.8	9.1	13.6	31.8	10.4	10.7	46.9	8.5	11	13.7	22.4	8.4	7.9	0	20.9	13.6	13.4	5.9	23.6	16.7	14.7	33.2	31.2	36.8	21.2	2.6	31.9
17	26	Uğur Mumcu Sağlık Ocağı	13.8	14.9	15.5	11.7	44.9	56.6	83.6	76.9	74.9	52.7	15.6	86.2	35	11.8	8.6	38.3	10.7	10.5	52.7	14.9	11.1	26.3	2.5	14.1	12.6	20.3	0	8.1	14.3	16.3	8.9	15.1	6.7	16.4	15.3	16.9	23.3	18.6	16
11	27	Yenimahalle Belediyesi	6.8	14.2	23.5	5.5	37.7	64.2	78.5	77	82.9	44.7	7.5	81.1	42.6	4.8	0.6	31.3	3.7	8.4	44.7	7.9	3.1	21.2	10.5	8.8	5.6	12.4	8	0	8.2	8.5	16.9	14.4	2.3	24.4	23.3	24.5	16	13.3	24
72	28	İstikbal Mehmetoğulları Mgz	6.8	15.6	29.5	5.5	32	71.4	81.4	80.7	89.2	46.1	9.4	84	49.8	8.1	8.5	31.1	7	11.7	46.1	7.7	6.3	24.1	17.4	11.4	6.2	12.9	15.4	8.5	0	9.2	24.1	17.7	9.5	30.8	29.8	31.7	9.3	12.7	30.5
37	29	Çank.Ü.Hazırlık Bölümü	2.1	11.5	28.4	7.7	37.4	71.1	75.4	76.2	87.4	41	0.8	78	49.5	5.1	8.2	25.9	6.4	7.2	41	2.7	5.6	18.1	17	5.5	2.5	5.8	15.5	8.2	8	0	20.1	13.2	9.2	29.7	27.7	31.4	15.7	6.7	28.3
40	30	İstikbal Dilmen Ev	21.2	12.1	8.4	19.7	53	54.8	87	68	67.3	58.5	20.1	89.6	31.3	19.3	16.7	45.2	17.8	14.8	58.5	22	16.9	29.7	6.3	17.2	20.7	23.7	8.1	16.1	22.4	19.3	0	14.6	14.7	9.6	7.6	15.1	31.4	22	8.3
32	31	YÖK	13.6	4.5	22.6	17.3	48.3	69	79.4	70.3	81.6	52.7	12.4	82	45.5	11.6	15.4	37.6	12.8	7.2	52.7	14.3	12.7	22	16.6	9.5	13.7	16	15.1	14.9	17.7	11.7	14.3	0	13.3	23.8	21.9	29.3	26.7	14.4	22.5
11	32	İstikbal Gökerler	8.4	12.4	21.9	5	39.3	61.9	80.1	76.3	81.3	46.3	9.1	82.6	40.3	6.3	2.1	32.8	5.2	7.9	46.3	9.4	4.7	22.7	8.9	10.4	7.2	14	6.4	1.6	9.7	10.1	15.3	14	0	22.8	21.7	22.2	17.6	14.9	22.4
40	33	İstikbal ALPAK	28	20.8	0.2	26.8	52.9	56.8	95.7	69.9	58.5	65.6	28.8	92.7	23.1	25.4	23.8	52.5	24.9	23.5	65.6	29.1	24	38.4	13.4	25.9	26.8	32.4	15.2	23.2	29.5	28	8.7	23.3	21.8	0	1.2	18.4	38.5	30.7	3
18	34	İstikbal Zirve	28.1	19.6	1.3	26.9	54	56.1	94.5	68.7	59.7	65.7	27.6	91.5	24.2	26.1	23.9	52.6	25	22.3	65.7	29.2	24.1	37.2	13.5	24.7	26.9	31.2	15.3	23.3	29.6	26.8	7.5	22.1	21.9	2.4	0	17.7	38.6	29.5	1.8
31	35	İpragaz Dolum Tesisleri	30.5	27.1	17.9	27.7	53.1	39.7	98.6	78.7	70.1	67.6	31.9	101	18.1	28	24.9	54.5	27.3	25.5	67.6	32	26	41.3	15.8	29.2	28.8	35.3	17.6	24.4	31.9	31.3	15	29.6	22.8	18.7	16.7	0	31	33.6	17.4
25	36	Pursaklar İMKB Lisesi	15.3	24	38	14.2	22.7	68.7	89.3	89.4	97.4	46.5	17.8	91.9	47.1	16	16.4	31.5	14.9	19.7	46.5	16.2	14.2	32	24.6	19.9	14.2	20.9	22.5	16.4	8.7	17.1	31.4	25.6	18.2	38.9	37.8	29	0	20.6	38.5
40	37	İstikbal Şanal	7.3	13.3	30.2	12.7	42.3	74.2	68.7	78.4	89.1	46.4	6.1	71.3	52.6	7.8	13.1	31.3	9.1	8.9	46.4	8	10.7	11.4	20.6	6.6	7.4	2.6	19.1	13.1	13	5.4	21.8	14.9	14.2	31.4	29.4	34.5	20.7	0	30.1
37	38	Timurtaş İ.Ö.O	28.8	20.3	3.1	27.6	55.8	56.8	95.2	69.3	61.5	66.4	28.3	92.1	26	26.7	24.6	53.2	25.6	23	66.4	29.8	24.8	37.9	14.2	25.4	27.6	31.9	16	24	30.3	27.5	8.2	22.8	22.6	4.2	1.8	18.4	39.3	30.2	0

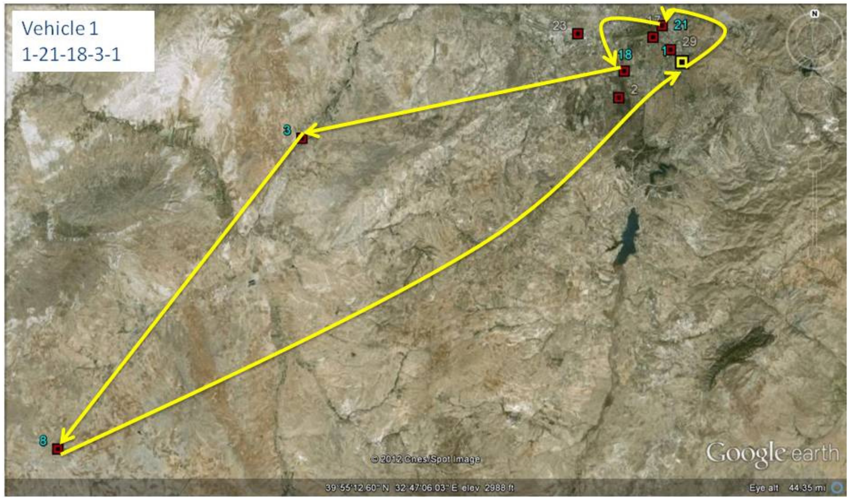
Appendix 2 Selected Nodes, Bloodmobile and Shuttle Tours Found for Ankara Instance



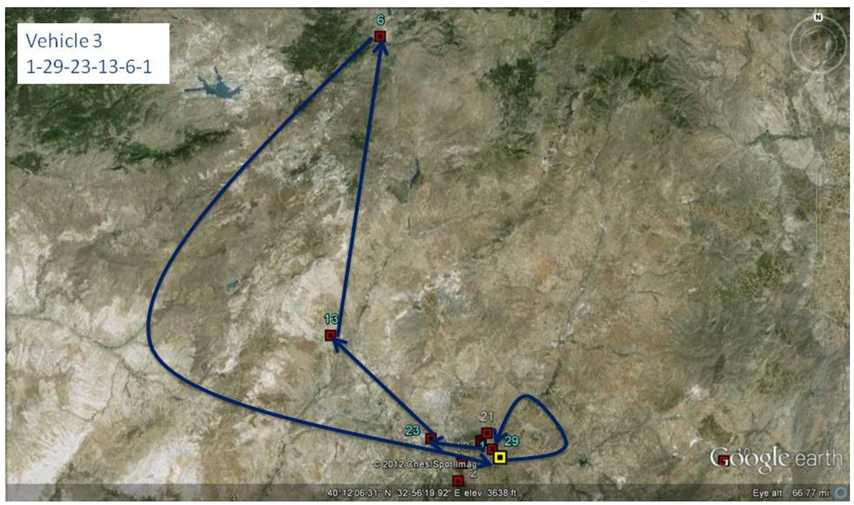
Selected Nodes



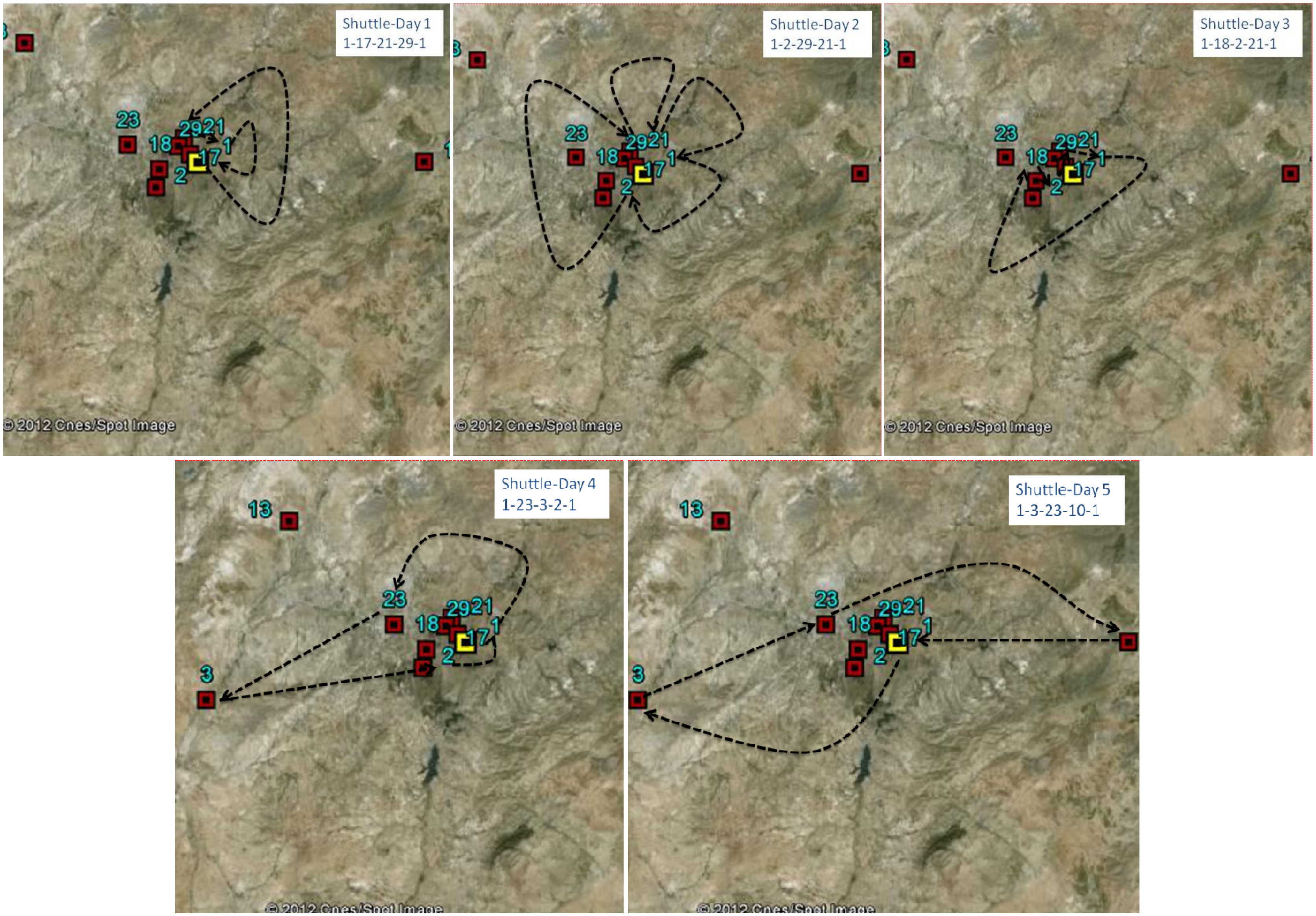
Covered Areas by different bloodmobiles

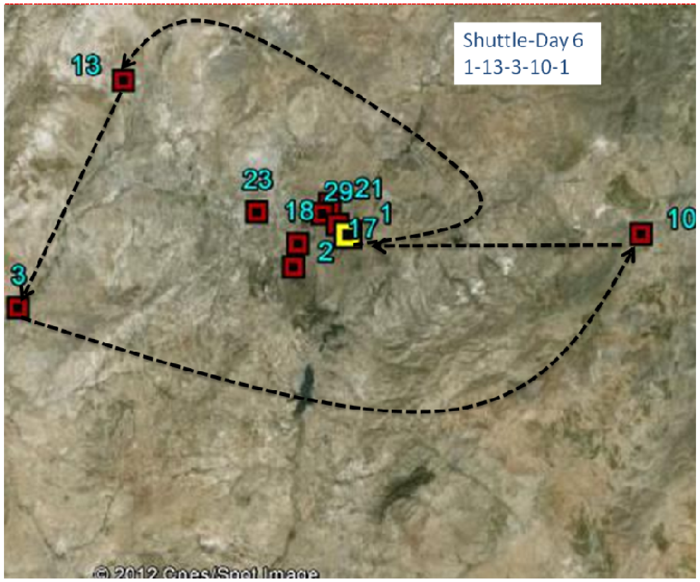

Vehicle 1
1-21-18-3-1
23
21
18
1
29
2
3
8
Google earth


Vehicle 2
1-17-2-10-1
17
21
1
29
10
2
Google earth


Vehicle 3
1-29-23-13-6-1
6
13
23
21
29
Google earth

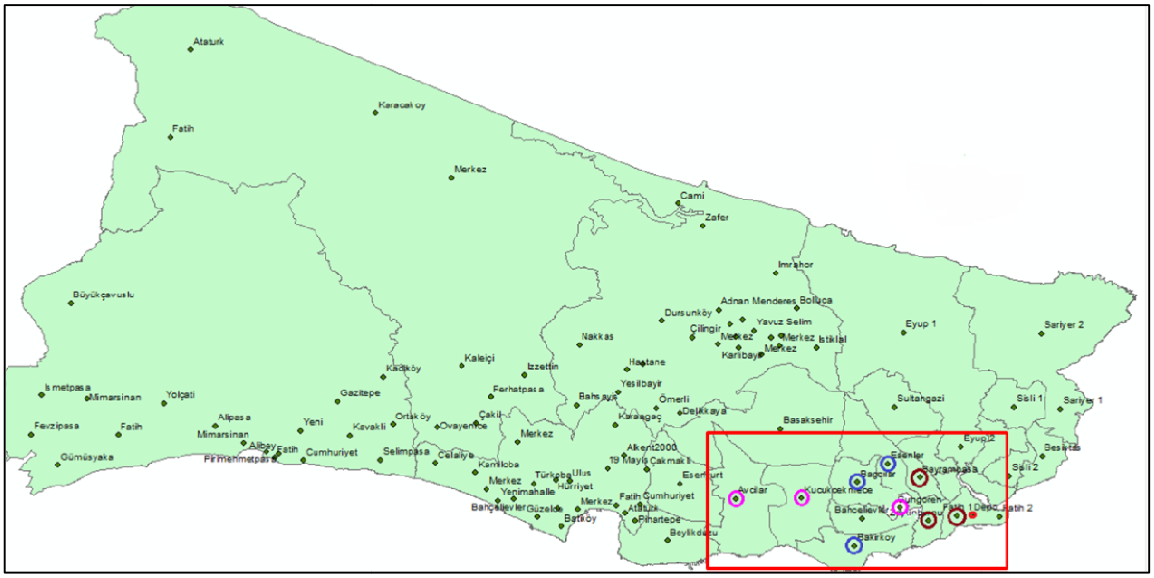
Shuttle Tours



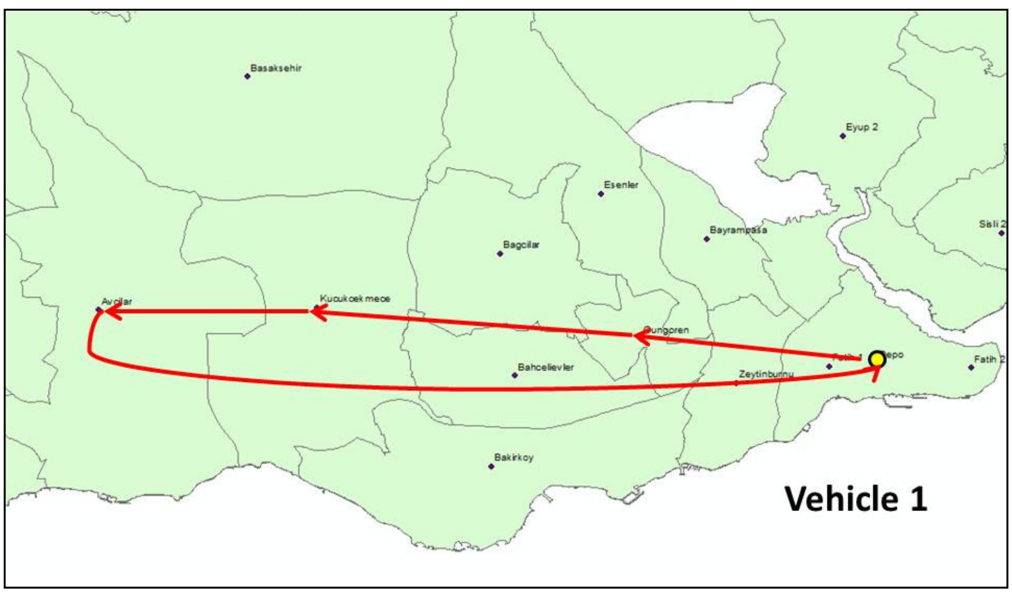

Shuttle-Day 6
1-13-3-10-1
13
23
29
21
18
1
17
10
2
3
© 2012 Cnes/Spot Image

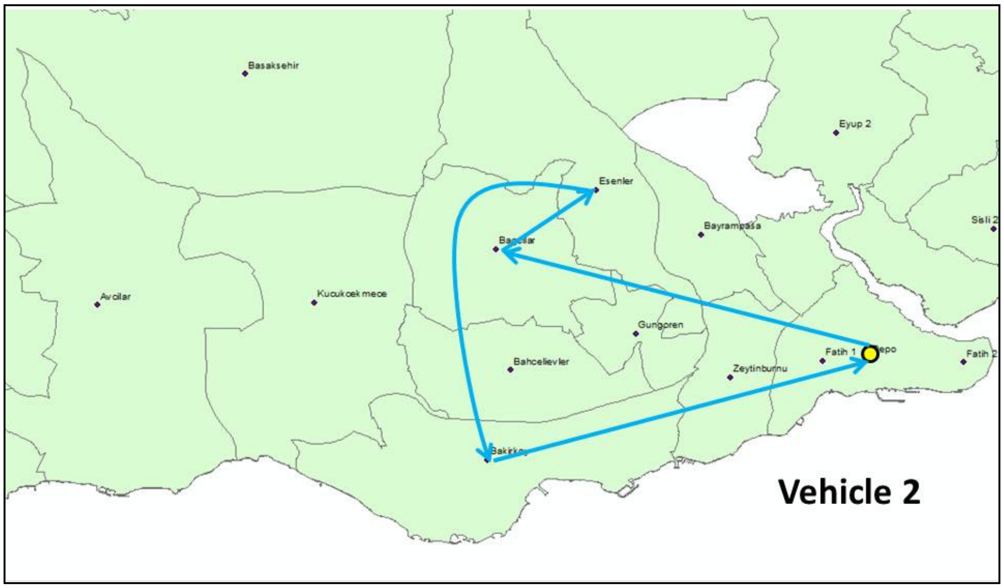
Appendix 3 Selected Nodes, Bloodmobile and Shuttle Tours Found for Istanbul Instance

Selected Nodes



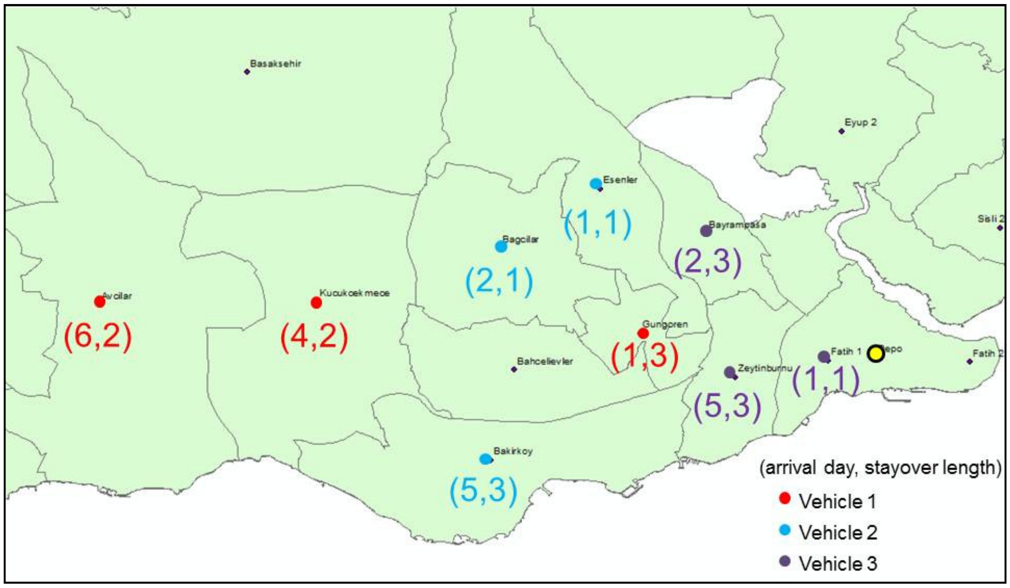
Bloodmobile Tours



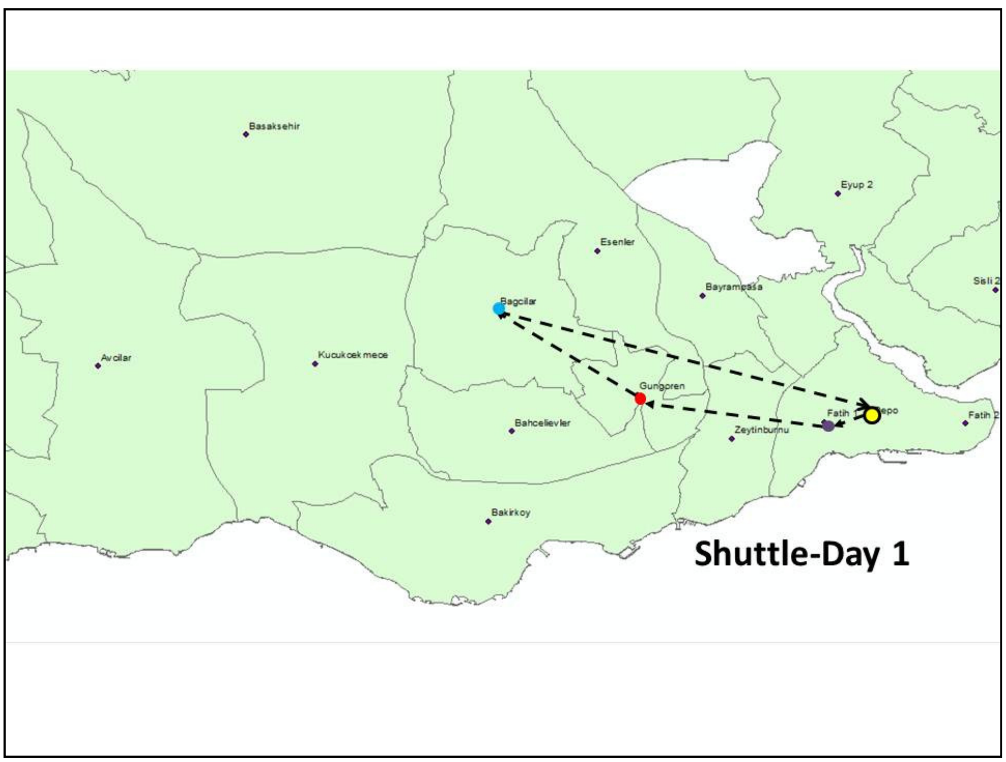

Basaksehir
Eyup 2
Esenler
Bayrampasa
Sisli 2
Avcilar
Kucukcekmece
Gungoren
Fatih 1
Fatih 2
Bahcelievler
Zeytinburnu
Vehicle 2

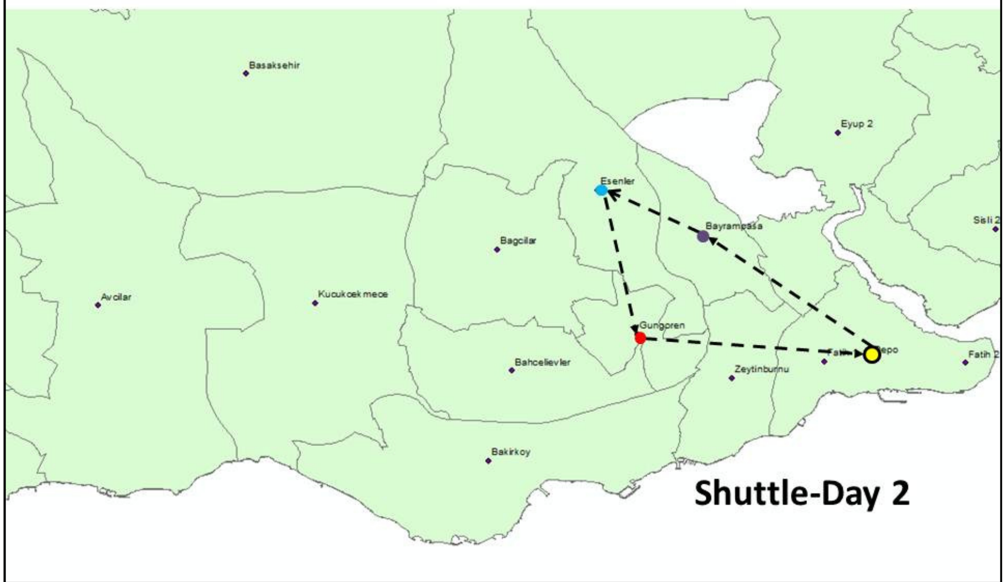

Basaksehir
Eyup 2
Esenler
Bagcilar
Bayrampasa
Sisli 2
Avcilar
Kucukcekmece
Gungoren
Fatih 2
Bahcelievler
Zeytinburnu
Bakirkoy
Vehicle 3

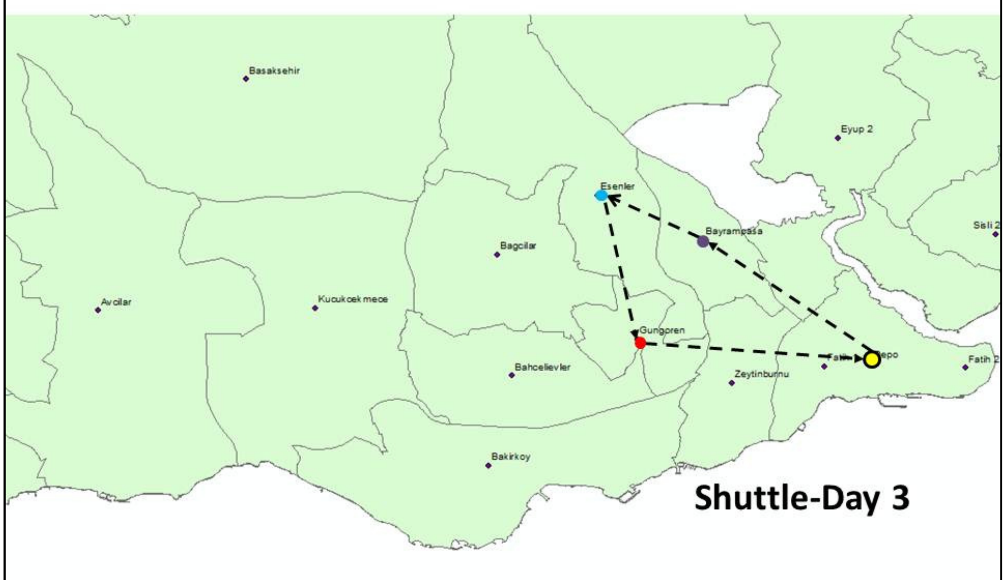
Selected nodes with labels

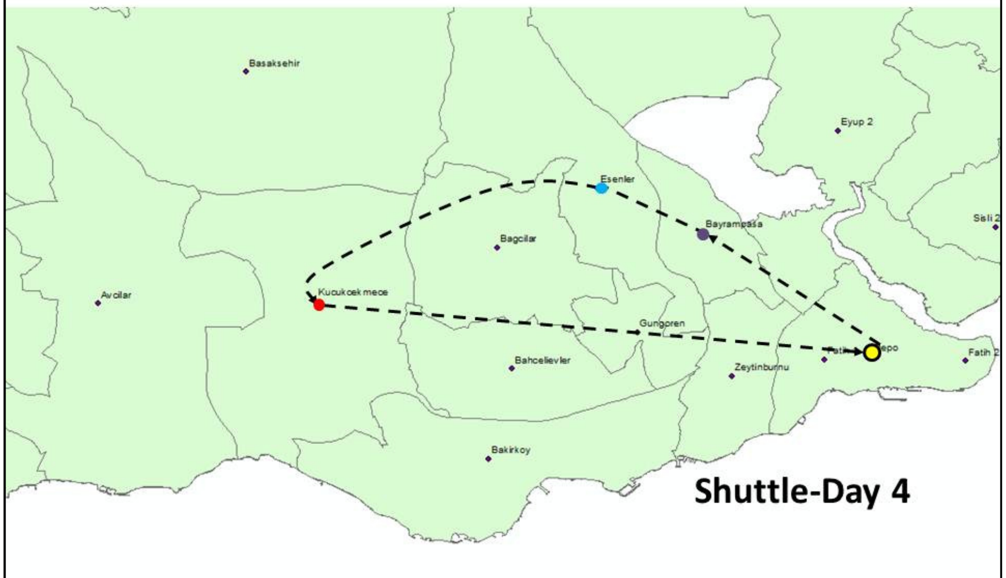


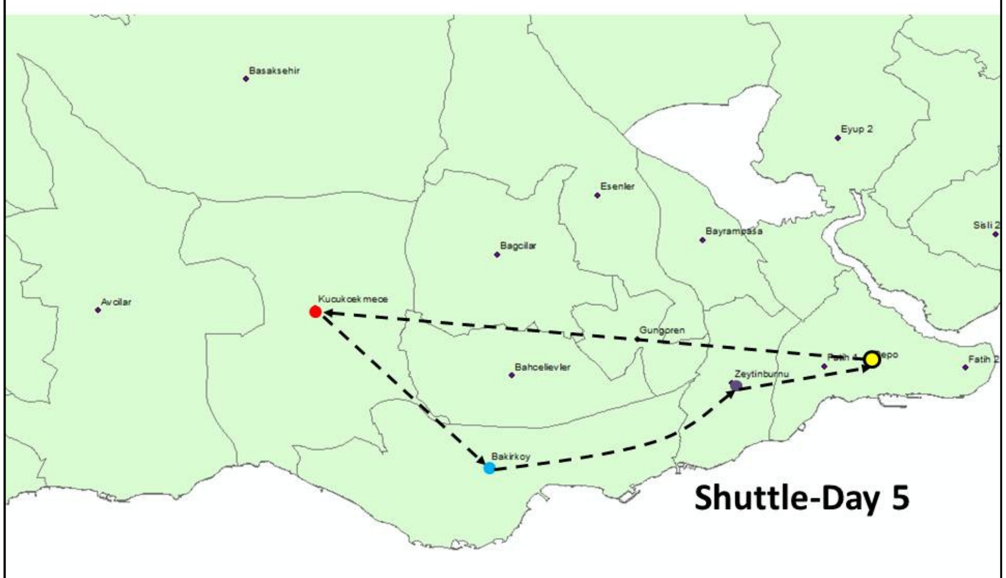
Shuttle tours

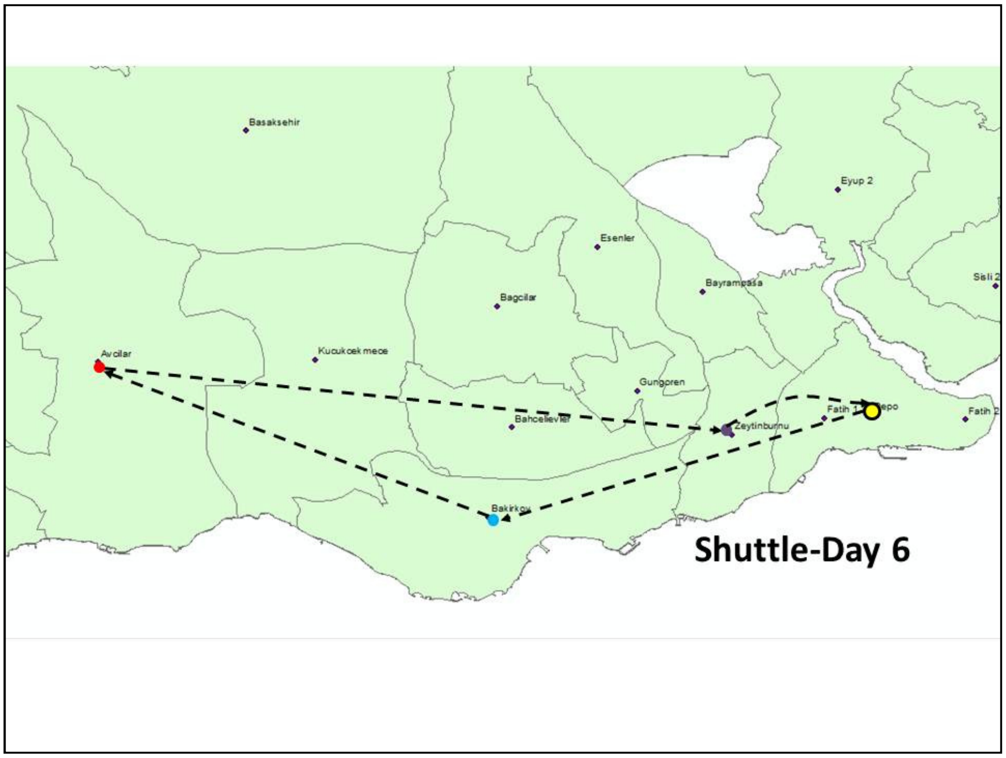



Basaksehir
Eyup 2
Esenler
Bayrampasa
Sisli 2
Bagcilar
Avcilar
Kucukcekmece
Gungoren
Fatih 2
Bahcelievler
Zeytinburnu
Bakirkoy
Shuttle-Day 2


Basaksehir
Eyup 2
Esenler
Bayrampasa
Sisli 2
Bagcilar
Avcilar
Kucukcekmece
Gungoren
Fatih 2
Bahcelievler
Zeytinburnu
Bakirkoy
Shuttle-Day 3

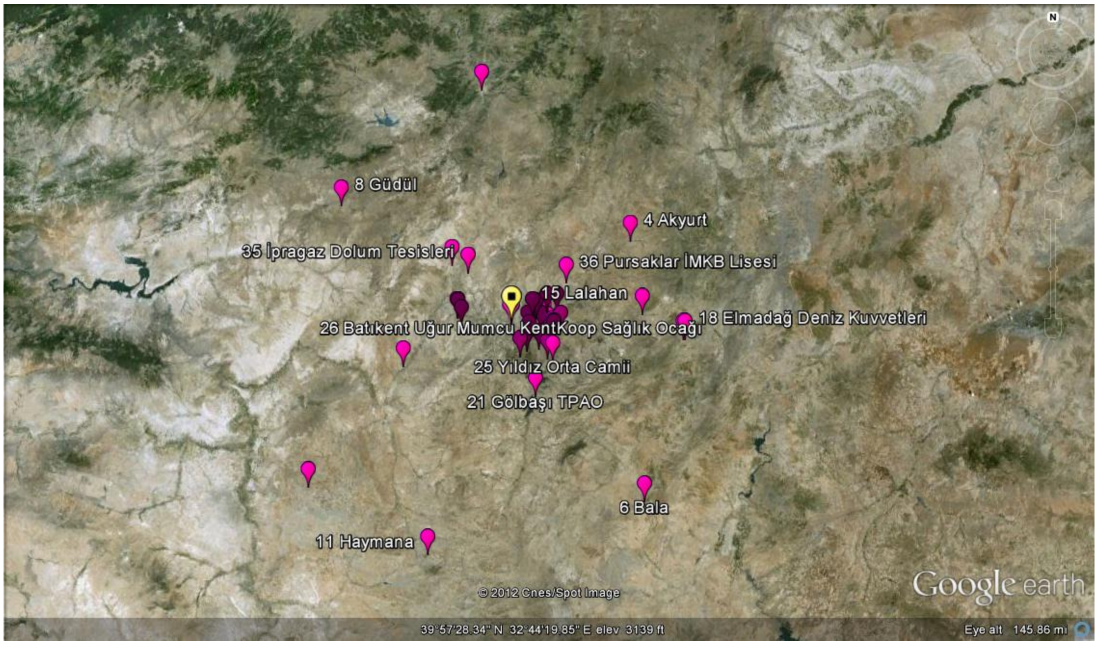

Basaksehir
Eyup 2
Esenler
Bayrampasa
Sisli 2
Bagcilar
Avcilar
Kucukcekmece
Gungoren
Fatih 2
Bahcelievler
Zeytinburnu
Bakirkoy
Shuttle-Day 4


Basaksehir
Eyup 2
Esenler
Bayrampasa
Sisli 2
Bagcilar
Avcilar
Kucukcekmece
Gungoren
Fatih 2
Bahcelievler
Zeytinburnu
Bakirkoy
Shuttle-Day 5

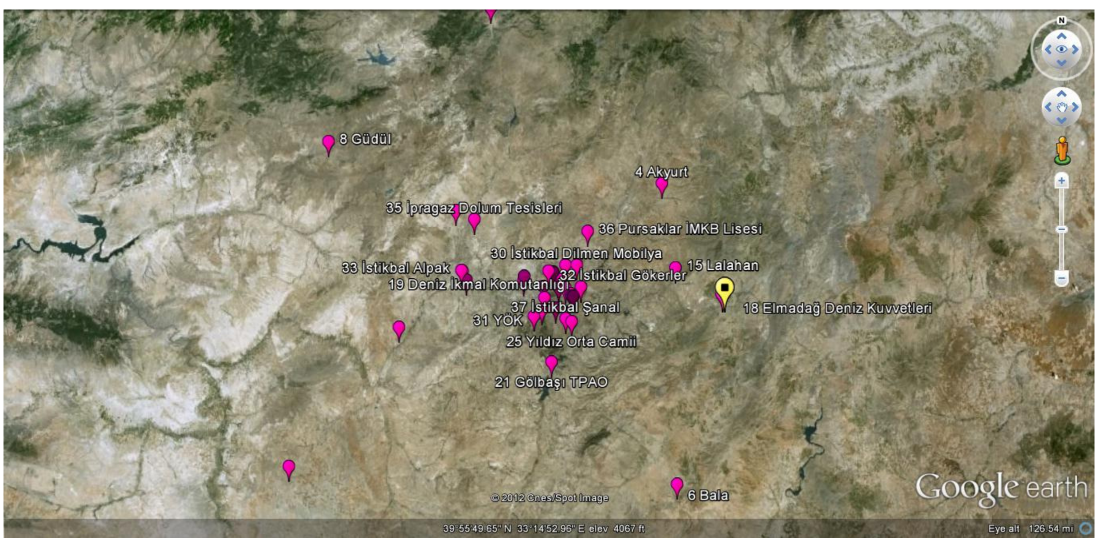

Basaksehir
Eyup 2
Esenler
Bayrampasa
Sisli 2
Bagcilar
Avcilar
Kucukcekmece
Gungoren
Zeytinburnu
Fatih 1
Fatih 2
Bahcelievler
Bakirkoy
Shuttle-Day 6

Appendix 4 Location of Depot in Random Instances

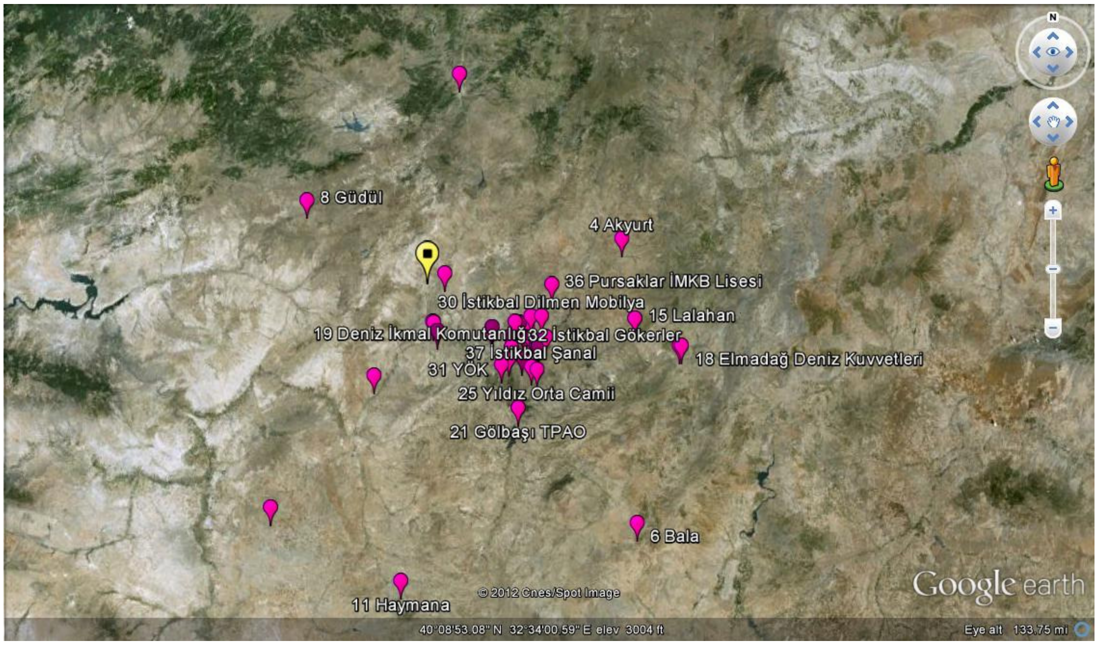
Instance 16:



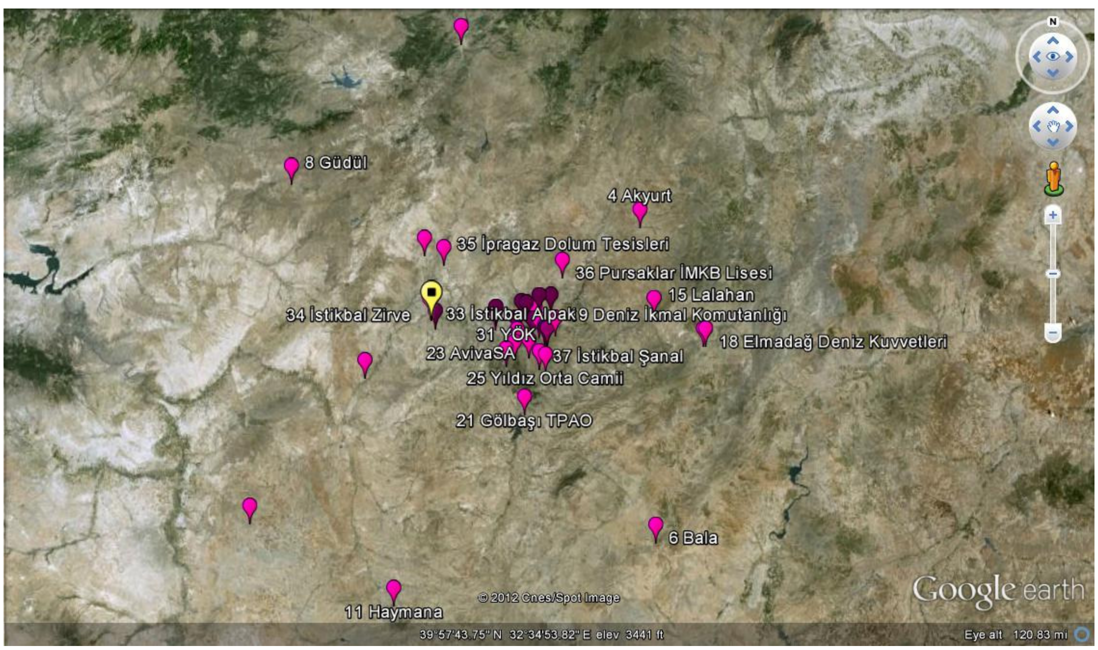
Instance 17:



Instance 18:

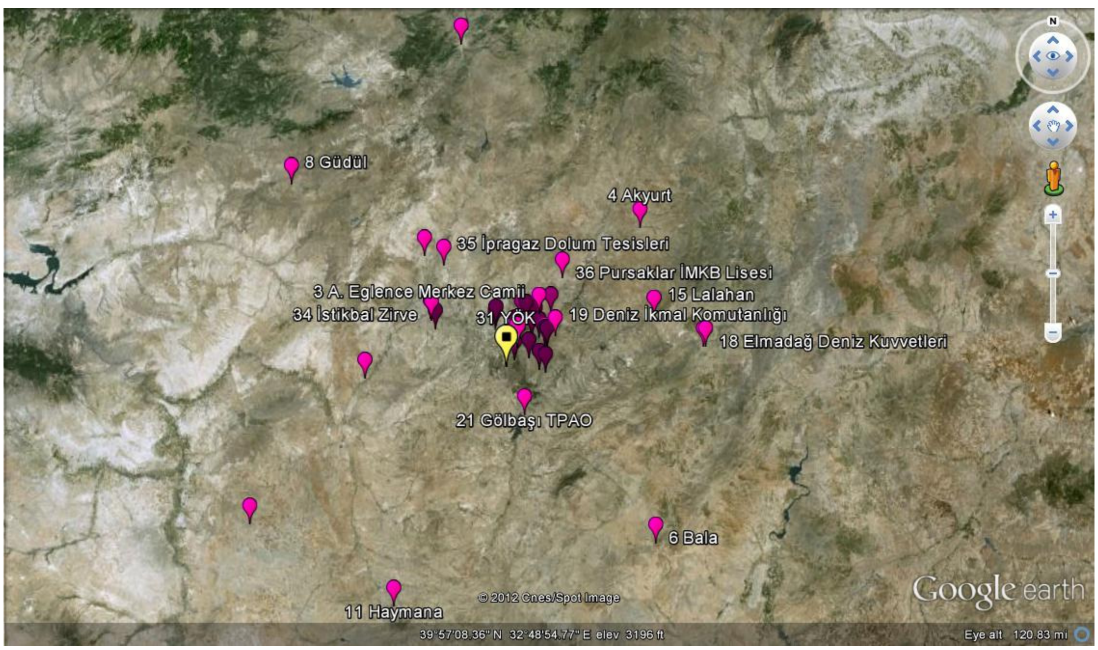


Instance 19:

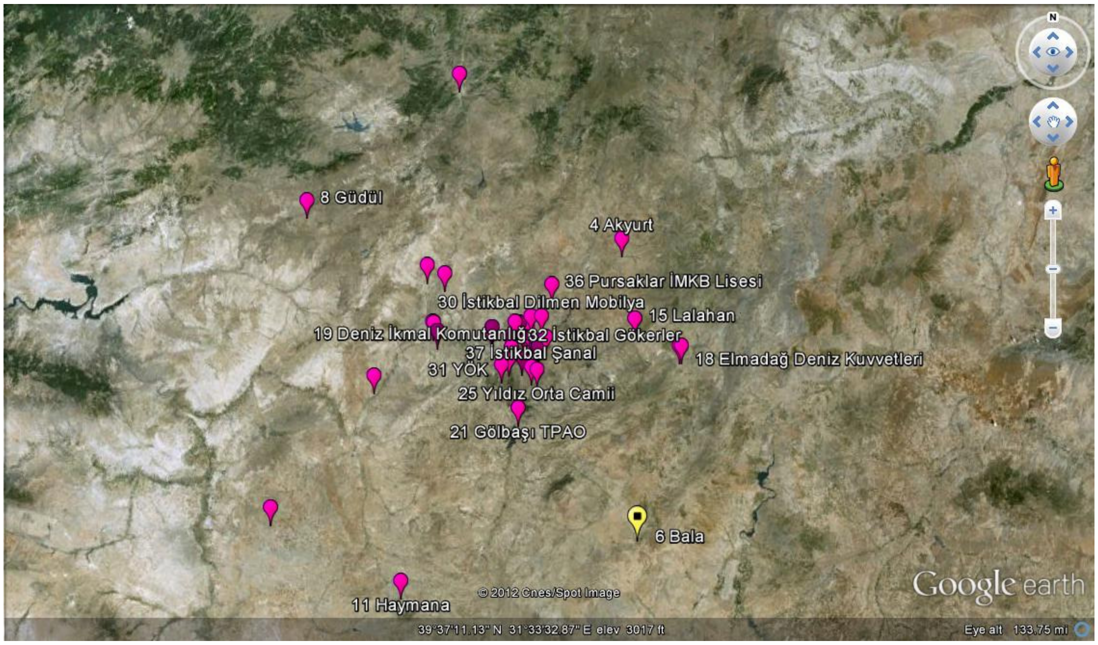


Instance 20:

Instance 21:



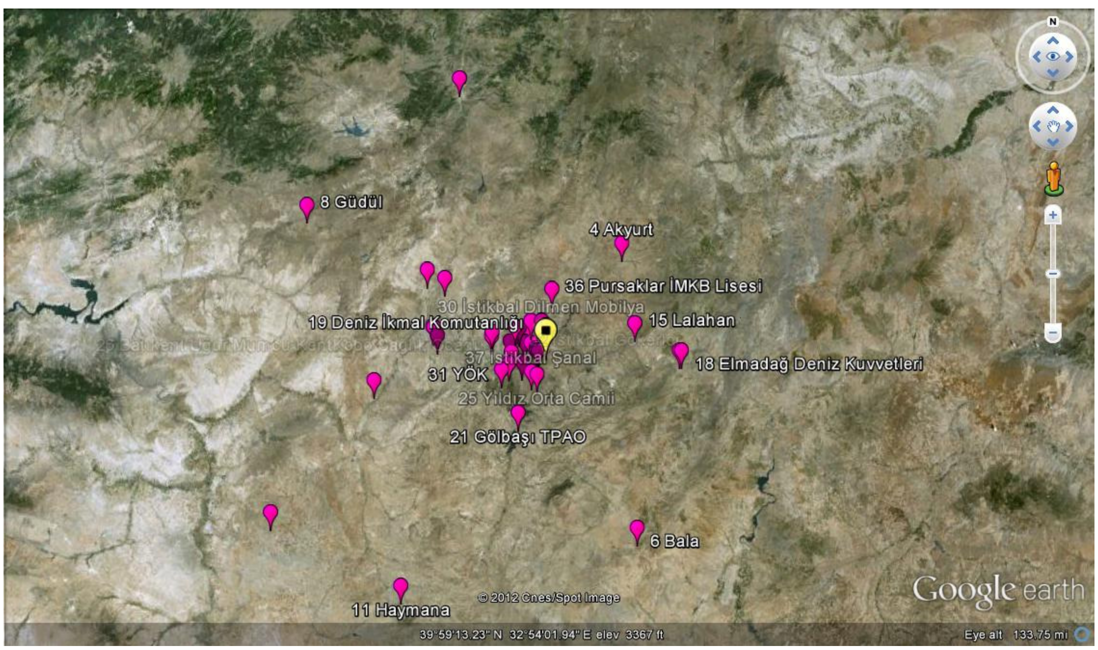
Instance 22:



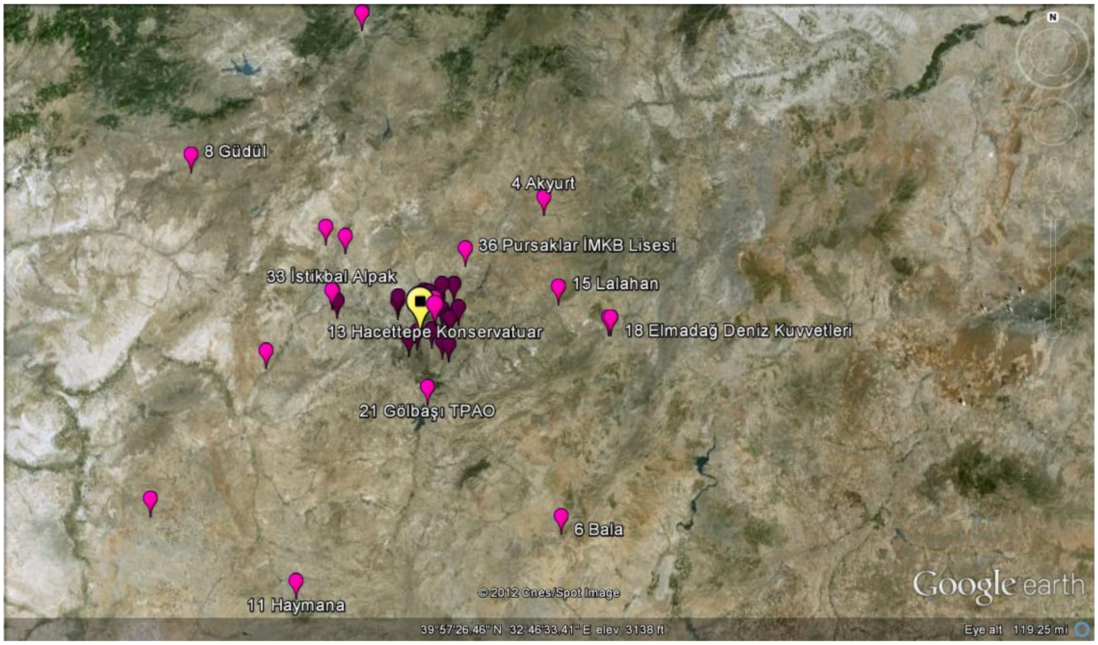
Instance 23:

Instance 24:

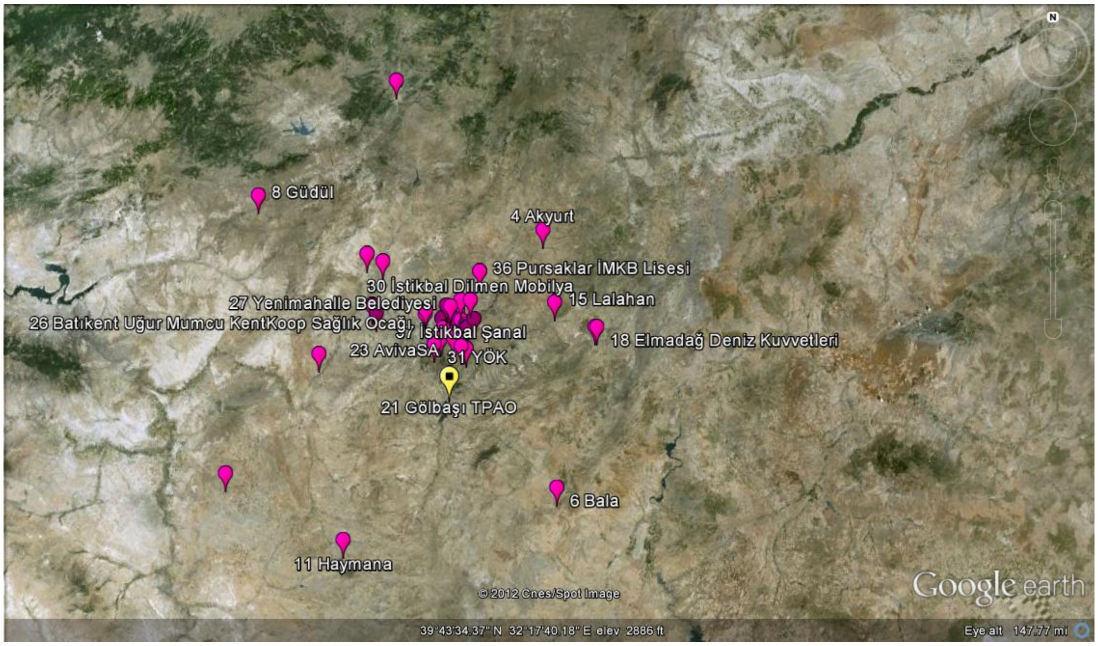
Instance 25:



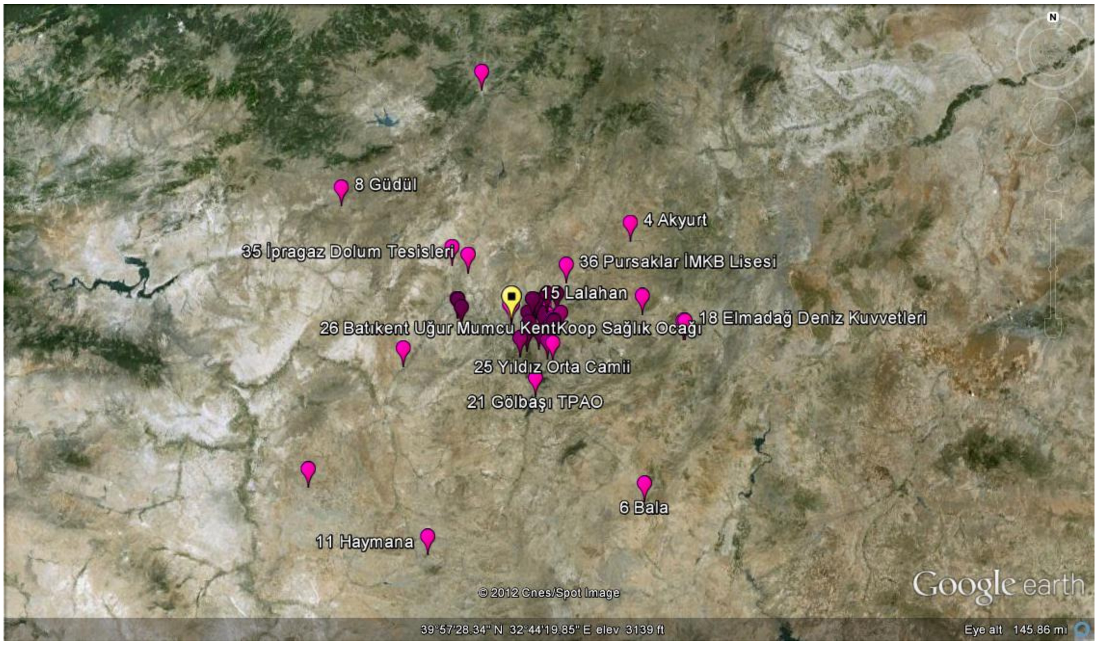
Instance 26:



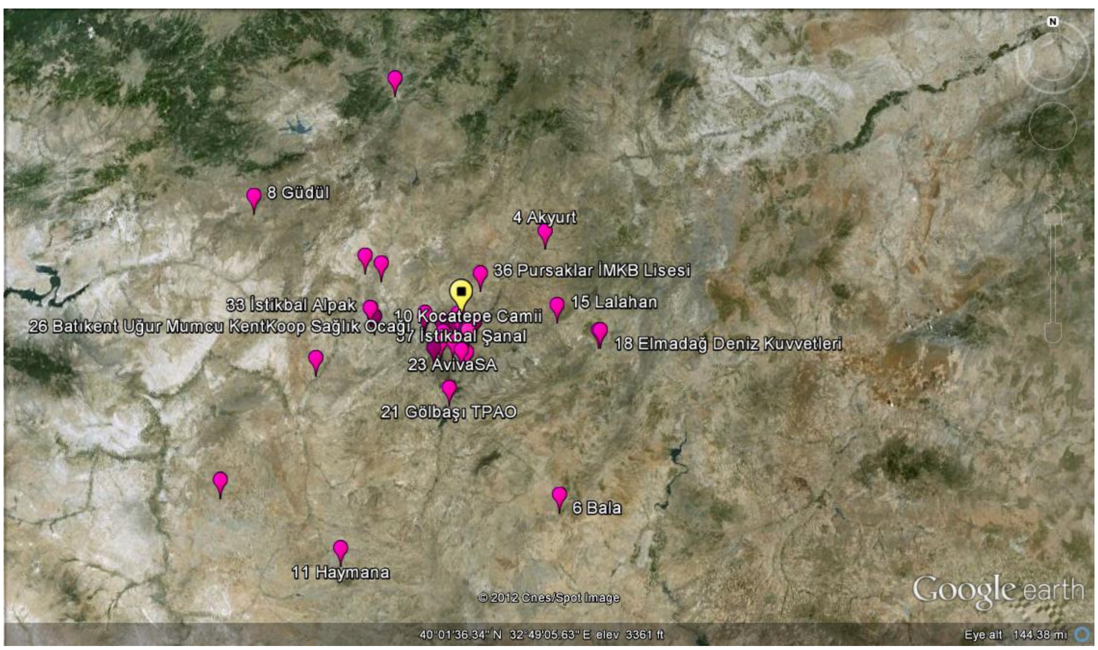
Instance 27 :



Instance 28:



Instance 29 :



Instance 30:

8 Güdül
4 Akyurt
36 Pursaklar İMKB Lisesi
33 İstikbal Alpak
10 Kocatepe Camii
15 Lalahan
19 Deniz İkmal Komutanlığı
38 Timurtaş İÖO
18 Elmadağ Deniz Kuvvetleri
31 YÖK
21 Gölbaşı TPAO
6 Bala
© 2012 Cnes/Spot Image
Google earth
11 Haymana
39°58'20.68" N 32°51'33.74" E elev 3315 ft
Eye alt 114.68 mi