

ROUTING AND SCHEDULING DECISIONS IN THE HIERARCHICAL HUB LOCATION PROBLEM

A THESIS

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By

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July, 2013

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ABSTRACT

ROUTING AND SCHEDULING DECISIONS IN THE HIERARCHICAL HUB LOCATION PROBLEM

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Hubs are facilities that consolidate and disseminate flow in many-to-many distribution systems. The hub location problem considers decisions including the locations of hubs on a network and also the allocations of the demand (non-hub) nodes to these hubs. In this study, a hierarchical multimodal hub network is proposed. Based on this network, a hub covering problem with a service time bound is defined. The hierarchical network consists of three layers. In this study, two different structures, which are ring(s)-star-star (R-S-S) and ring(s)-ring(s)-star (R-R-S), are considered. The multimodal network has three different types of vehicles at each layer, which are airplanes, big trucks and pickup trucks. For the proposed problems (R-S-S and R-R-S), two mathematical models are presented and strengthened with some valid inequalities. The computational analysis is conducted over Turkish and CAB data sets. Finally, we propose a heuristic algorithm in order to solve large-sized problems and also test the performance of this heuristic approach on Turkish network data set.

Keywords: hub location, hierarchical network design, multimode transportation

ÖZET

HİYERARŞİK ANA DAĞITIM ÜSSÜ YER SEÇİMİ PROBLEMİNDE ROTALAMA VE ÇİZELGELEME KARARLARI

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Çoklu dağıtım sistemlerinde, Ana Dağıtım Üsleri (ADÜ), akışı toplayan ve dağıtan yerlerdir. Yer seçimi problemi ise, ADÜ'lerin yerlerine ve ADÜ olmayan diğer noktaların ADÜ'lere nasıl atandığına karar verir. Bu çalışmada, hiyerarşik ve birden çok aracın kullanıldığı bir ağ yapısı incelenmektedir. Bu ağa bağlı olarak, hizmet zaman kısıtı olan bir ADÜ yer seçimi kapsama problemi tanımlanmaktadır. Hiyerarşik ağ, 3 katmandan oluşmaktadır. Bu çalışmada, 2 farklı ağ yapısı göz önünde bulundurulmaktadır. Bunlar sırasıyla; Halka(lar)-Yıldız-Yıldız (H-Y-Y) ve Halka(lar)-Halka(lar)-Yıldız (H-H-Y). Birden çok aracın kullandığı ağ, her bir katman için farklı araç bulundurmaktadır. Bunlar; uçaklar, büyük kamyonlar ve kamyonetlerdir. Önerilen her iki ağ yapısındaki problemler için matematiksel modeller sunulmuştur ve bu modeller, bazı geçerli eşitsizlikler ile güçlendirilmişlerdir. Sayısal analizler, Türkiye ve Amerika verileri kullanılarak yapılmıştır. Son olarak, büyük boyutlu problemleri çözebilmek için, sezgisel bir çözüm yolu önerilmiştir ve bu sezgisel çözüm yolunun performansı değerlendirilmiştir.

Anahtar Sözcükler: ADÜ yer seçimi, hiyerarşik ağ tasarımı, birden çok araçlı ulaşım

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Chapter 1

Introduction

Hubs are switching, transshipment and sorting points in many-to-many distribution networks. Instead of having direct link between each origin-destination (o-d) pair, hubs provide the connection between each o-d pair by using fewer links and also concentrate demand flows to allow economies of scale. Hubs consolidate flows from different origins and disseminate them based on their destination. Hubs are considered in different sectors such as cargo delivery, telecommunication, air transportation, etc. The hub location problem is to decide on the locations of hubs and the allocations of the demand (non-hub) nodes to the hubs over a distribution network.

Pioneering works of the hub location problem can be considered as the study of O’Kelly [1, 2, 3]. In these researches, O’Kelly defines the hub location problem and also he proposes the first mathematical model, which happens to be quadratic. Campbell [4]

categorizes the hub location problem into four problems based on the objective function; the p-hub median problem, the hub location problem with fixed costs, the p-hub center problem and hub covering problem. For each problem, he presents linear formulations.

In this research, we design a cargo delivery system. Therefore, we consider the time-definite deliveries with minimum cost. In order to ensure the cargo deliveries in a given time bound, also airplanes are used. Furthermore, the appropriate type of network is chosen to minimize the cost of segments (links) and vehicles.

From operations research point of view, we consider a hub covering problem on a hierarchical multimodal hub network. The main aim is to minimize the number of segments and vehicles between hubs while serving all origin-destination pairs in a given time bound. We propose a three layered hierarchical network with airport hubs, ground hubs and demand nodes. Also, we consider a multimodal network with three different vehicles at three different layers at the hierarchy. At the top layer, airplanes; at the second one, big trucks and at the third layer, pickup trucks are used.

Since the main aim of this research is to reduce the number of segments and vehicles, ring structure(s) is considered at the top layer. The proposed network is called Ring(s)-Star-Star (R-S-S) network. Also, the ring structure(s) can be used at the second layer, which is called Ring(s)-Ring(s)-Star (R-R-S) network. By considering ring structure(s), the routing and scheduling decisions are included into the proposed problems.

In Chapter 2, the cargo delivery system is explained in detail. Also, the classical hub location problem is described and the similarities between the cargo delivery and hub networks are discussed. Furthermore, motivations and aims of this study are explained. Finally, we propose and describe the hierarchical multimodal hub network.

In Chapter 3, we review the related hub location literature. We explain the studies based on the classical hub location problem, the hub location problem with incomplete hub

network structure, ring structure(s), multimodal network structure and hierarchical hub network structure, respectively.

In Chapter 4, two mathematical models for two different network configurations (R-S-S and R-R-S) are proposed. These models are explained in detail and some valid inequalities are presented.

In Chapter 5, the settings of the computational studies are defined. In addition to this, the performances of the valid inequalities proposed in Chapter 4 are tested.

In Chapter 6, the computational studies of the R-S-S model are carried out on the Turkish network and the CAB data set. We analyze the results in detail and perform sensitivity analysis on these results.

In Chapter 7, the computational studies of the R-R-S model are carried out on the Turkish network and the CAB data set. We conduct sensitivity analysis and make interpretations on the results.

In Chapter 8, a heuristic algorithm is proposed. By using this heuristic approach, computational studies are conducted over the Turkish network. Also, the performance of the models proposed in Chapter 4 and heuristic algorithm are compared.

In Chapter 9, we consider the possible extension to our study. We propose a mathematical model for the Ring(s)-Ring(s)-Ring(s) (R-R-R) network.

Chapter 10 presents some final remarks based on our study.

Chapter 2

Problem Definition and Motivation

In this chapter, we present the motivation behind this study and based on this motivation, we define the problem. In Section 2.1 we give the basic explanation of cargo delivery system and its relation to the hub location network. In Section 2.2 the motivation of this study is presented. In Section 2.3 a hierarchical hub location network is proposed and based on this network, the problem is defined.

2.1 Cargo Delivery Systems and the Hub Location Network

Cargo transportation is one of the most significant and also challenging services in any country. It is important and compulsive because it must provide a maximum level of customer satisfaction in a very competitive environment. Therefore, cargo delivery

system must be well-understood. Thus, we now explain the cargo transportation system in detail.

A cargo delivery system consists of branch offices and operation centers. Branch offices collect and distribute cargoes from/to customers directly and operation centers collect and distribute cargoes from/to the branch offices or they send cargoes to another operation centers. Although there can be more than one branch office in a city, operation centers do not exist in every city. Thus, each branch office must be assigned to an operation center.

The journey of a cargo can be described as follows. First of all, a cargo is picked up from a customer by the branch office or the customer takes his cargo to the branch office. After a specific time, all cargoes are shipped from branch office to the allocated operation center. After the arrival of the cargoes from their branch offices to the allocated operation center, all cargoes are sorted according to their destination and they are loaded to larger vehicles. After that, the larger vehicles depart from the operation center to the other operation centers. When the larger vehicles arrive at their destined operation centers, all cargoes are unloaded and they are sorted according to their destined branch office. Finally, branch office takes the cargoes from the operation center and delivers them to the destined customer.

A cargo delivery system is illustrated in Figure 2.1. In this figure, small red depots and big blue warehouses represent branch offices and operation centers, respectively. Branch offices are named by letters and operation centers by numbers. As you can see, all branch offices are allocated to the operation centers. For instance, branch office *a* and branch office *l* are assigned to operation center 4. Also, we can give an example of the journey of a cargo. For example, assume that the origin and destination of the cargo is branch office *h* and *b*, respectively. Firstly, the cargo is sent from the branch office *h* to its allocated operation center 3. There, together with the outgoing cargoes of branch

offices i and k , which are destined to the branch offices which are also assigned to operation center 1, the cargo is shipped from operation center 3 to the operation center 1. After the arrival of all cargoes at operation center 1, all cargoes split up according to their destined branch office. Finally, the cargo is shipped from operation center 1 to its destination that is branch office b . In this example, the cargo goes through two operation centers that are 3 and 1. In Figure 2.1, you can see the path of the cargo. In a different example, it can go through just one operation center. For instance, consider the case where origin and destination of the cargo are branch office c and d , respectively. In this case, initially the cargo is sent from branch office c to the operation center 5 and after that it is send from operation center 5 to the branch office d .

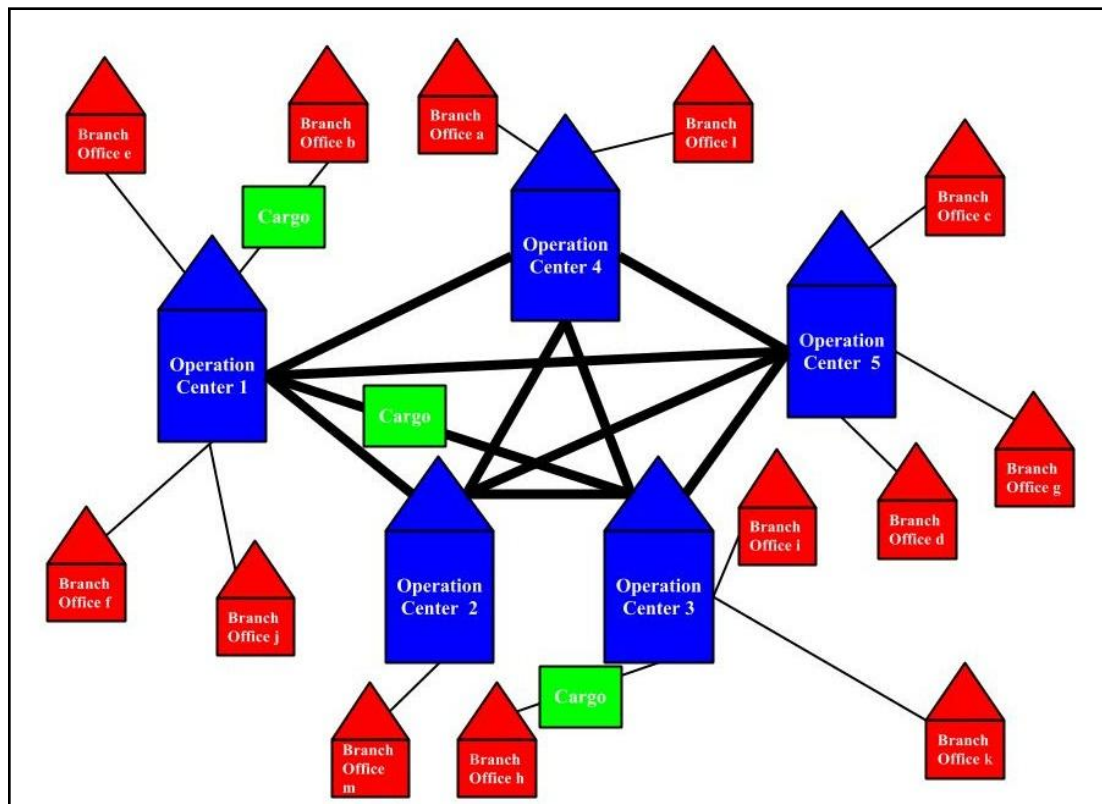


Figure 2.1: Cargo Delivery System Representation

The hub location network consists of demand nodes (non-hub nodes) and hubs. Demand nodes can be considered as the origin or destination of a demand and hubs are switching, transshipment and sorting point in many-to-many distribution network. In Figure 2.2, demand nodes and hubs are represented as circles and rectangles. Instead of a link between every demand node pair, flows can be concentrated through hubs. There are two types of hub networks; single allocation and multiple allocation. In single allocation hub network, each demand node is assigned to exactly one hub. On the other hand, in multiple allocation hub network, demand nodes can be allocated to more than one hub. The hub location problem is basically to decide on the locations of hubs and the allocations of demand nodes to hubs. In the hub location problem three main assumptions are usually made. First, hub network is assumed to have a complete structure with a link between each hub pair. Second, there is economies of scale for bulk transportation between hubs. Lastly, direct transportation between demand node pairs (without using any hubs) is not allowed.

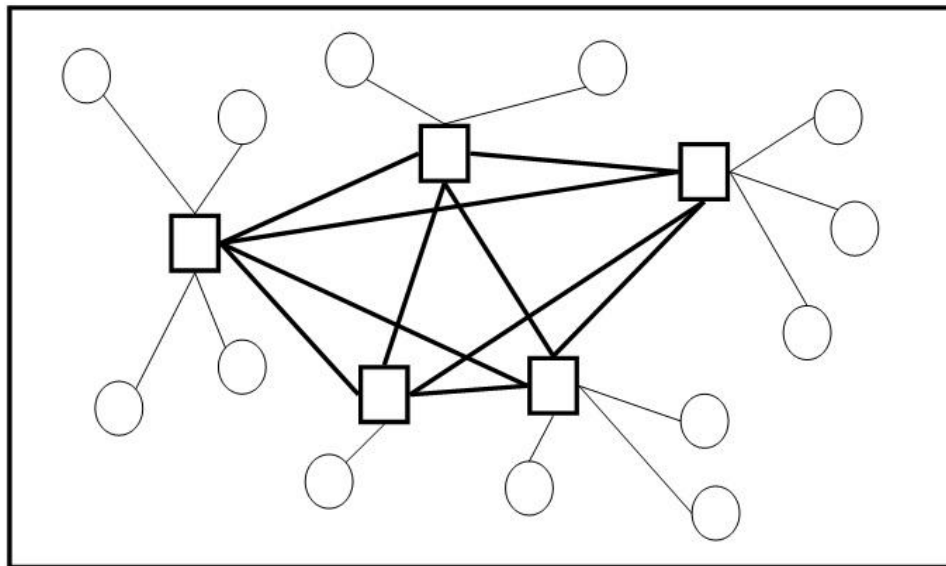


Figure 2.2: The Hub Location Network

According to the explanation of a cargo delivery system, cargo delivery networks and hub location network are very similar. The branch offices and operation centers in cargo delivery networks can be considered as demand nodes and hubs, respectively. Also, using larger trucks between operation centers results in economies of scale in hub location networks. Therefore, the cargo delivery problem can be considered as the hub location problem. Some researchers have also studied the cargo delivery problem in hub location networks (Kara and Tansel [5], Tan and Kara [6], Yaman et al. [7], Alumur and Kara [8], Yaman et al. [9] and Alumur et al. [10]). Kara and Tansel [5] motivated the importance of synchronization in cargo delivery system. Later, Yaman et al. [9] combined the release time scheduling and hub location problem on a cargo delivery application, which is very similar to our problem explained in Section 2.3.

2.2 Motivations and Aims of the Study

The classical hub location problem proposed by O’Kelly [1, 2, 3] considers only the cost minimization. However, in real life, cargo companies give similar attention to the customer satisfaction. Cargo companies try to maximize their customer satisfaction. In Turkey, there are several big cargo companies. Therefore, there is a very competitive environment. In order to attract more customers, cargo companies focus on service levels. Service level in cargo delivery is usually referred to as the delivery time. Reducing the delivery time is generally considered as to increase customer satisfaction and thus cargo companies offer different delivery time promises.



Figure 2.3: Turkey Map with City Numbers [11]

Especially, in Turkey, cargo companies aim to deliver cargoes in 24 hours time bound (next day delivery). However, due to the geographical structure of Turkey, delivery within 24 hours with trucks is almost impossible. For instance, distance between city 22 (Edirne) and city 30 (Hakkari) is 2042 km (Figure 2.3). Even if the truck travels at a speed of 90 km/hr that is the maximum speed limit in Turkey, travel time is approximately 23 hours. However, due to the bad conditions of highways in Turkey, a truck cannot travel with that speed. Also, since trucks cannot travel 23 hours without stops, delivery within 24 hours cannot be possible between city 22 and 30 by a truck. Rather than 90 km/hr, a truck can travel with the average speed of 70 km/hr in Turkey. With the average speed of 70 km/hr, 47 of the 3240 origin-destination pair cities in Turkey cannot be reached within 24 hours even without any stop. For instance, travel time between city 4 (Ağrı) and city 17 (Çanakkale), city 13 (Bitlis) and city 39 (Kırklareli), city 9 (Aydın) and city 65 (Van) exceed 24 hours time bound. Thus, in order to provide next day delivery promise between all city pairs, cargo companies in Turkey have started to use airplanes in their distribution networks.

On the other hand, operating airplanes is very costly and so number of airplanes must be limited. In the classical hub location problem, hub network is complete with a link between each hub pair. While using airplanes, having a complete hub network causes a high cost. Therefore, the structure of the hub network must be reconsidered and changed in order to decrease the number of airplanes and thus the cost. While decreasing the number of airplanes, also the utilization of airplanes is increased.

When changing the structure of the hub network, we want to integrate routing and scheduling decisions, so we can have a cost-efficient hub network structure.

Based on these motivations, three main goals are set. First one is to cover all origin-destination pairs in a predetermined time bound in order to increase the customer satisfaction. Second target is to minimize the number of highway and airline segments. We want to cover all origin-destination pairs with the minimum flights and trips. The last one is to minimize the number of vehicles, which are airplanes and big trucks in order to decrease the total operating cost of vehicles.

2.3 The Proposed Hub Location Problem

Since trucks and airplanes are included at the same time in the network, a hierarchical multimodal network is considered. The proposed network is a three layered hierarchical multimodal network. This hierarchical multimodal network has two different types of hubs which are ground hubs and airport hubs. Figure 2.4 shows a hierarchical multimodal network with 18 hubs. In this network, nodes 0-4 are the airport hubs; nodes 5-17 are the ground hubs and little circles with no numbers represent the demand points. In this representation, airline segments are illustrated as the thick lines between nodes 0-4; highway segments are illustrated with the thin lines between demand nodes and hubs (ground hubs or airport hubs), and with dashed lines between ground hubs and airport hubs.

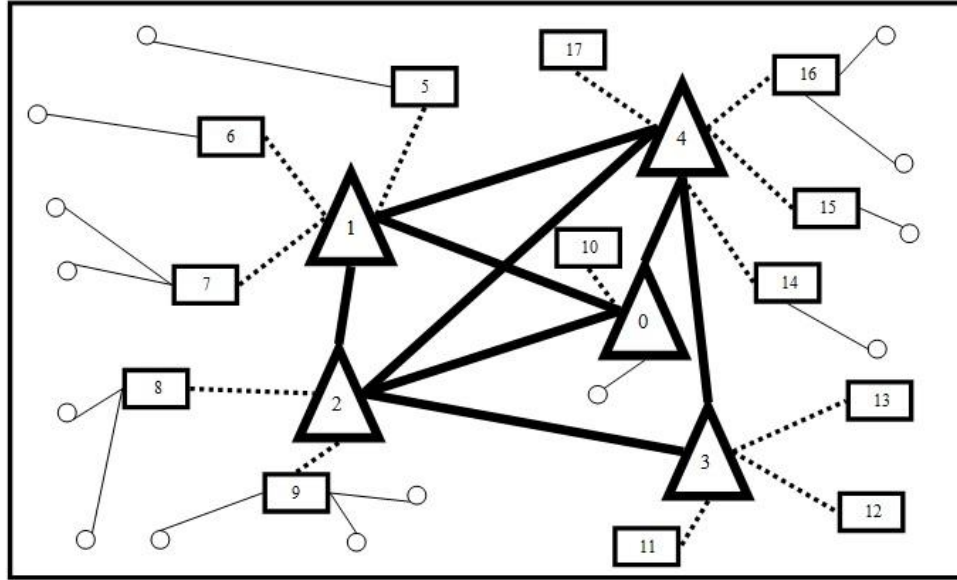
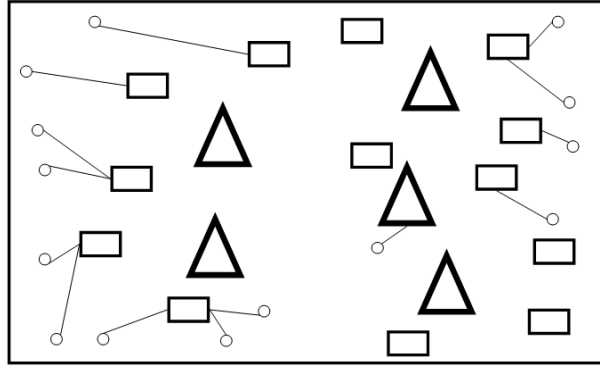


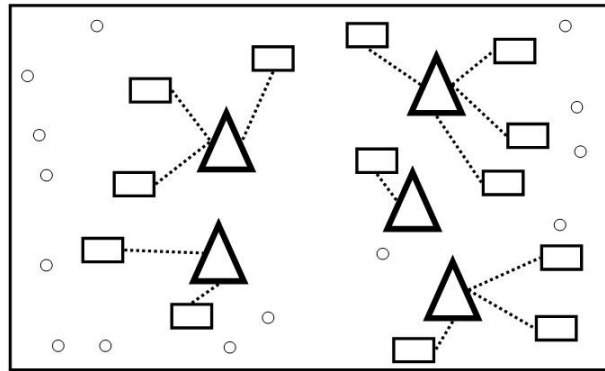
Figure 2.4: Representation of a Multimodal Hierarchical Network

The third layer of the network consists of the allocations of demand points to the ground hubs and airport hubs (Figure 2.5(a)). At this layer, a star structure is used for the allocation of demand points. Each demand node is connected to exactly one hub (a ground or an airport hub) with a highway link. On these highway segments, pickup trucks are used.

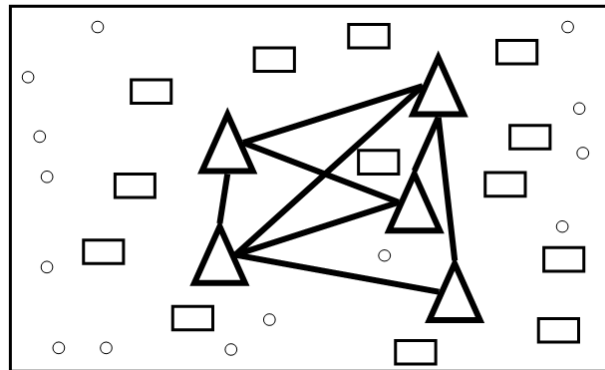
The second layer includes the allocation of ground hubs to the airport hubs (Figure 2.5(b)). At the second layer, a star structure is considered for the allocation of the ground hubs, as well. Each ground hub is connected to exactly one airport hub with a highway link. Big trucks, which are faster and have more capacity than pickup trucks, are used at these highway segments and so economies of scale is considered.



(a) Third Layer



(b) Second Layer



(c) First Layer

Figure 2.5: Layers of the Hierarchical Hub Network

A mesh structure is considered at the first (top) layer (Figure 2.5(c)). Airport hubs are connected with each other with an airline segment. On these airline segments, airplanes are considered.

As we stated earlier; one of the aims of this study is to decrease the number of vehicles by changing the structure of the network. If a mesh structure is considered for the top layer of the hierarchy, high number of airplanes is required. Therefore, instead of a mesh hub network, another type of network topology can be used. Since the main aims are to decrease the number of airplanes and so to increase the utilization of the airplanes on hand, ring structure(s) can be efficient for the structure at the top layer. Therefore, ring structure(s) is considered at the top layer of hierarchy (Figure 2.6). This network is called as Ring(s)-Star-Star (R-S-S) network. In order to construct the ring structure(s), routing and scheduling decisions must be considered together. In other words, Vehicle Routing Problem (VRP) is considered at the top layer.

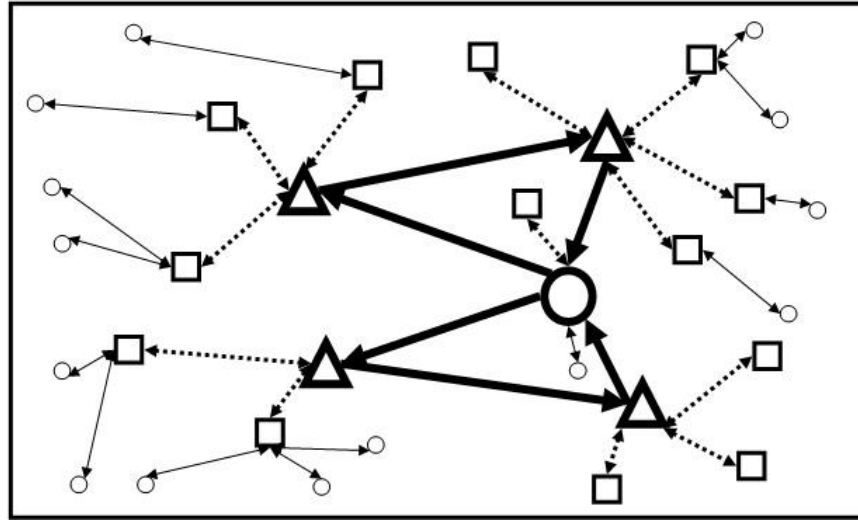


Figure 2.6: Ring(s)-Star-Star Network

With the rings structure at the top layer, the route of the airplane is decided while covering all origin-destination pairs in a given time bound. Tours are considered in the

routing decisions. In this study, we consider “first pick then deliver” type of service, which means that there are two separate tours. One of them is pickup tour(s) and the other is delivery tour(s). Initially, in the pickup tour(s), all demands are picked from their origins and they are sent to a specific airport hub. In these tours, there is no delivery. After all demands arrive at this airport hub, then in the delivery tour(s), all demands are sent to their final destinations. Since we need a specific airport hub in order to collect all demands at one point, one of the airport hubs is assigned as the central airport hub. In Figure 2.6, central airport hub is represented as a big circle instead of triangle. If one airplane is not enough to cover all origin-destination pairs, there can be more than one airplane which travels among the airport hubs by drawing circles. Therefore, ring(s) can be constructed.

For the “first pick then deliver” type of service that we analyze, picking up from the origin and delivering to the destinations must be symmetrical. Therefore, the route of the delivery tour(s) is the reverse route of the pickup tour(s). In order to show the necessity of the reverse ordering, an example is analyzed in detail. Consider Figure 2.7. The hubs and demand nodes are numbered so that the central airport hub is 0, the airport hubs are from 1 to 4, the ground hubs are numbered from 5 to 8, and finally, demand nodes are from 9 to 12. In this example, we assume that all travel times between connected nodes are 1, except the travel time between 7 and 11, which is assumed to be 2. Then, we calculate the release times for all vehicles at the hubs. Based on the network at the Figure 2.7, at time 4, all demands are at the central airport hub and so at time 8, all demands can be delivered to their destination. Let us consider the flow from 10 to 11 in more detail. The cargo will travel along the path 10-6-2-1-0 in its pick-up tour and arrives at the central airport hub at time 4. Then, it will be loaded on the airplane 0-4-3-0 to be unloaded at node 4 at time 5. Finally, it will travel along the path 4-7-11 with the arrival time of 8. Now consider the case where the delivery route is in the same order of the pick-up route (instead of the reverse one). Again, the cargo will travel along the path

10-6-2-1-0 in its pick-up tour and arrives at the central airport hub at time 4. Then, it will be loaded on the airplane 0-3-4-0 to be unloaded at node 5 at time 6. Finally, it will travel along the path 4-7-11 with the arrival time of 9, which is higher than the time bound 8. Therefore, in order to satisfy the time bound, delivery tour(s) must be reverse of the pick-up tour(s).

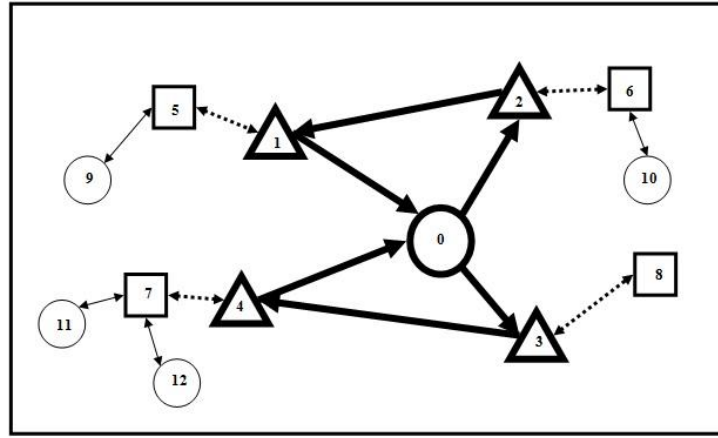


Figure 2.7: Pick-up Tour(s)

Since all origin-destination pairs must be covered in a given time bound, the tour of an airplane is also bounded by the time. Therefore, the flights of the airplane must be scheduled according to the time bound. The airplane(s) must complete the flights in half of the time bound for pickup tour so that they can complete delivery tours in the other half. Thus, we aim to utilize the airplane(s) by incorporating scheduling decisions.

Based on the proposed hierarchical multimodal network, the problem with ring structure(s) at the top layer can be defined as follows, given a set of demand nodes, a set of possible locations for ground hubs, a set of possible locations for airport hubs, the location of the central airport hub, the number of hubs to be located, the time bound and the travel time parameters; our proposed problem determines the location of ground hubs and airport hubs, the allocation of demand nodes to the hubs (ground or air), the allocation of the ground hubs to the airport hubs and the location of airline segments

while ensuring that all origin-destination pairs can be served in the given time bound. In the objective function, number of total flights (airline segments) is minimized.

Similar to the ring structure(s) of the top layer, another ring structure(s) can be considered at second layer as well in order to decrease the number of the big trucks and to increase the utilization of the big trucks on hand (Figure 2.8). This topology is referred to as Ring(s)-Ring(s)-Star (R-R-S) network. With that configuration, when ring structure is considered on the second layer, routing and scheduling decisions are included at that layer, too. Therefore, in this problem, routings are considered for both top and second layer of this hierarchical network.

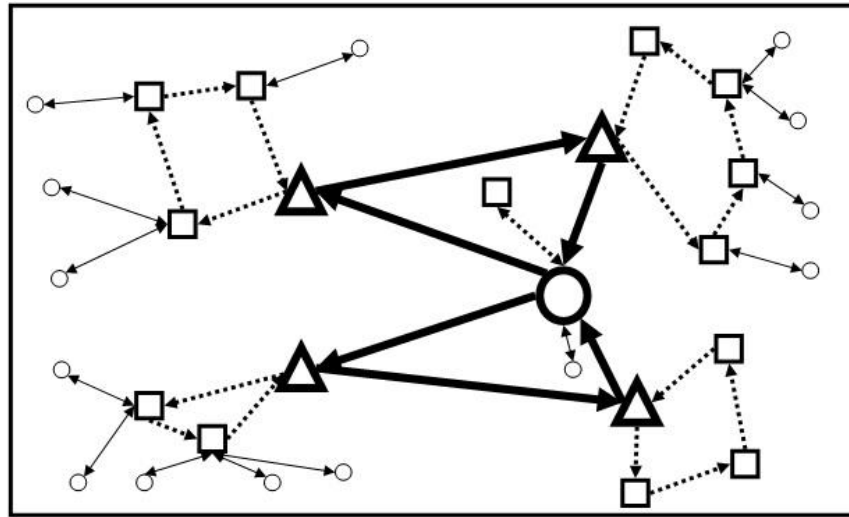


Figure 2.8: Ring(s)-Ring(s)-Star Network

Based on this hierarchical multimodal network, this problem is similar to the R-S-S problem. In this one, the locations of highway segments between hubs are also decided and in the objective function, the weighted sum of the number of flights and number of road trips (highway segments) is minimized.

Chapter 3

Literature Review

In this chapter, we review the hub location literature in four main categories. The first one is devoted to the pioneering works of the classical hub location problem. In this section, basic assumptions of the hub location problem are stated. In the following sections, some of these assumptions are relaxed and new problems based on the relaxed assumption are explained. The second part is based on the studies on the hub location problem with incomplete network structure. The third one is related to the literature on the hub location problem with ring structure(s). In the fourth part, the literature on the hub location problem with multimodal network is presented. Finally, the literature on the hierarchical hub location problem is reviewed. Also, the study on the hub location problem with both hierarchical and multimodal network is analyzed.

3.1 The Standard Hub Location Problems

The research interest in hub location problem is started with the studies of O’Kelly [1, 2, 3]. He basically defines this problem as follows; given a set of demand nodes, positive flow between origin-destination pairs and the required number of hubs, the hub location problem consists of two main decisions, which are the locations of hubs and the allocation of demand nodes to these hubs.

O’Kelly [3] presented the first mathematical formulation for the hub location problem. In this formulation, the objective is minimizing the transportation cost while satisfying the flow balance. Flow is considered as airline passengers. This first mathematical formulation in the hub location literature is later categorized as single allocation p-hub median problem. There are three main assumptions for this problem. First, the hubs in the network are fully interconnected. Second, there is economies of scale, which means there is a discount factor (α) for hub-hub links. Finally, there is no direct link between non-hub nodes.

Let W_{ij} be the flow between demand nodes i and j , and C_{ij} be the transportation cost of a unit of flow between demand nodes i and j , define x_{ik} as 1 if demand node i is allocated to the hub k , and 0 otherwise. In this situation, x_{kk} is 1, if demand node k is a hub and 0, otherwise. The first integer programming formulation for the single allocation p-hub median problem proposed by O’Kelly [3] is as follows;

$$\text{Minimize} \quad \sum_i \sum_j w_{ij} \left(\sum_k c_{ik} x_{ik} + \sum_m c_{jm} x_{jm} + \alpha \sum_k \sum_m c_{km} x_{ik} x_{jm} \right) \quad (3.1)$$

subject to

$$(n - p + 1)x_{kk} - \sum_i x_{ik} \geq 0 \quad \forall k \quad (3.2)$$

$$\sum_k x_{ik} = 1 \quad \forall i \quad (3.3)$$

$$\sum_k x_{kk} = p \quad (3.4)$$

$$x_{ik} \geq 0 \quad \forall i, k \quad (3.5)$$

In the above formulation, the objective function (3.1) calculates the transportation cost. This objective function is quadratic because of the fact that hub-to-hub link is a product of two allocation decisions. Constraint (3.2) ensures that no demand node is allocated to a non-hub node. Also, Skorin-Kapov et al. [12] suggested that constraint (3.2) can be replaced with:

$$x_{ik} \leq x_{kk} \quad \forall i, k \quad (3.6)$$

Constraints (3.3) and (3.5) ensure that every demand node must be allocated to exactly one hub. Constraint (3.4) ensures that number of hubs to be open is p .

Due to the quadratic nature of the objective function, the hub location problems differ from the classical location problems. In classical location problem, each demand node is allocated to the nearest facility. However, in the hub location problem, nearest allocation strategy may not give the optimal solution. Therefore, allocation decisions of demand nodes must also be determined.

Based on the classification of the hub location problem made by Campbell [4], the hub location problem consists of the p -hub median problem, the hub location problem with fixed costs, the p -hub center problem and hub covering problems.

3.1.1 The p-hub Median Problem

In the p-hub median problem, the objective is to minimize the total transportation cost while satisfying the flow balance between origin-destination pair and also ensuring that the number of hubs to locate is p .

Campbell [4] presented the first linear integer programming formulation for the single allocation p-hub median problem. Later, Skorin-Kapov et al. [12] proposed a new mixed integer formulation for this problem, which gives tighter LP relaxation bounds. However, large size problems cannot be solved with this formulation. Then, Ernst and Krishnamoorthy [13] produced a different linear integer programming formulation with fewer decision variables and constraints in order to solve larger problems. They reduced the size of the problem by considering transfers among hubs as a multicommodity flow problem. Kara [14] proved that the p-hub median problem is NP-hard. In order to solve this problem, also some heuristic approaches are considered by Skorin-Kapov and Skorin-Kapov [15], Campbell [16], Ernst and Krishnamoorthy [13, 17] and recently Ilic et al. [18].

3.1.2 The Hub Location Problem with Fixed Costs

In this problem, in addition to the total transportation cost, fixed cost of opening a hub is also included into objective function. O'Kelly [19] proposed the first formulation for the single allocation hub location problem with fixed costs. This formulation is in a quadratic integer form. Since the number of hub is not fixed, the capacitated and uncapacitated versions of this problem are considered. Campbell [4] presented the first linear programming formulation for the single allocation uncapacitated and capacitated hub location problem with fixed costs. For the capacitated version, Ernst and Krishnamoorthy [20] produced a new formulation, which is based on the linear integer programming formulation proposed by Ernst and Krishnamoorthy [13] for the p-hub

median problem. Heuristic approaches are studied by Abdinnour-Helm and Venkataramanan [21], Abdinnour-Helm [22], Topcuoglu et al. [23], Cunha and Silva [24] and Chen [25].

3.1.3 The p-hub Center Problem

The objective of the p-hub center problem is to minimize maximum transportation cost. Campbell [4] presented the first formulations for the different type of p-hub center problem. Kara and Tansel [26] proposed several linear formulations for the single allocation p-hub center problem. Ernst et al. [27] produced a new formulation for the single allocation p-hub center problem. This new formulation has more continuous variable, but fewer constraints than the formulation proposed by Kara and Tansel [26] and in terms of CPU time requirements, formulation developed by Ernst et al. [27] is better. Some heuristics are developed to solve this problem (see, e.g., Pamuk and Sepil [28], Meyer et al. [29] and Ernst et al. [27]).

3.1.4 Hub Covering Problem

In hub covering problems, the objective is to minimize the number of hubs to cover all demand while satisfying a budget constraint or a time bound constraint. Campbell [4] presented the first mixed integer formulations for the hub covering problems. Kara and Tansel [30] proposed various linear formulations for the single allocation hub set covering problem. Ernst et al. [31] developed a new formulation for this problem, which is based on the formulation proposed by Ernst et al. [27] for the p-hub center problem. In terms of CPU time requirements, formulation presented by Ernst et al. [31] performs better. Some heuristic approaches for the hub covering problem are Calik et al. [32] and Hwang and Lee [33].

For comprehensive surveys on hub location, we refer the reader to Campbell et al. [34], Alumur and Kara [35], Kara and Taner [36], and Campbell and O’Kelly [37].

3.2 The Hub Location Problem with Incomplete Hub Network Structure

The classical hub location problem is two-level with complete-star structure (complete for hub allocations and star for allocations of demand points). In the complete hub structure, hubs are fully interconnected that is one of the basic assumptions of the hub location problem. In the hub location literature, there exist some studies that relax this assumption and consider the incomplete hub network.

O’Kelly and Miller [38] introduced the incomplete hub network design to the literature. Nickel et al. [39] consider the multiple allocation hub location problems for urban public transport network. In addition to the total transportation cost, they also minimize the fixed cost of hub links. Campbell et al. [40, 41] introduced the hub arc location problems to the literature. In this problem, rather than locating hub facilities, hub arcs are located. Yoon and Current [42] also study the multiple allocation hub location problem with an incomplete hub network. They minimize total transportation cost and fixed cost of locating hubs and hub links. Alumur et al. [43] focus on the single allocation hub location problems over the incomplete hub networks. They define the single allocation incomplete p-hub median, the incomplete hub location with fixed costs, the incomplete hub covering and the incomplete p-hub center network design problems and proposed mathematical formulations for these problems.

The hub location problem is also studied in the context of telecommunication networks. In these networks, objective is to minimize the total cost of locating hubs and hub links. Therefore, for telecommunication applications, incomplete hub network design is considered. Many different types of network topologies such as star, tree, ring, and path are studied in the literature. Klincewicz [44] presented a review on the different type of the network structure of the location problem.

3.3 The Hub Location Problem with Ring Structure(s)

Based on the type of the proposed network, ring structure(s) concept in the literature is reviewed. “Ring structure(s)” on the hub location problem is firstly presented by Nagy and Salhi [45] as the many-to-many hub location-routing problem. In this study, it is stated that many-to-many location-routing problem can be reduced to the classical hub location problem when routing problem is not considered. They presented a mixed integer programming formulation and they proposed some solution techniques to solve this problem. They presented a hierarchical heuristic, in which hub location is considered as a master problem and routing problems as subproblems. Routing problems are solved via neighborhood search heuristic proposed by Nagy and Salhi [46]. Liu et al. [47] presented a mixed truck delivery system which allows both hub-and-spoke shipments and direct shipments. A heuristic is developed to decide the mode of delivery (hub-and spoke or direct) and perform vehicle routing in both delivery modes. Wasner and Zäpfel [48] presented a multi-depot hub location vehicle routing model for network design of parcel services. This model can be seen as a location-routing problem with the decision of the location of hubs and depots, and decision of routes between hubs/depots and their allocated demand points. Hub location part of this problem differs from the classical hub location problem with two aspects. Firstly, in this model, there can be a direct shipment between two demand points. Second one is that transportation cost between two hubs depends on the number of transports between those two hubs. They presented a mixed integer optimization model. However, due to the complexity of this model, a heuristic, which is based on local search procedure, was developed. A case study for Austria, which consists of one possible hub location, ten possible depot locations and 2042 demand points, was conducted. Çetiner et al. [49] proposed the combined hub location-routing problem, which includes the hub location decisions and also routing decision between demand points. This problem is developed for the postal delivery system in Turkey. In this study, multiple-allocation is allowed and it is assumed

that the hubs and the vehicles are uncapacitated. An iterative two-stage heuristic is developed to solve this problem. In the first stage, hub locations and the allocation of non hub nodes are determined. In the second stage, routes between demand points are decided. After the second stage, the distances between demand points are updated in order to solve the new hub location problem. Camargo et al. [50] presented a new formulation to the many-to-many hub location-routing problem. In this formulation, single allocation and uncapacitated hubs and vehicles are considered. The completion of a tour is bounded by a service level and each customer is visited exactly once. They solve the problem by using Benders decomposition algorithm. With this algorithm, large-size instances (up to 100 nodes) of this problem can be solved optimally.

3.4 The Hub Location Problem with Multimodal Network Structure

In the standard hub location problem, the mode decisions for type of transportation vehicles are not considered. The main assumption is that there are two transportation modes. One of them is between hubs and the other one is between hubs and non-hubs. In the literature, some researchers extend their study by considering transportation mode decisions in addition to location and allocation decisions and also by increasing number of transportation modes.

The first study of the hub location problem including the choice for transportation mode is proposed by O’Kelly and Lao [51]. In this study, there are two fixed hub locations, which are mini-hub and master-hub. This problem is solved by addressing two sub-problems. The first one is the decision of transportation mode (air or truck) while satisfying given time limitations. The second one is the allocation decision of cities to the mini-hub. Multimodal hub location and hub network design problem is first introduced by Alumur et al. [52]. In this study, in addition to the decisions of the

classical hub location problem, decision of the transportation mode is also considered. They presented a linear mixed integer programming model and they considered the different variants of this problem. Also, several valid inequalities and a heuristic are proposed.

3.5 The Hierarchical Hub Location Problem

As we mentioned before that classical hub location problem has two level structures. However, some studies relax that assumption and consider the hub network structure more than two levels. This type of network structure is referred as the hierarchical hub network.

Smilowitz and Daganzo [53] focus on the design of integrated package distribution systems for multiple transportation modes and multiple service level delivery network. They consider separate networks for each mode. For ground and air transportation mode, they propose ring(s)-ring(s)-complete and ring(s)-ring(s)-tree networks, respectively. They used continuum approximation approach to minimize the cost. Yaman [54] proposes a three level hub network, which consists of complete network at top level and star networks at the second and third level, is presented. According to its objective, this problem is considered as the hierarchical hub median problem. She also studies a different version of this problem by considering the service level quality. The author proposes a mixed integer programming model. Sahraeian and Korani [55] consider the same three level hub network structure as Yaman [54] did. However, they propose the maximal covering problem version with given cover radii.

Also, some researchers study both multimodal and hierarchical hub network structure together. Alumur et al. [10] presented a hierarchical multimodal hub location problem with time definite deliveries. In this study, a star-incomplete-star network with air and ground transportation mode is considered. They proposed a mixed integer programming

and a set of valid inequalities. In the mathematical model, they minimize the total transportation and operational costs.

In our study, a hub covering problem is proposed. Since we consider ring structure(s) at the top (and also second) layer(s), the proposed hub network is incomplete. Also, the hub network is multimodal and hierarchical. The similarities and differences between the proposed problem and the related hub location problems in the literature can be seen in the Table 3.1.

Table 3.1: Hub Network Design Literature

Year	Author(s)	Allocation Type	Hub Network	Topology	Hierarchical/ Multimodal hub network	Objective	Solution Strategy	Solution Size
1998	Nagy and Salhi [44]	Single	2-level	Complete-Ring(s)	No/No	Fixed Costs	Heuristic	249*249
2003	Liu et al. [46]	Single	2-level	Complete-Ring(s)	No/No	Minimize total distance	Heuristic	(10,15,20,25)*5
2009	Calik et al. [31]	Single	2-level	Incomplete-Star	No/No	Cover	Exact and Heuristic	CAB (10*10,15*15, 20*20) & TR (81*81)
2009	Ahumur et al. [42]	Single	2-level	Incomplete-Star	No/No	All	Exact	CAB (25*25) & TR (81*16)
2012	Ahumur et al. [51]	Single	2-level	Incomplete-Star	No/Yes	All	Exact and Heuristic	TR (25*8, 81*16) & CAB (25*15)
2013	Camargo et al. [49]	Single	2-level	Complete-Ring(s)	No/No	Fixed Costs	Exact	AP (10*10, ..., 100*100)
2001	Nickel et al. [38]	Multiple	2-level	Incomplete-Star	No/No	Fixed Costs	Exact and Heuristic	CAB (10*10)
2004	Wasner and Zapfel [47]	Multiple	2-level	Complete-Ring(s)	No/No	Fixed Costs	Heuristic	Austria (2042*10)
2008	Yoon and Current [41]	Multiple	2-level	Incomplete-Star	No/No	Fixed Costs	Exact and Heuristic	100*100
2010	Çetiner et al. [48]	Multiple	2-level	Complete-Ring(s)	No/No	Median	Heuristic	TR (81*38)
2009	Yaman [53]	Single	3-level	Complete-Star-Star	Yes/No	Median	Exact	CAB (25*25*25) & TR (30*17*10, 81*21*10)
2010	Salraeian and Korani [54]	Single	3-level	Complete-Star-Star	Yes/No	Maximal Cover	Heuristic	CAB (25*25*25)
2012	Ahumur et al. [10]	Single	3-level	Star-Incomplete-Star	Yes/Yes	Median	Exact	TR (81*22*19)
2013	Dükkancı and Kara	Single	3-level	Ring(s)-Star-Star & Ring(s)-Ring(s)-Star	Yes/Yes	Cover	Exact and Heuristic	TR (81*22*19) and CAB (25*25*25)

Chapter 4

Model Formulations

In this chapter, we formulate the hierarchical hub location problem with three layered structure. The organization of this chapter is as follows. Section 4.1 provides the mathematical formulation of the hierarchical hub location problem on a ring(s)-star-star (R-S-S) network. In addition to the mathematical formulation, some valid inequalities are proposed. In Section 4.2, the hierarchical hub location problem on a ring(s)-ring(s)-star (R-R-S) network is formulated.

4.1 The Hierarchical Hub Location Problem on a Ring(s)-Star-Star Network

In this problem, the hierarchical hub network is based on the R-S-S structure (Figure 4.1).

4.1.1 Problem Formulation

We propose a linear mixed integer mathematical model for the proposed problem. Given the node set, potential ground hub and airport hub locations, the model outputs the network configuration with ground hubs, airport hubs, the allocations of demand points to the ground or airport hubs and the allocations of ground hubs to the airport hubs, and the required airline segments with the minimum number of airline links while obeying the time bound.

Let D be the set of demand points, H be the set of possible hub locations ($H \subseteq D$), A be the set of possible airport hub locations ($A \subseteq H$), and O be the central airport hub ($O \in A$). Also, it is assumed that travel time data is symmetrical and satisfies triangular inequality.

The parameters of our mathematical model are as follows;

p = number of hubs

t_{ij} = travel time from node $i \in D$ to node $j \in D$ by truck

t_{ij}^{air} = travel time from node $i \in D$ to node $j \in D$ by airplane

α = discount factor of time for ground transportation

m_l = loading-unloading time at airport $l \in A$

T = time bound for each origin-destination pair

M = maximum travel time between a ground hub and an airport hub plus loading-unloading time at that airport

The decision variables of our mathematical model also depicted in Figure 4.1 are as follows;

$x_{ij} = 1$ if demand point $i \in D$ is allocated to hub $j \in H$; 0 otherwise

$y_{jl} = 1$ if hub $j \in H$ is allocated to airport hub $l \in A$; 0 otherwise

$u_{kl} = 1$ if there is a directed link between airport hub $k \in A$ and airport hub $l \in A$; 0 otherwise

r_j = the earliest time that all pickup trucks arrive at their allocated hub $j \in H$

$r_l^{airplane}$ = the earliest time that airplane departs from airport hub $l \in A$ towards other airport hubs

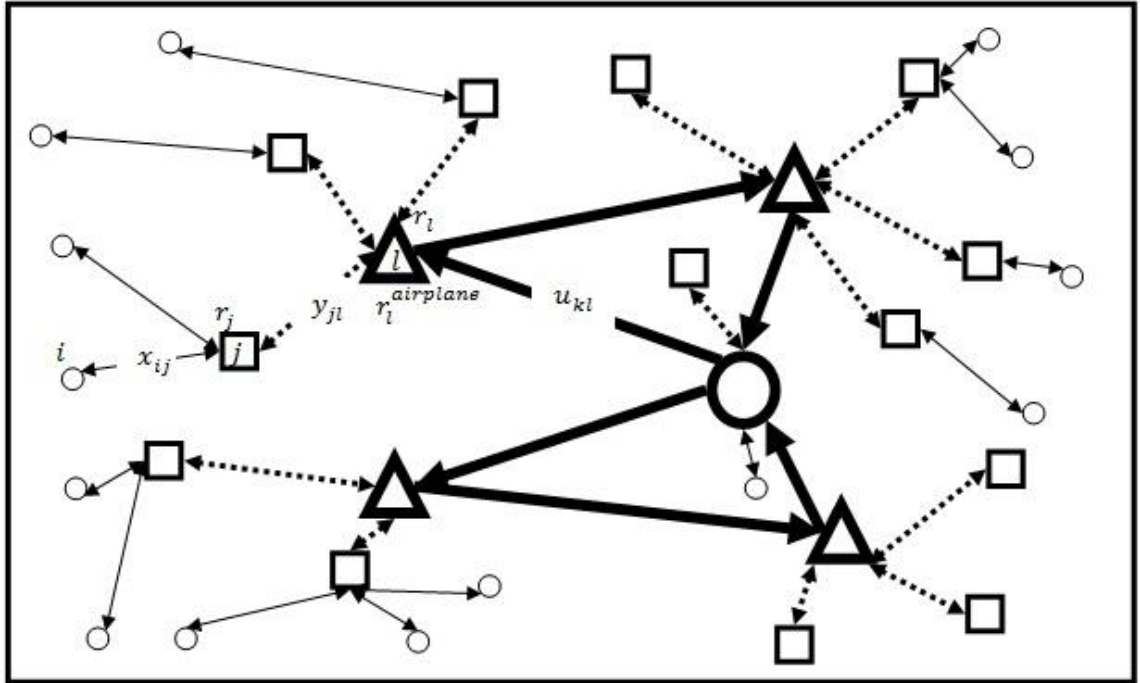


Figure 4.1: R-S-S Network

The mixed integer programming formulation of the proposed problem is as follows;

$$(R-S-S) \quad \text{Minimize} \quad \sum_{k \in A} \sum_{l \in A \setminus \{k\}} u_{kl} \quad (4.1)$$

subject to

$$\sum_k x_{ik} = 1 \quad \forall i \quad (3.3)$$

$$\sum_k x_{kk} = p \quad (3.4)$$

$$x_{ik} \leq x_{kk} \quad \forall i, k \quad (3.6)$$

$$\sum_{l \in A} y_{jl} = x_{jj} \quad \forall j \in H \quad (4.2)$$

$$y_{jl} \leq y_{ll} \quad \forall j \in H, l \in A \quad (4.3)$$

$$y_{jj} \leq x_{jj} \quad \forall j \in A \quad (4.4)$$

$$y_{00} = 1 \quad (4.5)$$

$$\sum_{l \in A \setminus \{k\}} u_{kl} = y_{kk} \quad \forall k \in A \quad (4.6)$$

$$\sum_{l \in A \setminus \{k\}} u_{lk} = y_{kk} \quad \forall k \in A \quad (4.7)$$

$$\sum_{l \in A \setminus \{0\}} u_{0l} = \sum_{l \in A \setminus \{0\}} u_{l0} \quad (4.8)$$

$$r_j \geq t_{ij} x_{ij} \quad \forall i \in D, j \in H \quad (4.9)$$

$$r_l^{airplane} \geq r_j + (\alpha t_{jl} + m_l) y_{jl} - M(1 - y_{jl}) \quad \forall j \in H, l \in A \setminus \{j\} \quad (4.10)$$

$$r_k^{airplane} - r_l^{airplane} + T u_{kl} \leq T - (t_{kl}^{air} + m_l) u_{kl} \quad \forall k \in A \setminus \{0\}, l \in A \setminus \{k\} \quad (4.11)$$

$$r_k^{airplane} \geq (t_{0k}^{air} + m_k) u_{0k} \quad \forall k \in A \setminus \{0\} \quad (4.12)$$

$$2r_0^{airplane} \leq T \quad (4.13)$$

$$x_{ik} \geq 0 \quad \forall i, k \quad (3.5)$$

$$y_{jl} \in \{0,1\} \quad \forall j \in H, l \in A \quad (4.14)$$

$$u_{kl} \in \{0,1\} \quad \forall k \in A, l \in A \setminus \{k\} \quad (4.15)$$

$$r_l^{airplane} \geq 0 \quad \forall l \in A \quad (4.16)$$

The objective function (4.1) minimizes the operational cost of airline links between airport hubs. Observe here that, multiplying each link with a parameter, one can easily convert this function to operational cost.

The Constraints (3.3)-(3.6) are the classical hub location constraints as explained in the Chapter 2. By Constraint (4.2), a hub is allocated to exactly one airport hub. Constraint (4.3) guarantees that no hub is allocated a non airport hub. That is, if a hub is allocated to an airport hub, then this airport hub must be opened. Due to Constraint (4.4), if an airport hub is established in a node, then in this node, a hub must be opened. Constraint (4.5) establishes the central airport hub. Constraints (4.6) and (4.7) construct the ring structure(s) for the airport hubs (top layer of the hierarchical network). Constrains (4.8) allows to structure with more than one ring, which means that there can be more than one airplane, if necessary.

Constraint (4.9) calculates the earliest time that pickup trucks arrive at their allocated hub. Constraint (4.10) determines the earliest time that all pickup trucks from demand points and big trucks from ground hubs, which are allocated to the same airport hub, arrive at that airport hub. With Constraint (4.11), we ensure that the earliest time that an airplane departs from any airport hub is within predetermined time bound. We remark here that Constraint (4.11) also acts as sub-tour breaking constraints. Constraint (4.12) calculates the earliest time that airplane departs from the airport hub, which has a directed link from the central airport hub. We compute this time separately in order to complete ring structure(s) for the top layer. By Constraints (4.13), we guarantee that all origin-destination pairs are covered in a given time bound. Since we assume the

symmetric travel time data, we consider the pickup and delivery as the same, so we multiply by 2. Finally, constraints (4.14) – (4.16) are the domain constraints

This mathematical model is a mixed binary programming model with $O(n^2)$ binary variables, $O(n)$ non-negative variables, and $O(n^2)$ constraints.

4.1.2 Valid Inequalities

In this section, some valid inequalities are presented. These valid inequalities are based on the time restriction.

Actually, the first one is a variable fixing rule, which can be included into the model as pre-processing. However, in our model, we consider it as a valid inequality. For $i \in D$ and $j \in H \setminus \{i\}$, if $t_{ij} > T/2$, then demand node i cannot be allocated to the hub (ground or airport) j , since travel time between the city i and city j exceeds half of the time bound T . Therefore, the inequality

$$(t_{ij} - T/2)x_{ij} \leq 0 \quad \forall i \in D, j \in H \setminus \{i\} \quad (4.17)$$

is valid. With Constraint (4.17), if $t_{ij} > T/2$, then x_{ij} will be equal to 0 that means demand node i cannot be assigned to hub j .

For $i \in D$, $j \in H \setminus \{i\}$ and $l \in A \setminus \{i, j\}$, if $t_{ij} + \alpha * t_{jl} + m_l > T/2$, then demand node i cannot be allocated to the ground hub j and ground hub j cannot be allocated to the airport hub l at the same time. Therefore, the inequality

$$x_{ij} + y_{jl} \leq 1 \quad \forall i \in D, j \in H \setminus \{i\}, l \in A \setminus \{i, j\}, \text{ if } t_{ij} + \alpha * t_{jl} + m_l > T/2 \quad (4.18)$$

is valid. With Constraint (4.18), if travel from demand node i to the airport hub l through ground hub j exceeds the half of the time bound, then x_{ij} and y_{jl} will not be equal to 1 at the same time.

The performances of these two valid inequalities are explained in detail in Chapter 5.

4.2 The Hierarchical Hub Location Problem on a Ring(s)-Ring(s)-Star Network

This problem considers the hierarchical hub location on the R-R-S network. In this network, the second layer also consists of ring(s) (Figure 4.2).

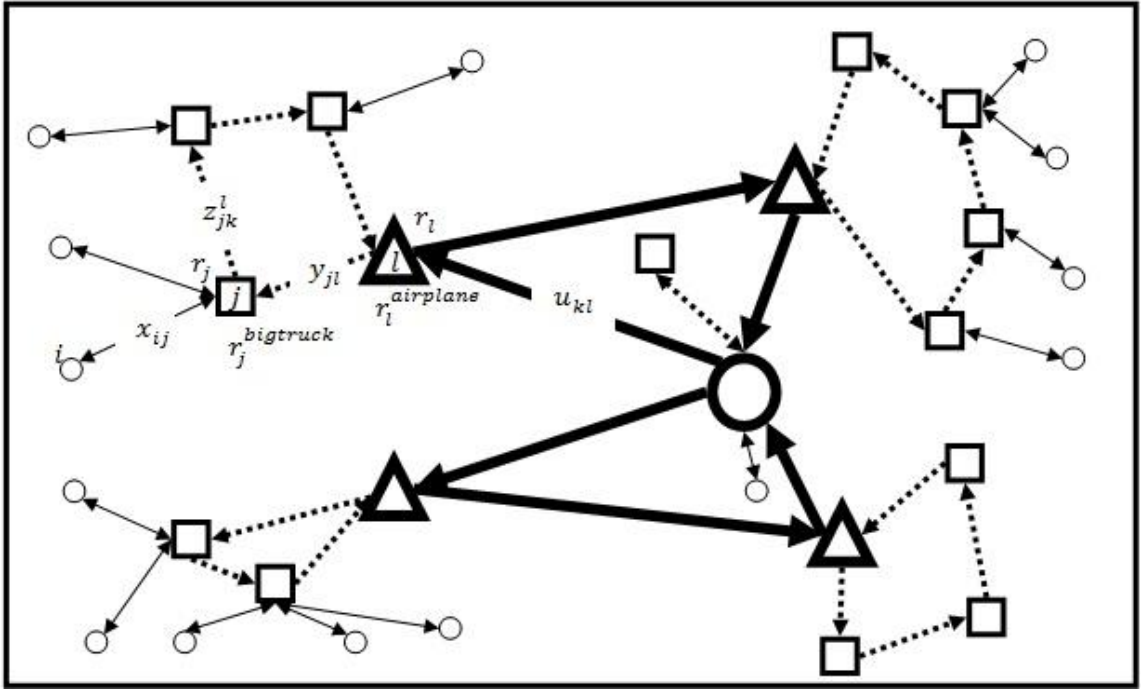


Figure 4.2: R-R-S Network

4.2.1 Problem Formulation

For this problem, a linear mixed integer mathematical model is presented. Given the node set, potential ground hub and air hub locations, the model outputs the network configuration with ground hubs, airport hubs, the allocations of demand points to the ground or airport hubs and the allocations of ground hubs to the airport hubs, and the

required airline and highway segments with the minimum number of airline and highway links while obeying the time bound.

Let D be the set of demand points, H be the set of possible hub locations ($H \subseteq D$), A be the set of possible airport hub locations ($A \subseteq H$), and 0 be the central airport hub ($0 \in A$).

The parameters and decision variables explained in Section 4.1.1 are also valid for this problem. The additional parameters and variables are as follows;

β = coefficient for airline segments between airport hubs

γ = coefficient for ground segments between hubs (ground or air)

$z_{jk}^l = 1$ if there is a directed link between hub $j \in H$ and hub $k \in H$ and these two hubs are allocated to the same airport hub $l \in A$

$r_l^{bigtruck}$ = the earliest time that big truck departs from hub $l \in H$ towards other hubs

The mixed integer programming formulation of the proposed problem is as follows;

$$(R-R-S) \quad \text{Minimize} \quad \beta \sum_{k \in A} \sum_{l \in A \setminus \{k\}} u_{kl} + \gamma \sum_{j \in H} \sum_{k \in H \setminus \{j\}} \sum_{l \in A} z_{jk}^l \quad (4.19)$$

subject to

$$\sum_k x_{ik} = 1 \quad \forall i \quad (3.3)$$

$$\sum_k x_{kk} = p \quad (3.4)$$

$$x_{ik} \leq x_{kk} \quad \forall i, k \quad (3.6)$$

$$\sum_{l \in A} y_{jl} = x_{jj} \quad \forall j \in H \quad (4.2)$$

$$y_{jl} \leq y_{ll} \quad \forall j \in H, l \in A \quad (4.3)$$

$$y_{jj} \leq x_{jj} \quad \forall j \in A \quad (4.4)$$

$$y_{00} = 1 \quad (4.5)$$

$$\sum_{l \in A \setminus \{k\}} u_{kl} = y_{kk} \quad \forall k \in A \quad (4.6)$$

$$\sum_{l \in A \setminus \{k\}} u_{lk} = y_{kk} \quad \forall k \in A \quad (4.7)$$

$$\sum_{l \in A \setminus \{0\}} u_{0l} = \sum_{l \in A \setminus \{0\}} u_{l0} \quad (4.8)$$

$$\sum_{j \in H \setminus \{k\}} z_{jk}^l = y_{kl} \quad \forall k \in H, l \in A \setminus \{k\} \quad (4.20)$$

$$\sum_{j \in H \setminus \{k\}} z_{kj}^l = y_{kl} \quad \forall k \in H, l \in A \setminus \{k\} \quad (4.21)$$

$$\sum_{j \in H \setminus \{l\}} z_{jl}^l = \sum_{j \in H \setminus \{l\}} z_{lj}^l \quad \forall l \in A \quad (4.22)$$

$$r_j \geq t_{ij} x_{ij} \quad \forall i \in D, j \in H \quad (4.9)$$

$$\begin{aligned} r_k^{airplane} - r_l^{airplane} + T u_{kl} \\ \leq T - (t_{kl}^{air} + m_l) u_{kl} \end{aligned} \quad \forall k \in A \setminus \{0\}, l \in A \setminus \{k\} \quad (4.11)$$

$$r_k^{airplane} \geq (t_{0k}^{air} + m_k) u_{0k} \quad \forall k \in A \setminus \{0\} \quad (4.12)$$

$$\begin{aligned} r_j^{bigtruck} - r_k^{bigtruck} + T z_{jk}^l \\ \leq T - \alpha z_{jk}^l t_{jk} \end{aligned} \quad \forall l \in A, j \in H \setminus \{l\}, k \in H \setminus \{j\} \quad (4.23)$$

$$r_j^{bigtruck} \geq \alpha t_{lj} z_{lj}^l \quad \forall j \in H, l \in A \setminus \{j\} \quad (4.24)$$

$$r_j^{bigtruck} \geq r_j \quad \forall j \in H \quad (4.25)$$

$$r_k^{airplane} \geq r_k^{bigtruck} + m_k \quad \forall k \in A \quad (4.26)$$

$$2r_0^{airplane} \leq T \quad (4.13)$$

$$x_{ik} \geq 0 \quad \forall i, k \quad (3.5)$$

$$y_{jl} \in \{0,1\} \quad \forall j \in H, l \in A \quad (4.14)$$

$$u_{kl} \in \{0,1\} \quad \forall k \in A, l \in A \setminus \{k\} \quad (4.15)$$

$$z_{jk}^l \in \{0,1\} \quad \forall j \in H, k \in H \setminus \{j\}, l \in A \quad (4.27)$$

$$r_l^{airplane} \geq 0 \quad \forall l \in A \quad (4.17)$$

$$r_l^{bigtruck} \geq 0 \quad \forall l \in H \quad (4.28)$$

In this model, the objective function (4.19) minimizes the weighted sum of the operational cost of airline and highway segments among airport hubs and ground hubs ($\gamma < \beta$). Again, multiplying each link with a parameter, one can easily convert this function to operational cost.

Constraints (3.3)-(3.6); (4.2)-(4.9); (4.11)-(4.17) are from the R-S-S model. Constraints (4.20) and (4.21) construct the ring structure(s) for the ground hubs (second layer of the hierarchical hub network). Constrains (4.22) allows to structure with more than one ring for one airport hub, which means that there can be used more than one big truck, if necessary.

With Constraint (4.23), we ensure that the earliest time that a big truck departs from any ground hub is within predetermined time bound. Also, we remark that Constraint (4.23) acts as sub-tour breaking constraints for the big truck tours. Constraint (4.24) calculates the earliest time that a big truck departs from the ground hub, which has a directed link from its allocated airport hub. We compute this time separately in order to complete ring structure(s) for the second layer. Constraint (4.25) ensures that a big truck departs from the hub, after the arrival of all demands from its demand nodes. Constraint (4.26) guarantees that an airplane departs from the airport hub, after the arrival of all demands from its ground hubs and loading of all demands to the airplane.

Constraints (4.27) and (4.28) are the domain constraints for the additional variables.

This mathematical model is a mixed binary programming model with $O(n^3)$ binary variables, $O(n)$ non-negative variables, and $O(n^3)$ constraints.

We remark here that; since we do not change star structure for the third layer, the two valid inequalities from the R-S-S model can be used for this model, too. So, Constraints (4.17) and (4.18) are also used for this model.

Chapter 5

Computational Settings and the Performance of the Valid Inequalities

In this chapter, we present data sets for the computational studies and the performance of the proposed valid inequalities. The organization of this chapter is as follows. Section 5.1 presents two data sets and their settings. In Section 5.2 we evaluate the performance of the valid inequalities.

5.1 Data Sets

In our computational studies, we use two different data sets, which are Civil Aeronautics Board (CAB) and Turkish network (TR) data sets. CAB data set is based on the airline passenger interactions between 25 cities in United States in 1970. Initially, O’Kelly [3]

introduced this data set. Then, almost all of the hub location researchers used and referred CAB data set. Recently, a Turkish network introduced to literature by Tan and Kara [6]. This data set consists of 81 cities in Turkey as demand points. For data on the CAB and Turkish network data sets, the reader is referred to Beasley [56].

For Turkish network, we consider 81 cities of Turkey as demand points, 22 of 81 cities as potential ground hub and 19 of 22 cities as potential airport hub.



Figure 5.1: Turkey Map with cities and potential hub set

In Figure 5.1, numbers represent the city plate numbers of the 81 cities of Turkey. There are 22 potential hub nodes which are represented as circles. The 19 potential airport hubs are among these 22 nodes except Afyon (3), Aksaray (68) and Düzce (81) since there are not any airports in these cities. The central airport hub is considered as Ankara (6) due to its geopolitical advantageous location. Also, Ankara has the second biggest amount of flow in Turkey.

The time discount factor α is taken as 0.9. The distance data is taken from Tan and Kara [6]. The travel times are calculated by assuming that the trucks travel at a speed of 70 km/hr. Also, it is assumed that the airplanes travel at a speed of 700 km/hr. The loading/unloading time at an airport is taken as 30 minutes.

For R-R-S model, coefficients β and γ in the objective functions are taken as 10 and 5 in order to show the airline segments are more costly than the ground segments.

For CAB data set, we consider 25 cities of USA as demand points, potential ground and airport hubs.

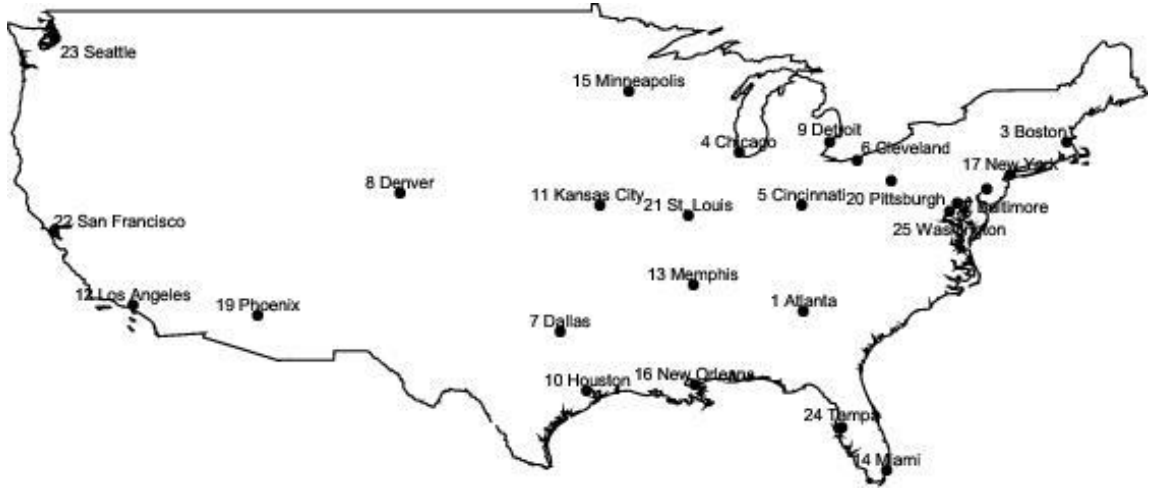


Figure 5.2: USA Map with 25 cities

In Figure 5.2, 25 nodes represent the demand nodes, potential ground and airport hubs on the USA map. The central airport hub is assigned to Atlanta (1) since it can be considered as located in the center of most of the cities.

The distance data is taken from O’Kelly [3]. The other settings are the same as on the Turkish network.

Computational studies are carried on a server with 4 * AMD Opteron Interlagos 6282 SE and 96 GB of RAM and we used optimization software Gurobi version 5.0.2.

5.2 Performance of the Valid Inequalities

First of all, we tested the performance of the two valid inequalities proposed at Section 4.1.2 on Turkish network. In order to compare the results, we solved the R-S-S model for four different cases, which are without any valid inequalities, with valid inequality 1, with valid inequality 2 and with both valid inequalities. The results are depicted in Table 5.1.

Table 5.1: Performance of the Valid Inequalities

T (hours)	p	No Valid Inequalities			Valid Inequality 1			Valid Inequality 2			Valid Inequalities 1 & 2		
		LP Gap (%)	CPU (sec)	Nodes	LP Gap (%)	CPU (sec)	Nodes	LP Gap (%)	CPU (sec)	Nodes	LP Gap (%)	CPU (sec)	Nodes
20	4	100	16.35	6878	93.33	1.38	1809	85.19	35.47	4789	84.13	2.03	186
20	5	100	22.59	6861	93.33	1.91	2567	85.19	3.93	1989	84.62	1	289
20	6	100	25.65	11115	93.33	1.78	1875	85.19	4.65	580	84.62	1.24	235
19	5	100	119.99	62882	95	15.16	14845	87.88	70.86	46934	82.96	9.59	6090
19	6	100	774.9	205396	93.75	471.79	93363	84.85	83.05	43834	78.7	23.49	16829
19	7	100	921.56	193631	93.75	29.67	42728	84.85	47.47	16372	78.7	20.71	15631
18	6	100	1634.21	979047	95.83	587.58	195782	88.6	1510.33	1909969	82.92	45.59	95145
18	7	100	4053.67	2468013	95.83	958.12	802993	88.6	2973.94	4549037	82.92	87.49	142728
18	8	100	12616.09	12426118	95.83	1331.65	1686378	88.6	2747.19	1200807	82.92	177.87	228203
17	6	100	2653.43	1561049	92.86	777.06	148201	85.71	4417.5	4102597	78.57	94.44	85117

The first two columns of Table 5.1 represent the parameters; the time bound (T) and number of hubs to be opened (p). “No Valid Inequalities” columns show the results without the inclusion of any valid inequalities. “Valid Inequality 1” and “Valid Inequality 2” columns indicate solutions with the inclusion of Valid Inequality 1 and Valid Inequality 2, respectively. Finally, “Valid Inequalities 1&2” columns represent solutions with the inclusion of both Valid Inequalities 1&2. The columns indicated by “LP Gap (%)” and “CPU (sec)” show the gap of the linear programming relaxation from the optimal value and the CPU time requirement in seconds, respectively. Finally, the columns represented by “Nodes” present number of nodes which are evaluated in branch-and-bound tree.

As can be seen from Table 5.1, the gap of linear programming relaxation (LP gap) for “No Valid Inequality” case is 100% for each instance because in these instances, the objective function value for the linear programming relaxation is equal to 0. When we compare LP gap for each case, the inclusion of valid inequalities 1 and 2 separately and together decreases the LP gap for all instances. Also, for all instances, lowest LP gaps are obtained by the inclusion of both valid inequalities 1 and 2.

As you can see from Table 5.1, with the inclusion of just Valid Inequality 1, CPU time is decreased for all 10 instances. Also, with the inclusion of just Valid Inequality 2, there is an improvement in the CPU time for all instances except 2 ($T = 20/p = 4$ and $T = 17/p = 6$). Finally, with the inclusion of both Valid Inequality 1 and 2, again CPU time is reduced for all 10 instances. When we compare the “Valid Inequality 1”, “Valid Inequality 2” and “Valid Inequality 1&2” columns in terms of the CPU time, the highest improvement can be observed on the “Valid Inequality 1&2” column for all instances except one. At the instance with $T = 20$ and $p = 4$, the model with Valid Inequality 1 is faster than then the model with Valid Inequality 1 and 2 by approximately 0.65 seconds.

When we consider the number of nodes in the branch-and-bound tree, with the inclusion of valid inequalities 1 and 2 separately and together, the number of nodes generally decreases. For all instances, the inclusion of both valid inequalities causes the lowest number of nodes.

Since for all instances, including both valid inequalities results the lowest LP gap and number of nodes to be evaluated in the branch-and-bound tree and also for most of the instances (9 out of 10), the inclusion of Valid Inequality 1&2 has highest improvement in the CPU time, we include these two valid inequalities for the rest of the computational studies.

Chapter 6

Computational Analysis of the R-S-S Model

In this chapter, the computational results for the R-S-S model are analyzed. In Section 6.1 the effects of the time bound (T) and the number of hubs to be located (p) is presented. In Section 6.2 the hierarchical hub location problem on a star-star-star (S-S-S) network is presented and also the optimal solutions with S-S-S and R-S-S models are compared. Section 6.3 analyzes results based on the percentage of the coverage in a time bound. In Section 6.4, the effects of the location of the central airport hub are evaluated. Finally, Section 6.5 presents the effect of the discount factor for time (α).

6.1 Effects of the T bound and the p value

Initially, we varied the time bound and number of hubs to be established on Turkish network. The time bound is evaluated between 24 and 14 hours. When the time bound is between 1 hour and 12 hours, the problem is infeasible. Also, instances for 13 hours cannot be solved within 1 day-CPU time. On the other hand, for parameter p , the number of hubs for each T bound, we started from the first feasible p value. We tried to have results for 5 or 6 different p values as long as the CPU time allows. The CPU time requirement of the model increases exponentially with p . Thus for some T values we only report results with 2 or 3 different p values. The results can be seen in Table 6.1 and 6.2.

The first two columns on the Table 6.1 and Table 6.2 represent the two parameters; T and p . The third and fourth columns on the table present the optimal objective function value, which is the number of airline links and number of airplanes, respectively. Fifth column lists the locations of airport hubs. The sixth column presents the location of ground hubs and their allocated airport hubs in the parenthesis. Finally, the last column indicates the CPU time to solve the instances to optimality.

As can be seen from Table 6.1, 2 airline segments and 2 airport hubs with 1 airplane are enough to cover all origin-destination pairs in Turkey within 24, 23, 22 hours. When we decrease T to 21 hours, 3 airport hubs are required with 3 airline segments. Then, if we increase p from 3 to 4, 2 airport hubs with 2 airline segments are enough to cover because of two additional ground hubs which shows the importance of the ground hubs. Additionally, when $T = 20$ and $p = 3$, the problem instance is infeasible. If we increase p from 3 to 4, then there is a solution with 3 airport hubs and one ground hub rather than 4 airport hubs.

Table 6.1: Results of R-S-S Model on TR Data Set (Ankara (6), $20 \leq T \leq 24$)

T (hours)	p	Objective Function	Number of Airplanes	Locations of Airport Hubs	Locations of Ground Hubs(allocated Airport Hubs)	CPU time (sec)
24	2	2	1	6, 25	-	0.1
24	3	2	1	6, 23	21(23)	0.23
24	4	2	1	6, 23	44(23), 65(23)	1.41
24	5	2	1	6, 65	23(6), 25(6), 55(6)	0.6
24	6	2	1	6, 23	21(23), 34(6), 61(6), 68(6)	0.5
24	7	2	1	6, 23	1(23), 7(6), 21(23), 27(6), 61(6)	1.08
23	2	2	1	6, 25	-	0.1
23	3	2	1	6, 23	44(23)	0.27
23	4	2	1	6, 65	27(6), 61(6)	0.6
23	5	2	1	6, 23	16(6), 21(23), 25(23)	0.74
23	6	2	1	6, 23	25(23), 44(23), 61(6), 65(23)	0.67
23	7	2	1	6, 21	23(21), 27(6), 35(6), 61(6), 81(6)	0.73
22	2	2	1	6, 23	-	0.11
22	3	2	1	6, 23	25(23)	0.24
22	4	2	1	6, 23	21(23), 25(23)	2.89
22	5	2	1	6, 23	44(23), 55(6), 65(23)	3.07
22	6	2	1	6, 23	21(23), 25(23), 44(23), 61(23)	1.32
22	7	2	1	6, 23	1(6), 20(6), 25(23), 44(23), 65(23)	1.13
21	3	3	1	6, 21, 25	-	0.26
21	4	2	1	6, 25	1(6), 65(25)	0.8
21	5	2	1	6, 25	1(6), 21(25), 65(25)	0.92
21	6	2	1	6, 25	1(6), 23(25), 65(25), 81(6)	1.82
21	7	2	1	6, 25	23(25), 27(6), 55(6), 61(25), 65(25)	2.79
21	8	2	1	6, 25	7(6), 16(6), 26(6), 27(6), 61(25), 65(25)	0.81
20	4	3	1	6, 21, 25	81(6)	2.03
20	5	3	1	6, 21, 25	34(6), 61(25)	1
20	6	3	1	6, 21, 25	27(21), 34(6), 38(21)	1.24
20	7	3	1	6, 21, 25	7(6), 34(6), 68(6), 81(6)	1.33
20	8	3	1	6, 21, 25	5(6), 23(25), 27(6), 34(6), 38(21)	1.44
20	9	3	1	6, 21, 25	5(6), 23(21), 27(6), 34(6), 3(6), 81(6)	1.12

Table 6.2: Results of R-S-S Model on TR Data Set (Ankara (6), $14 \leq T \leq 19$)

T (hours)	P	Objective Function	Number of Airplanes	Locations of Airport Hubs	Locations of Ground Hubs(allocated Airport Hubs)	CPU time (sec)
19	5	5	2	6, 21, 25, 26	27(21)	9.59
19	6	4	1	6, 21, 25, 34	26(6), 27(21)	23.49
19	7	4	1	6, 21, 25, 34	23(21), 26(6), 27(21)	20.71
19	8	4	1	6, 21, 25, 34	7(6), 16(6), 27(21), 81(6)	12.33
19	9	4	1	6, 21, 25, 34	16(6), 23(25), 27(21), 61(25), 65(21)	31.29
19	10	4	1	6, 21, 25, 34	7(6), 23(5), 26(6), 27(21), 65(21), 3(6)	18.02
18	6	6	2	6, 16, 23, 25, 65	20(6)	45.59
18	7	6	2	6, 16, 23, 25, 65	20(6), 21(23)	87.49
18	8	6	2	6, 27, 34, 61, 65	16(34), 20(6), 23(27)	177.87
18	9	6	2	6, 23, 34, 61, 65	16(6), 20(6), 21(23), 25(23)	408.78
18	10	6	2	6, 27, 34, 61, 65	20(6), 21(65), 23(27), 25(61), 44(6)	177.3
18	11	6	2	6, 23, 26, 61, 65	16(26), 20(6), 21(23), 25(23), 27(23), 34(26)	483.98
17	6	7	2	6, 16, 20, 25, 27, 65	-	94.44
17	7	7	2	6, 1, 25, 34, 35, 65	27(1)	559.84
17	8	7	2	6, 16, 25, 26, 27, 65	20(26), 35(6)	2282.25
16	6	9	4	6, 16, 20, 44, 61, 65	-	59.17
16	7	9	4	6, 20, 34, 44, 61, 65	26(6)	2382.76
16	8	8	3	6, 7, 16, 25, 27, 65	21(25), 55(6)	8509.38
15	8	10	3	6, 20, 21, 25, 27, 34, 61, 65	-	4510.63
14	8	11	4	6, 20, 21, 25, 27, 34, 61, 65	-	3633.69
14	9	10	3	6, 1, 20, 21, 25, 34, 61, 65	16(34)	38645.65
≤ 12	22	infeasible				

When we further decrease the time bound to 19 hours, 2 airplanes are required to cover all cities in Turkey with 4 airport hubs and one ground hub and also we need 5 airline

segments (Table 6.2). If we continue to decrease the time bound to 16, 15, 14 hours, which are very tight time bounds for the Turkish network, the number of airline segments increases to 9, 10, 11 and also the number airplanes increases to 3 or 4. Also, as it can be seen in the table, for each time bound level, when we increase p , the additional hub is opened as a ground hub because each additional airport hub can lead to increase the number of airline segments, which our model try to minimize as the objective function.

For the loose time bound such as 24, 23, 22 and 21 hours, there are many alternative optimal solutions. Generally, for this time bounds, 2 airport hubs are required. One of them is Ankara (06) as the central airport hub and the other one is usually from the eastern part of Turkey, such as Diyarbakır (21), Elazığ (23), Erzurum (25) and Van (65). For instance, let $T = 23$ and $p = 5$. 2 airport and 3 ground hubs are opened. The location of one airport hub is Ankara (06) and the other one is Elazığ (23) (Figure 6.1).

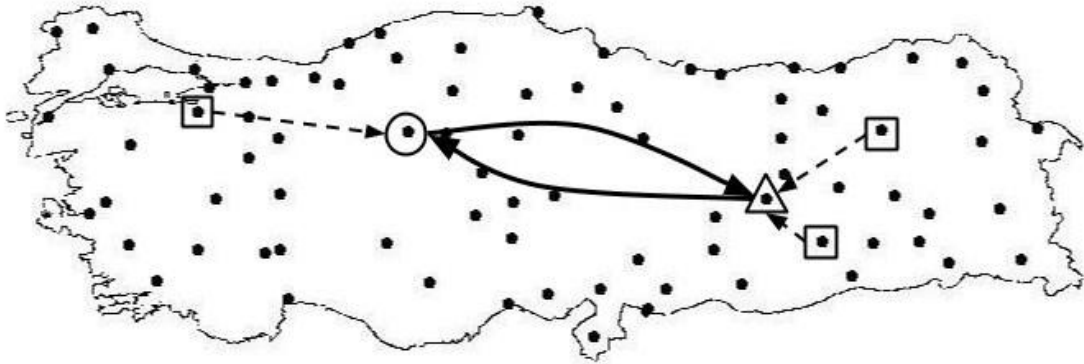


Figure 6.1: Result of the R-S-S Model on Turkey map ($T = 23$, $p = 5$)

When we reduce the time bound, the number of airport hubs increases. For $T = 20$, three airport hubs are required, which are Ankara (6), Diyarbakır (21) and Erzurum (25) which serve western, south-eastern and north-eastern part of Turkey, respectively. When we decrease T to 19 hours, one more airport hub is required, because Ankara (6) cannot

cover Edirne (22) and Kırklareli (39). Therefore, a new airport hub is opened in Eskişehir (26) or İstanbul (34). For $T = 18$, number of airport hubs is equal to 5 for all instances. In these instances, again Ankara (6) serves the western side of Turkey with one more airport hub which is Bursa (16), Eskişehir (26) or İstanbul (34). The three other airport hub serve the eastern part of Turkey. One of them is Elazığ (23) or Gaziantep (27), which are located in the south-eastern of Turkey. One of them is Erzurum (25) or Trabzon (61), which are located in the north-eastern of Turkey. The last one is Van (65), which is in the most eastern part of Turkey. For example, when $T = 18$ and $p = 6$; 5 airport and one ground hub are opened in order to serve within 18 hours. The locations of airport hubs are Ankara (6), Bursa (16), Elazığ (23), Erzurum (25) and Van (65). With the same time bound, the problem is infeasible, if the number of hubs to be opened is equal to 5. Therefore, the additional ground hub has an important role. In this instance, the location of ground hub is Denizli (20), which cover the southwestern cities of Turkey such as Aydın (9) and Muğla (48) (Figure 6.2).

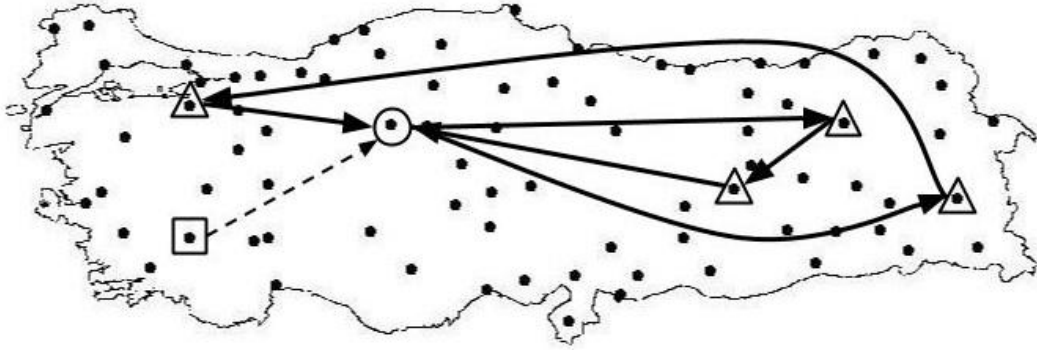


Figure 6.2: Result of the R-S-S Model with $T = 18$, $p = 6$

We also remark here that, Van (65) is the only city that remains as a serving airport hub for all instances when time bound is 18 hours or less. The reason for that is to serve Hakkari (30), which is the farthest city from Ankara (06). Since all demands are

collected at the central airport hub, demands from Hakkari (30) are sent to Ankara through airport hub at Van (65). If the time bound is 12 hours or less, then there is no feasible solution due to the Hakkari (30). Even if an airport hub is opened in Van (65), Hakkari (30) cannot be covered when the central airport hub is Ankara (06).

When we decrease the time bound and increase the number of hubs to be opened, the CPU time generally increases because the influence of the number of hubs to be opened on the CPU time requirement is bigger than the effect of the time bound.

If the time bound is between 24 and 20 hours, the model is solved within a few seconds for all instances. If it is between 19 and 14 hours, the CPU time requirement is within 2 hours except two instances. These two instances are; $T = 16/p = 8$ and $T = 14/p = 9$. When $T = 16$ and $p = 7$, the optimal objective function value is equal to 9. With one additional hub ($T = 16/p = 8$), this value decreases to 8, which causes the high CPU time (Table 6.2). In the second instance, then $T = 14$ and $p = 8$, the optimal objective function value is equal to 11. With one more hub ($T = 14/p = 9$), it reduces to 10, which again increases the CPU time (Table 6.2).

Next, we report the results on the CAB data set. For the CAB data set, we also varied the time bound and number of hubs to be located. The central airport hub is Atlanta. Since USA is much bigger than Turkey in terms of area, the service time level must be higher. Therefore, we varied T from 72 to 28 hours and p from the first feasible value to the threshold value which is explained for Turkish data set. The R-S-S model is infeasible when time bound is 22 hours or less. The results can be found in Table 6.3 and 6.4.

Table 6.3: Results of R-S-S Model on CAB Data Set (Atlanta (1), $50 \leq T \leq 72$)

T (hours)	p	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	2	1	1, 12	-	0.07
72	3	2	1	1, 19	12(19)	0.26
72	4	2	1	1, 19	22(19), 23(19)	1.94
70	2	2	1	1, 12	-	0.07
70	3	2	1	1, 19	18(1)	0.29
70	4	2	1	1, 22	4(1), 23(22)	1.83
68	2	2	1	1, 19	-	0.14
68	3	2	1	1, 19	22(19)	0.23
68	4	2	1	1, 23	19(1), 22(23)	1.42
66	2	2	1	1, 19	-	0.19
66	3	2	1	1, 12	22(12)	0.34
66	4	2	1	1, 8	22(8), 23(8)	1.29
64	2	2	1	1, 8	-	0.2
64	3	2	1	1, 12	22(12)	1.16
64	4	2	1	1, 8	12(8), 23(8)	1.95
62	2	2	1	1, 22	-	0.17
62	3	2	1	1, 22	24(1)	1.91
62	4	2	1	1, 22	19(22), 23(22)	1.88
60	2	2	1	1, 22	-	0.16
60	3	2	1	1, 8	22(8)	0.75
60	4	2	1	1, 12	19(12), 22(12)	0.63
58	2	2	1	1, 22	-	0.15
58	3	2	1	1, 22	11(1)	0.35
58	4	2	1	1, 22	12(22), 23(22)	0.68
56	2	2	1	1, 22	-	0.08
56	3	2	1	1, 22	9(1)	0.23
56	4	2	1	1, 22	8(1), 12(22)	0.78
54	3	2	1	1, 8	23(8)	0.29
54	4	2	1	1, 22	8(1), 19(22)	0.67
54	5	2	1	1, 12	8(1), 22(12), 23(12)	0.71
52	3	2	1	1, 22	8(22)	0.16
52	4	2	1	1, 22	8(1), 13(1)	0.67
52	5	2	1	1, 12	8(12), 19(12), 23(12)	0.75
50	3	3	1	1, 12, 22	-	0.8
50	4	2	1	1, 8	22(8), 23(8)	0.62
50	5	2	1	1, 8	13(1), 22(8), 23(8)	1.96

Observe from Table 6.3 that one airplane and two airport hubs are enough to cover United States when the time bound is between 52 and 70 hours. The location of one airport hub is Atlanta as the central airport hub. The other one is in one of the east side cities of USA, which is either Denver (8), Los Angeles (12), Phoenix (19), San Francisco (22) or Seattle (23).

Table 6.4: Results of R-S-S Model on CAB Data Set (Atlanta (1), $28 \leq T \leq 48$)

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
48	3	3	1	1, 8, 22	-	1.02
48	4	3	1	1, 19, 22	23(22)	1.8
48	5	3	1	1, 19, 23	9(1), 12(19)	2.07
46	3	3	1	1, 8, 22	-	0.66
46	4	3	1	1, 19, 22	23(22)	1.37
46	5	3	1	1, 19, 22	9(1), 22(19)	2.73
44	4	3	1	1, 19, 23	3(1)	1.95
44	5	3	1	1, 8, 22	12(22), 18(1)	2.26
44	6	3	1	1, 19, 22	2(1), 3(1), 8(19)	1.76
42	4	5	2	1, 9, 19, 23	-	1.98
42	5	3	1	1, 19, 23	15(1), 18(1)	2.75
42	6	3	1	1, 19, 23	2(1), 8(19), 15(1)	5
40	4	5	2	1, 19, 20, 23	-	4.58
40	5	4	1	1, 5, 19, 23	22(19)	20.28
40	6	4	1	1, 18, 19, 23	3(18), 15(1)	89.03
38	5	5	2	1, 19, 20, 23	22(19)	25.25
38	6	5	1	1, 6, 8, 22, 23	19(8)	86.04
38	7	5	1	1, 8, 20, 22, 23	6(20), 19(8)	147.98
36	5	5	1	1, 2, 11, 12, 23	-	13.72
36	6	5	1	1, 6, 8, 12, 23	17(6)	121.87
36	7	5	1	1, 6, 8, 12, 23	2(1), 14(1)	197.9
34	5	5	1	1, 8, 9, 12, 23	-	21.77
34	6	5	1	1, 8, 9, 12, 23	14(1)	42.51
34	7	5	1	1, 6, 8, 12, 23	2(1), 20(6)	116.21
32	6	6	2	1, 6, 11, 12, 23	10(11)	380.44
32	7	6	2	1, 2, 11, 12, 23	7(11), 10(11)	1019.49
32	8	6	2	1, 6, 11, 12, 23	2(6), 7(1), 10(1)	1932.36
30	7	6	2	1, 11, 12, 18, 23	8(11), 10(1)	316.5
30	8	6	2	1, 11, 12, 23, 25	8(11), 10(1), 20(25)	408.97
30	9	6	2	1, 3, 11, 12, 23	8(11), 9(1), 10(1), 18(3)	565.89
28	8	8	2	1, 4, 8, 12, 13, 23, 25	24(1)	2418.7
28	9	7	2	1, 11, 12, 16, 18, 23	8(11), 9(1), 24(1)	11031.02
28	10	7	2	1, 10, 11, 12, 20, 23	8(11), 14(1), 19(12), 22(12)	7029.8
≤ 22	25	infeasible				

If the time bound is between 44 and 50 hours, then generally one airplane and three airport hubs are required (Table 6.4). Except the central airport hub, the other two are chosen from again the east side cities. When we reduce T to 42 hours or less, the second airplane is needed for the low p value. If we increase p , then again just one airplane is enough to cover. For 42 hours or less, Seattle (23) is the only city that remains the airport hub because Seattle is the farthest city from Atlanta and in order to cover that city, an airport hub must be opened in Seattle. Also, for 36 hours or less, Los Angeles (12) is the other city where an airport hub is located. When the time bound is 32 hours or less, 2 airplanes are required.

Similar to Turkish network, when we reduce T and increase p , generally, the CPU time increases. When the time bound is between 42 and 72 hours, the problem is solved within a few seconds. If it is between 28 and 40 hours, the CPU time does not exceed two hours except one instance. This instances is $T = 28/p = 8$. When $T = 28$ and $p = 7$, the optimal objective function value is equal to 8. With one additional hub ($T = 28/p = 8$), the problem try to find a solution with a lower objective function value, which is 7 in this instance, so it causes the high CPU time.

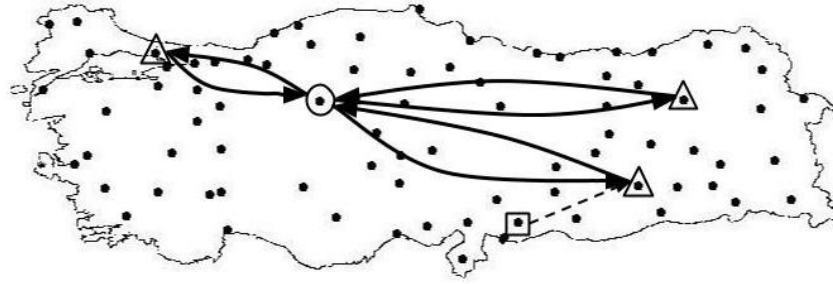
6.2 Comparison of the Solutions of the S-S-S and R-S-S Models

In this section we aim to analyze the effect of the routing at the top layer of the hierarchical network. For that, we first construct the model when there is no routing at the top level, i.e. the three layered network when all layers have star structure. Alumur et al. [10] presented the hierarchical hub location problem on a star-incomplete (mesh)-star network. They propose a linear mixed integer mathematical model for this problem. In this model, cost and flow are also considered. We adapt this model to the S-S-S model by eliminating cost and flow part. Also, at the second layer, we consider the star

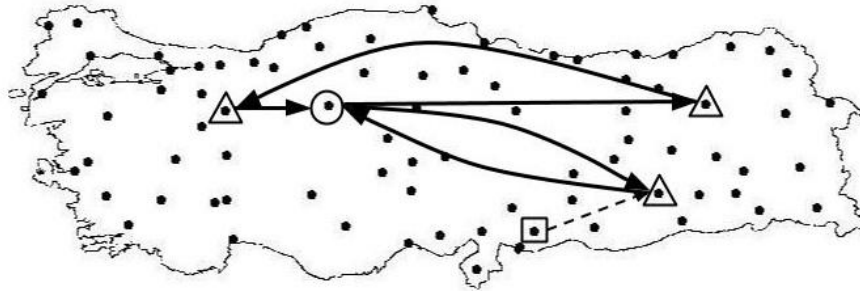
structure instead of an incomplete (mesh) structure. Therefore, we propose the S-S-S model, which is the updated version of model in Alumur [10]. The objective functions of the S-S-S and R-S-S models are the same. We first carried out a computational study for the S-S-S model on Turkish network. The results are summarized in Appendix 1. Secondly, some solutions of the S-S-S and R-S-S models are compared. Next, these instances are evaluated in detail.

For example, consider $T = 19$ and $p = 5$ case of the S-S-S model. In Figure 6.3(a), you can see the results on the Turkish map. Based on this solution, 4 airport hubs and one ground hub are opened. The airport hubs are Ankara (06), Diyarbakır (21), Erzurum (25) and İstanbul (34) and the ground hub is Gaziantep (27). Since there are 3 airport hubs except the central airport hub, three airplanes are used to cover Turkey within 19 hours.

On the other hand, when we consider the R-S-S model for this instance, the number of airplanes decreases from 3 to 2 in order to cover Turkey (Figure 6.3(b)). Also, the location of just one airport hub changes from İstanbul (34) to Eskişehir (26). The locations of other hubs (airport and ground) remain the same.



(a) The Outputs of S-S-S Model

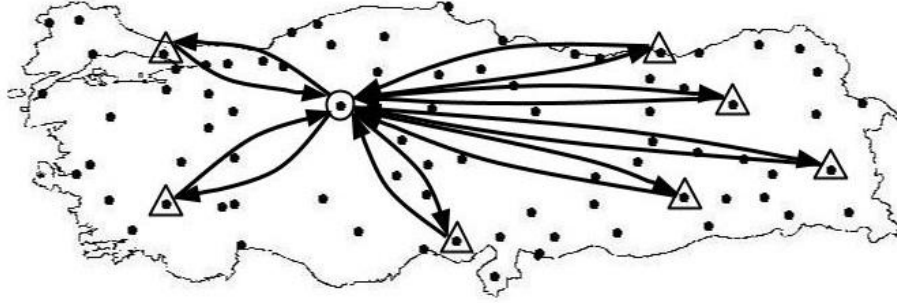


(b) The Outputs of R-S-S Model

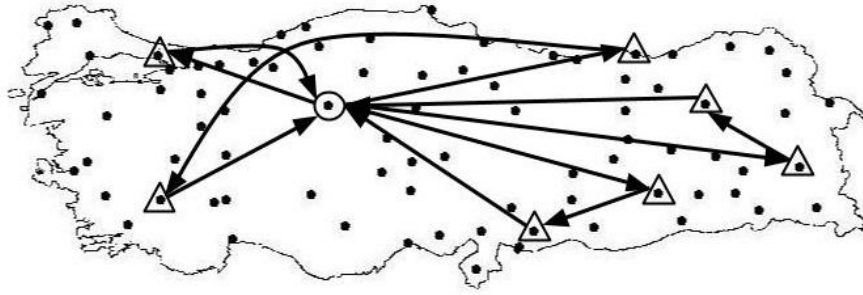
Figure 6.3: Results with $T = 19$, $p = 5$

In the second instance, T and p are equal to 14 and 8, respectively. Based on the S-S-S solution, 8 airport hubs are opened, which are Adana (01), Ankara (06), Denizli (20), Diyarbakır (21), Erzurum (25), İstanbul (34), Trabzon (61) and Van (65) (Figure 6.4(a)). In this case, 7 airplanes are required to cover Turkey.

When we solved the R-S-S model, just 4 airplanes are enough to cover Turkey within 14 hours (Figure 6.4(b)). Again, the location of just one airport hub changes from Adana (01) to Gaziantep (27). The locations of other airport hubs do not change.



(a) The Outputs of S-S-S Model



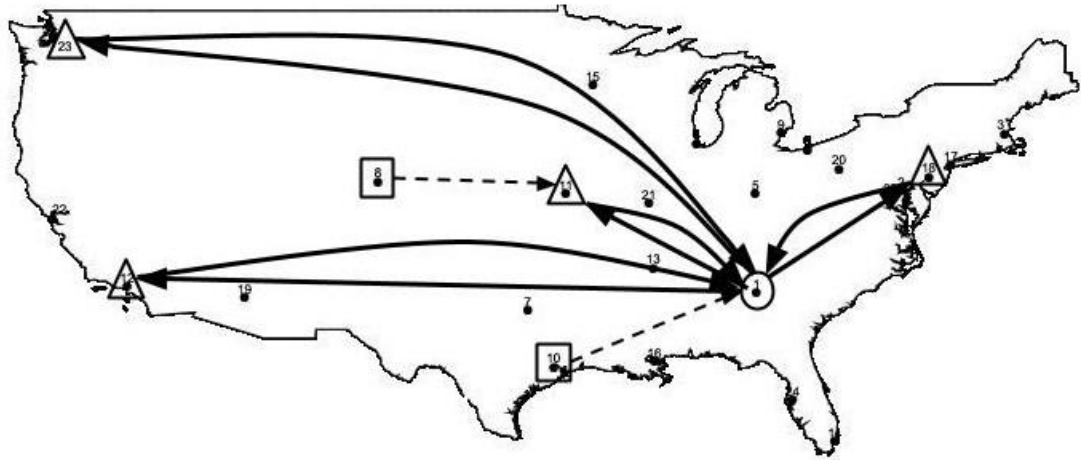
(b) The Outputs of R-S-S Model

Figure 6.4: Results with $T = 14$, $p = 8$

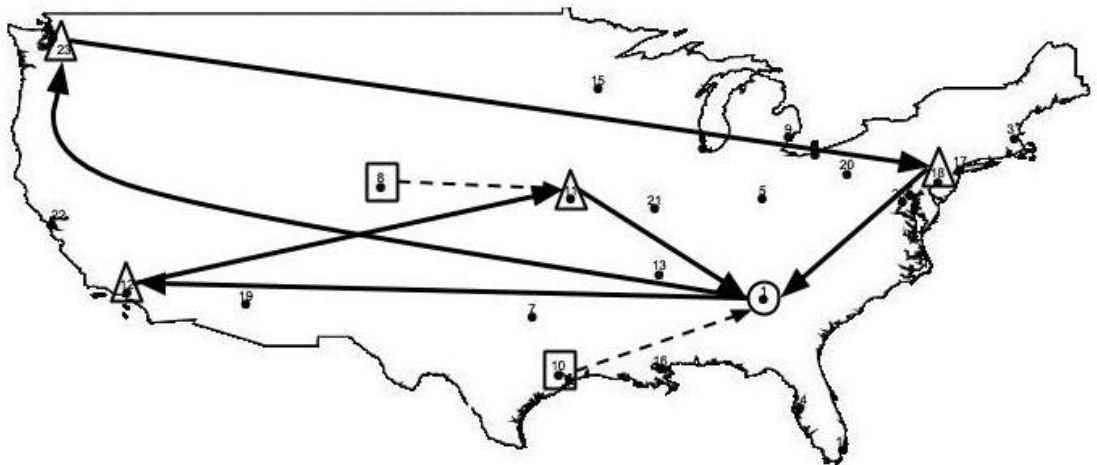
A similar analysis is also carried out over CAB data set. The results of the S-S-S model are summarized in Appendix 2. Furthermore, some solutions of the S-S-S and R-S-S models are compared on CAB data set. We now analyze these instances in detail.

For example, for $T = 30$ and $p = 7$ case. The resulting map of the S-S-S solution is depicted in Figure 6.5(a). According to the solution, 5 airport hubs and 2 ground hubs are opened. The airport hubs are located in Atlanta (1), Kansas City (11), Los Angeles (12), Philadelphia (18) and Seattle (23) and the ground hubs are established in Denver (8) and Houston (10). 4 airplanes are used to serve USA within 30 hours.

When we consider the R-S-S model, we can reduce the number of airplanes from 4 to 2 even without changing the locations of ground and airport hubs (Figure 6.5(b)). As you can see in the maps, the locations of hubs are the same.



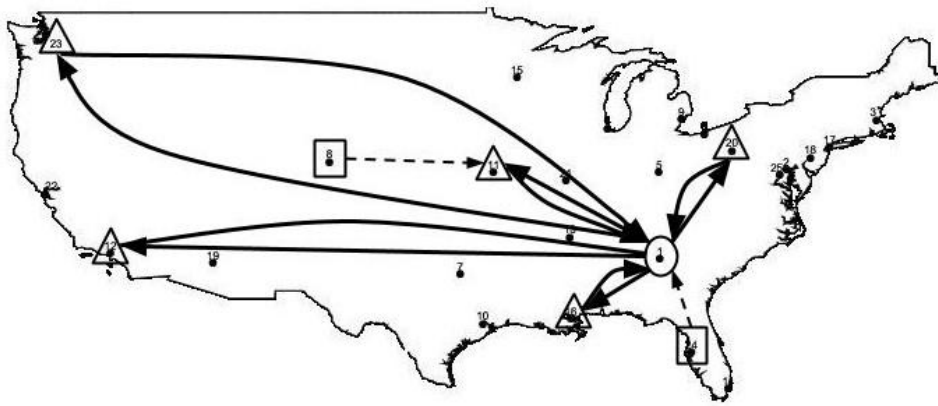
(a) The Outputs of S-S-S Model



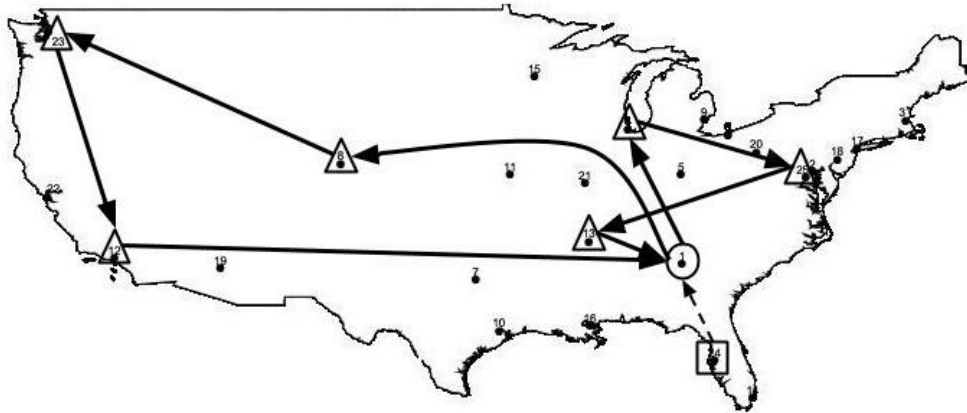
(b) The Outputs of R-S-S Model

Figure 6.5: Results with $T = 30$, $p = 7$

In the second instance, T and p are equal to 28 and 8, respectively. The solution of the S-S model can be seen in Figure 6.6(a). Based on this solution, 5 airplanes are required to cover the United States with 6 airport hubs and 2 ground hubs. The locations of airport hubs are Atlanta (1), Kansas City (11), Los Angeles (12), New Orleans (16), Pittsburgh (20) and Seattle (23). Furthermore, the locations of two ground hubs are Denver (8) and Tampa (24).



(a) The Outputs of S-S-S Model



(b) The Outputs of R-S-S Model

Figure 6.6: Results with $T = 28$, $p = 8$

On the other hand, when we solved the R-S-S model, 2 airplanes are enough to serve all 25 cities of USA within 28 hours. In this solution, 7 airport hubs and one ground hub are established (Figure 6.6(b)). The locations of airport hubs are Atlanta (1), Chicago (4), Denver (8), Los Angeles (12), Memphis (13), Seattle (23) and Washington (25); and the location of the ground hub is Tampa (24). The locations of three hubs change when compared to the solution of star-star-star network. Also, Denver (8) is used as an airport hub instead of a ground hub.

Several comparisons are conducted on both Turkish network and CAB data sets. As a result of these comparisons, we conclude that for the same time bound, by considering ring(s)-star-star network rather than star-star-star network, the number of airplanes and the number of airline segments can be reduced.

6.3 Analysis of the R-S-S Model Outputs for Specific Time Bounds

While analyzing the outputs, we observe that although all origin-destination pairs are covered within the fixed time bound T , some of them are covered within a bound far less than the time bound T over the proposed network. Therefore, we analyzed the percentage of the coverage in a time bound by calculating the service time for each origin-destination (o-d) pair on the Turkish data set. We evaluate some instances in this regard.

In the first instance, the time bound is 19 hours and the number of hubs to be established is equal to 5. After calculating the service time for every origin-destination pair, we compute the percentage of the coverage based on the service time (Table 6.5). This

analysis indicates that actually nearly 70% of origin-destination pairs are covered within 14 hours.

Table 6.5: The Coverage Percentages of o-d Pairs for $T = 19$, $p = 5$

Service Time (hours)	Percentage of the Coverage (%)
19	100
18	97.78
16	88.52
14	68.89
12	43.58

For the second instance, we take $T = 14$ and $p = 8$. The percentages are given in Table 6.6. According to this analysis, approximately 70% of all origin-destination pairs are covered within 10 hours. As it can be seen from Table 6.5 and 6.6, when we tighten up the time bound, the average service time also improves. For instance, in the first instance ($T = 19$), 43.58 % of origin-destination pairs is covered within 12 hours. In the second one ($T = 14$), this percentage increases to 95.89. Also, in the first instance, nearly 70% of origin destination pairs are covered within 14 hours. On the other hand this percentage of pairs is covered within 10 hours.

Table 6.6: The Coverage Percentages of o-d Pairs for $T = 14$, $p = 8$

Service Time (hours)	Percentage of Cover (%)
14	100
12	95.89
10	69.04
8	31.17

6.4 The Effects of the Different Central Airport Hubs on the Solutions

In this section, we analyze the effect of the central airport hub location on the solution time and the overall service quality of the R-S-S model. Therefore, different cities on the Turkish network are considered as the central airport hub. We first set İstanbul (34) as the central airport hub because it is the largest city of Turkey in terms of population, so it has the highest amount of demand in Turkey. We also consider İzmir (35) as it is the third largest city of Turkey after İstanbul (34) and Ankara (06). We varied the time bound and the number of hubs to be located, when the central airport hub is İstanbul (34) and İzmir (35). The results can be seen in Appendix 3 and Appendix 4. The tables are in the same format as in the Ankara case. As can be seen in the Turkish map, İstanbul and İzmir are located in the north-western and western part of Turkey, respectively. On the other hand, Ankara is nearly located in the center of Turkey. These geographical positions of the cities directly affect the results. One of the effects is that some p values become infeasible when the central airport hub is not Ankara. For instance, when $T = 23$ and $p = 2$, if the central airport hub is Ankara, there exists a solution. On the other hand, if it is İstanbul or İzmir, the problem is infeasible, because the time bound cannot be satisfied with two hubs. In order to satisfy the time bound, at least 4 and 3 hubs are required for İstanbul and İzmir, respectively.

We analyze four time bound levels for three different central airport hubs. The results can be seen in Table 6.7 and 6.8. As you can see from the table, if the central airport hub is Ankara, it requires less airline segments compared to İstanbul and İzmir because of the geographical position of the cities. For the loose service levels, each city requires one airplane. When we decrease the time bound, generally İstanbul and İzmir need more airplanes than Ankara does. When we consider the location of airport and ground hubs, generally they differ from each other. However, since all these three cities are located in

the west side of Turkey, usually airport hubs are opened in the eastern part of Turkey, such as Diyarbakır (21), Elazığ (23), Erzurum (25), Gaziantep (27), Trabzon (61) and Van (65). Lastly, when the central airport hub is Ankara, the CPU time requirements are lower compared to İstanbul and İzmir case for all instances.

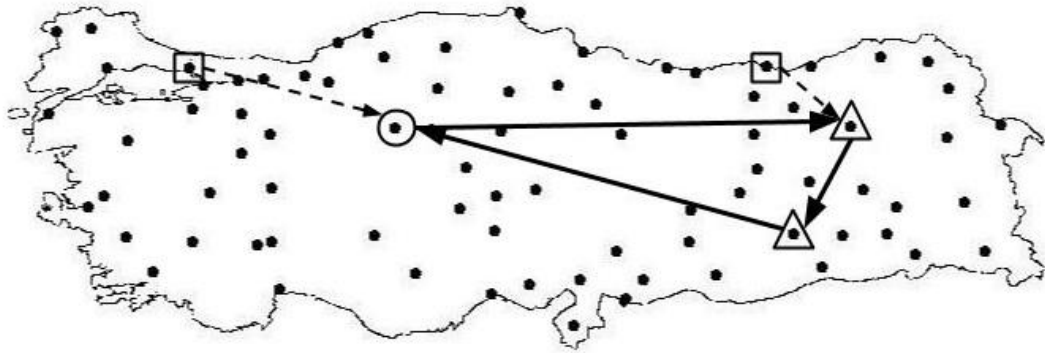
Table 6.7: Results with Different Central Airport Hub Locations 1 (TR Data Set)

T (hours)	P	Ankara			İstanbul			İzmir		
		Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)
24	3	2	1	0.23	2	1	0.42	3	1	0.49
24	4	2	1	1.41	2	1	1.51	3	1	4.31
24	5	2	1	0.6	2	1	2.37	3	1	8.69
22	4	2	1	2.89	4	1	3.73	4	1	6.01
22	5	2	1	3.07	3	1	35.67	4	1	64.59
22	6	2	1	1.32	3	1	30.32	4	1	53.65
20	5	3	1	1	6	2	24.45	5	2	40.99
20	6	3	1	1.24	5	2	48.26	5	1	54.31
20	7	3	1	1.33	5	2	1075.54	5	2	673.28
18	6	6	2	45.59	7	2	220.11	7	2	576.77
18	7	6	2	87.49	7	2	1648.95	7	2	3473.75
18	8	6	2	177.87	7	2	3578.53	7	2	8058.78

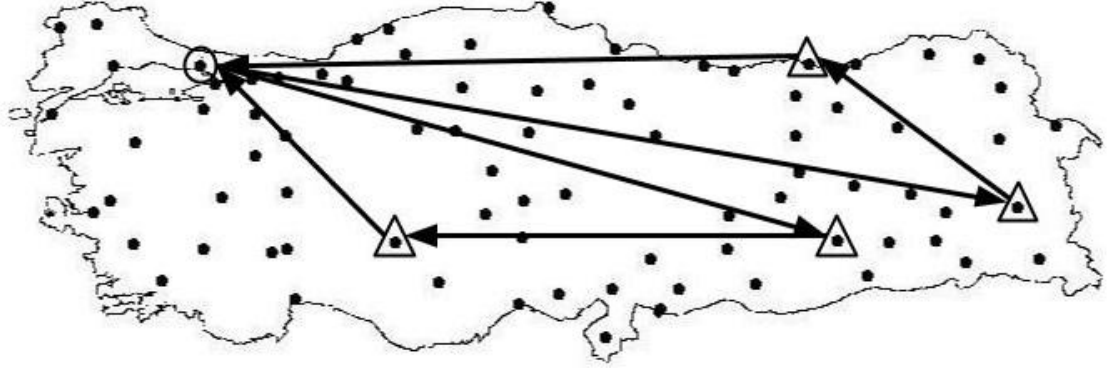
Table 6.8: Results with Different Central Airport Hub Locations 2 (TR Data Set)

T (hours)	p	Ankara			İstanbul			İzmir	
		Airport Hubs	Ground Hubs(allocated Airport Hubs)	Airport Hubs	Airport Hubs	Ground Hubs(allocated Airport Hubs)	Airport Hubs	Ground Hubs(allocated Airport Hubs)	Airport Hubs
24	3	6, 23	21(23)	34, 23	34, 23	44(23)	35, 6, 23	-	-
24	4	6, 23	44(23), 65(23)	34, 23	34, 23	25(23), 44(23)	35, 5, 23	25(23)	25(23)
24	5	6, 65	23(6), 25(6), 55(6)	34, 23	34, 23	21(23), 25(23), 44(23)	35, 23, 55	25(23), 65(23)	25(23), 65(23)
22	4	6, 23	21(23), 25(23)	34, 6, 21, 25	34, 6, 21, 25	-	35, 6, 21, 25	-	-
22	5	6, 23	44(23), 55(6), 65(23)	34, 25, 38	34, 25, 38	35(34), 65(25)	35, 6, 21, 25	23(21)	23(21)
22	6	6, 23	21(23), 25(23), 44(23), 61(23)	34, 25, 44	34, 25, 44	35(34), 42(34), 65(25)	35, 6, 21, 25	27(6), 68(6)	27(6), 68(6)
20	5	6, 21, 25	34(6), 61(25)	34, 21, 42, 61, 65	34, 21, 42, 61, 65	-	35, 6, 21, 25	27(21)	27(21)
20	6	6, 21, 25	27(21), 34(6), 38(21)	34, 6, 21, 25	34, 6, 21, 25	20(6), 27(21)	35, 5, 25, 27, 65	1(27)	1(27)
20	7	6, 21, 25	7(6), 34(6), 68(6), 81(6)	34, 6, 21, 25	34, 6, 21, 25	20(6), 27(21), 61(25)	35, 6, 21, 25	27(21), 65(25), 68(6)	27(21), 65(25), 68(6)
18	6	6, 16, 23, 25, 65	20(6)	34, 1, 25, 26, 55, 65	34, 1, 25, 26, 55, 65	-	35, 6, 25, 44, 61, 65	-	-
18	7	6, 16, 23, 25, 65	20(6), 21(23)	34, 6, 20, 25, 27, 65	34, 6, 20, 25, 27, 65	3(6)	35, 6, 21, 25, 27, 65	81(6)	81(6)
18	8	6, 27, 34, 61, 65	16(34), 20(6), 23(27)	34, 5, 25, 26, 27, 65	34, 5, 25, 26, 27, 65	20(25), 61(5)	35, 6, 21, 27, 61, 65	25(61), 68(6)	25(61), 68(6)

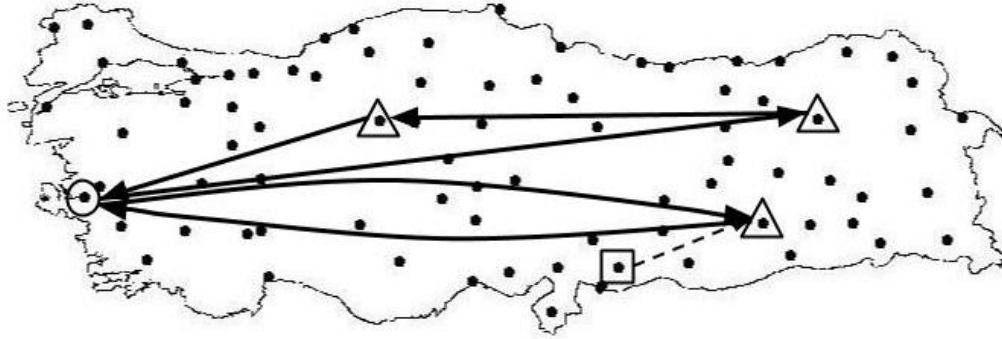
We now evaluate one of the instances in more detail. In this instance, the time bound is 20 hours and the number of hubs to be established is 5. If the location of the central airport hub is Ankara, one airplane is enough to cover Turkey within 20 hours. 3 airport hubs and 2 ground hubs are established (Figure 6.7(a)). The locations of airport hubs are Ankara (06), Diyarbakır (21) and Erzurum (25). The locations of the ground hubs are İstanbul (34) and Trabzon (61). If the central airport hub is chosen as İstanbul, then all 5 hubs need to be airport hubs and one additional airplane is required (Figure 6.7(b)). If the central airport hub is in İzmir, again 2 airplanes are used. 4 airport hubs and one ground hub are opened (Figure 6.7(c)).



(a) Central airport hub is Ankara



(b) Central airport hub is Istanbul



(c) Central airport hub is Izmir

Figure 6.7: Results with $T = 20$, $p = 5$

Since the location of Ankara is more centric than İstanbul and İzmir, the number of airline links, airplanes and airport hubs in Ankara case are lower compared to İstanbul and İzmir. Among these three results, generally the location of hubs changes. However, Diyarbakır is the only city that remains as an airport hub for these three cases because it is the only potential airport hub that can cover the south-eastern part of Turkey.

Next, we perform a similar analysis for the CAB data set. Some additional cities are considered as the central airport hub of the CAB data set. The first such city is New York (17) because it is the most populated city in USA. The second one is Los Angeles (12), which is the second biggest city in the United States in terms of population. The last one is Kansas City (11) since it is very near to the center of USA.

We varied the time bound and the number of hubs to be opened for these three different central airport hub locations as we did in the Atlanta case. The results for New York, Los Angeles and Kansas City can be found in Appendix 5, 6, 7, respectively. As you can see in the tables, the results differ from each other because each city is located in a different geographical location in USA. For instance, New York is located in the north-eastern part of USA. On the other hand, Los Angeles is in the south-western side and Kansas City is in the center of the United States.

We test four different time bound limits with four each central airport hub location. The results are summarized in Tables 6.9 & 6.10. As can be seen from Table 6.9, when $T = 72$ and $p = 1$; there aren't any feasible solution except for Kansas City case. Since the time bound is loose and Kansas City is located in the middle of USA, we do not need any airplanes to cover USA. When we increase p value, then there exist feasible solutions for each case. When we reduce the time bound to 60 hours, each case shows similar results. In order to serve the cities within 60 hours, 1 airplane is enough for each different central airport hub location. If the time bound is 48 hours and the central airport hub is Kansas City, then there is no feasible solution when p is equal to 3 because of Miami (14). When we increase p to 4, then a ground hub is opened in Miami (14), which is allocated to Cincinnati (5), so all cities are covered within 48 hours. If we tighten up the time bound to 36 hours and p is equal to 5, then again there exists no solution for Los Angeles and New York cases. Since these two cities are at the west and east peripheries of the country, they cannot serve Houston (10), which is located in the central south. By increasing the number of hubs, a ground hub is opened in Houston in

order to cover USA within 36 hours. When we consider the CPU time requirement, generally, Los Angeles case has the longest CPU time. Since Los Angeles is located in the west side and most of the cities in the CAB data set are located in the east side of the country, finding the optimal solution takes longer time.

When we consider the location of airport and ground hubs, generally they differ from each other due to geographical location of potential central airport hubs (Table 6.10). Since Atlanta and New York are in the east part of USA, they show some similarities in terms of the location of hubs. In these two cases, generally, airport hubs are opened in the west side of the country. These are Denver (8), Los Angeles (12), Phoenix (19), San Francisco (22) and Seattle (23). If the central airport hub is Los Angeles, then airport hubs are located in the east side such as Atlanta (1), Cincinnati (5), Memphis (13), Philadelphia (18), Pittsburgh (20), St. Louis (21), Baltimore (2) and etc. When we consider Kansas City as the central airport hub, the locations of the airport hubs are depend on the time bound. If the time bound is reduced, airport hubs are opened in the city of west edge such as Los Angeles and Seattle.

Table 6.9: Results with Different Central Airport Hub Locations 1 (CAB Data Set)

T (hours)	P	Atlanta			New York			Los Angeles			Kansas City		
		Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)
72	1	infeasible			infeasible			infeasible			0	0	0.01
72	2	2	1	0.07	2	1	0.1	2	1	0.3	0	0	0.08
72	3	2	1	0.26	2	1	0.54	2	1	4.79	0	0	0.11
60	2	2	1	0.16	2	1	0.09	2	1	0.19	2	1	0.15
60	3	2	1	0.75	2	1	0.3	2	1	5.25	2	1	0.67
60	4	2	1	0.63	2	1	2.2	2	1	8.95	2	1	0.8
48	3	3	1	1.02	3	1	0.53	3	1	0.68	infeasible		
48	4	3	1	1.8	3	1	4.99	3	1	14.31	3	1	2.25
48	5	3	1	2.07	3	1	7.58	3	1	16.62	3	1	7.19
36	5	5	1	13.72	infeasible			infeasible			5	1	25.7
36	6	5	1	121.87	5	1	962.02	6	2	526.79	5	1	83.32
36	7	5	1	197.9	5	1	687.05	6	2	797.28	5	1	674.74

Table 6.10: Results with Different Central Airport Hub Locations 2 (CAB Data Set)

T (hours)	p	Atlanta			New York			Los Angeles			Kansas City		
		Airport Hubs	Ground Hubs(allocated Airport Hubs)		Airport Hubs	Ground Hubs(allocated Airport Hubs)		Airport Hubs	Ground Hubs(allocated Airport Hubs)		Airport Hubs	Ground Hubs(allocated Airport Hubs)	
72	1										-	11	
72	2	1, 12	-		17, 19	-		12, 20	-		-	11, 1	
72	3	1, 19	12(19)		17, 12	8(17)		12, 18	17(18)		-	11, 19, 20	
60	2	1, 22	-		17, 8	-		12, 21	-		11, 8	-	
60	3	1, 8	22(8)		17, 19	23(19)		12, 21	5(21)		11, 23	22(23)	
60	4	1, 12	19(12), 22(12)		17, 19	8(19), 23(19)		12, 21	10(12), 11(12)		11, 8	12(11), 23(8)	
48	3	1, 8, 22	-		17, 13, 22	-		12, 1, 5	-				
48	4	1, 19, 22	23(22)		17, 13, 22	24(13)		12, 5, 13	14(13)		11, 5, 22	14(5)	
48	5	1, 19, 23	9(1), 12(19)		17, 13, 22	14(17), 19(22)		12, 13, 18	21(13), 24(13)		11, 20, 22	14(20), 23(22)	
36	5	1, 2, 11, 12, 23	-								11, 1, 12, 20, 23	-	
36	6	1, 6, 8, 12, 23	17(6)		17, 1, 11, 12, 23	10(1)		12, 2, 11, 23, 24	10(11)		11, 1, 6, 12, 23	24(1)	
36	7	1, 6, 8, 12, 23	2(1), 14(1)		17, 1, 11, 12, 23	10(1), 19(12)		12, 11, 23, 24, 25	10(11), 16(24)		11, 1, 5, 12, 23	3(5), 22(12)	

6.5 Analysis of the Effects of the Discount Factor of Time (α)

In this section, we analyze the influence of the different discount factor for time (α) on the resulting solutions for TR data set. The results are depicted in Table 6.11. There is an additional column on this table. The third column shows the discount factor value. On this analysis, α is varied between 0.2 and 0.8.

Table 6.11: Results with Different Discount Factor of Time (α)

T (hours)	p	α	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	2	0,8	2	1	6, 25	-	0.09
24	2	0,6	2	1	6, 23	-	0.08
24	2	0,4	2	1	6, 23	-	0.08
24	2	0,2	0	0	6	23(6)	0.06
19	5	0,8	5	2	6, 21, 25, 34	1(6)	9.47
19	5	0,6	3	1	6, 21, 25	1(6), 34(6)	1
19	5	0,4	2	1	6, 23	25(23), 65(23), 81(6)	2.72
19	5	0,2	0	0	6	25(6), 38(6), 65(6), 81(6)	0.16
16	7	0,8	9	3	6, 16, 20, 21, 27, 61, 65	-	1443.94
16	7	0,6	6	3	6, 27, 61, 65	16(6), 34(6), 3(6)	497.43
16	7	0,4	4	2	6, 61, 65	21(65), 27(6), 34(6), 3(6)	40.4
16	7	0,2	2	1	6, 65	7(6), 16(6), 20(6), 27(6), 61(6)	8.57

We test three distinct T - p pairs with different discount factor values. For all pairs, when we decrease the discount factor from 0.8 to 0.2, the number of airline segments and also the number of airplanes decrease. By reducing the discount factor, we actually increase the speed of the big trucks, which are operated between airport hubs and ground hubs. Since they serve faster, we do not need airplanes as before, so number of airline links and airplanes decreases. Also, when we decrease α , the number of airport hubs declines. On the other hand, with the faster big trucks, the significance of ground hubs goes up, so the number of ground hubs increases. Finally, we can conduct from Table 6.11 that decreasing the discount factor leads to lower the CPU time requirements.

Chapter 7

Computational Analysis of the R-R-S Model

In this chapter, the computational results for the R-R-S model are provided. In Section 7.1 the effects of the time bound and the number of hubs to be opened is evaluated. Section 7.2 presents the comparison between the R-S-S and R-R-S models. In Section 7.3 the effects of different central airport hub locations are analyzed. Section 7.4 compares the effect of the discount factor for time (α).

7.1 Effects of the T bound and the p value

In these computational studies, we varied the time bound from 24 to 16 hours and the number of hubs to be established from the first feasible value to a threshold value which is explained in Section 6.1. The results can be found in Table 7.1. Recall that for R-R-S

model, due to the second ring structure, the number of big trucks required is also an output of the model. There is an additional column on this table compared to the prior tables. The new column in the Table 7.1 is the fifth column which shows the number of big trucks.

If we increase the number of hubs to be opened (p), the number of airline or highway segments is generally increased. More airline and highway segments require more vehicles in order to serve the cities within time bound. On the other hand, when we reduce the time bound (T), we need more hubs in order to cover the cities within predetermined service time. More hubs cause to increase the number of airline and highway segments and so it increases the number of vehicles and also the objective function value. When we tighten the time bound, airplanes are more preferable than big trucks. For 18 hours or less, there is no usage of big trucks, because after this point, big trucks are not very effective compared to the airplanes due to the tight time bound.

The locations of airport and ground hubs are also affected by the time bound and the number of hubs to be located. Airport hubs are generally opened in the eastern side of Turkey in order to cover cities in the east. On the other hand, the locations of the ground hubs are very close to their allocated airport hubs. If they are far away from their assigned airport hubs, they may not make deliveries within the time bound because the big trucks are not as fast as airplanes. For instance, when $T = 24$ and $p = 6$, ground hubs, which are Afyon (3), Eskişehir (26) and Düzce (81), are allocated to Ankara (6) and these three cities are very near to Ankara. If $T = 22$ and $p = 5$, then ground hubs are Elazığ (23) and Malatya (44), which are closer and allocated to Diyarbakır (21). When we reduce the time bound, the number of ground hubs also decreases because big trucks are not very fast compared to airplanes if the time bound is tight. In order to ensure that all cities are covered within a tight time bound, airplanes and airport hubs are used.

Table 7.1: Results of R-R-S Model on Turkish Network (Ankara (6))

T (hours)	P	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	2	20	1	0	6, 23	-	0.76
24	3	30	1	0	6, 61, 65	-	39.31
24	4	35	1	1	6, 65	5(6), 55(6)	58.98
24	5	40	1	1	6, 23	26(6), 42(6), 3(6)	255.33
24	6	50	1	1	6, 25, 35	26(6), 3(6), 81(6)	1021.7
23	2	20	1	0	6, 23	-	0.78
23	3	30	1	0	6, 1, 25	-	30.56
23	4	35	1	1	6, 23	3(6), 68(6)	40.89
23	5	40	1	1	6, 23	16(6), 26(6), 81(6)	317.92
23	6	50	1	1	6, 25, 65	16(6), 26(6), 81(6)	2814.18
22	2	20	1	0	6, 23	-	0.65
22	3	30	1	1	6, 23	21(23)	28.77
22	4	35	1	1	6, 23	38(6), 68(6)	82.21
22	5	45	1	1	6, 21, 25	23(21), 44(21)	803.42
22	6	50	1	2	6, 23	21(23), 42(6), 44(23), 68(6)	889.15
21	3	30	1	0	6, 21, 25	-	17.69
21	4	40	1	1	6, 21, 23	25(23)	68.65
21	5	45	1	1	6, 25, 65	38(6), 68(6)	268.23
21	6	55	1	1	6, 21, 25, 65	16(6), 26(6)	5391.56
21	7	60	1	2	6, 21, 25	23(21), 42(6), 44(21), 68(6)	15427.06
20	4	40	1	1	6, 21, 25	81(6)	24.91
20	5	45	1	1	6, 21, 25	26(6), 81(6)	201.13
20	6	55	1	1	6, 25, 44, 65	26(6), 81(6)	3533.38
20	7	60	1	2	6, 21, 25	23(21), 26(6), 44(21), 81(6)	12959.27
19	5	60	2	0	6, 21, 25, 26, 44	-	179.31
19	6	60	1	0	6, 21, 25, 26, 42, 65	-	3031.87
19	7	70	1	1	6, 21, 25, 26, 42, 65	81(6)	23306.42
18	6	70	2	0	6, 20, 23, 34, 61, 65	-	4681.88
18	7	80	2	0	6, 20, 27, 34, 44, 61, 65	-	46406.62
17	6	70	2	0	6, 16, 25, 27, 35, 65	-	1920.52
17	7	80	2	0	6, 16, 20, 25, 44, 61, 65	-	46523.09
16	6	90	4	0	6, 20, 27, 34, 61, 65	-	1801.65
16	7	90	3	0	6, 20, 21, 34, 42, 61, 65	-	10258.93
≤12	22	infeasible					

Reducing the time bound and increasing the number of hubs to be opened generally increases the CPU time. Also, in this model, the influence of the number of hubs to be opened on the CPU time requirement is bigger than the effect of the time bound. The CPU times on this model are higher compared to the CPU times on a ring(s)-star-star model for the same instances because in addition to the top layer, this model also solve an additional Vehicle Routing Problem for the second layer. When the time bound is between 22 and 24 hours, the problem is solved within one hour. If it is between 16 and 21 hours, except 6 instances, the CPU time is not longer than 2 hours. The common feature of these six instances is the number of hubs to be located, which is 7. This shows the effect of p value on the CPU time requirement.

We carried out the computational study for the R-R-S model also on CAB data set. The settings of this computational study are the same as the one for ring(s)-star-star network on CAB data set. In this study, we assign Atlanta as the central airport hub. First of all, we varied T from 72 to 30 hours, and p from the first feasible value to the threshold value which is explained before. The results are summarized in Table 7.2 & 7.3.

Reducing the time bound and increasing the number of hubs to be opened has similar effects on the objective function value and the number of vehicles as in the Turkish network data set. Decreasing T and increasing p values usually lead to increase the weighted sum of the number airline and highway segments and also they increase the number of vehicles. For 42 hours or less, big trucks are not used in order to serve all the cities of USA. Rather than big trucks, just airplanes are required.

Table 7.2: Results of R-R-S Model on CAB Data Set (Atlanta (1), $54 \leq T \leq 72$)

T (hours)	P	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	20	1	0	1, 12	-	1.79
72	3	30	1	0	1, 8, 25	-	57.46
72	4	35	1	1	1, 23	6(1), 25(1)	275.92
70	2	20	1	0	1, 12	-	1.77
70	3	30	1	0	1, 8, 25	-	61.75
70	4	35	1	1	1, 12	5(1), 21(1)	207.88
68	2	20	1	0	1, 23	-	2.84
68	3	30	1	0	1, 12, 23	-	90.7
68	4	35	1	1	1, 12	6(1), 20(1)	265.99
66	2	20	1	0	1, 12	-	4.32
66	3	30	1	0	1, 19, 23	-	87.79
66	4	35	1	1	1, 8	5(1), 6(1)	256.24
64	2	20	1	0	1, 23	-	6.92
64	3	30	1	0	1, 19, 23	-	227.62
64	4	35	1	1	1, 22	2(1), 20(1)	249.2
62	2	20	1	0	1, 19	-	2.93
62	3	30	1	0	1, 19, 23	-	80.69
62	4	35	1	1	1, 8	5(1), 9(1)	248.38
60	2	20	1	0	1, 22	-	4.94
60	3	30	1	0	1, 12, 23	-	110.54
60	4	35	1	1	1, 12	2(1), 18(1)	308.1
58	2	20	1	0	1, 12	-	4.22
58	3	30	1	0	1, 12, 22	-	103.76
58	4	35	1	1	1, 22	9(1), 20(1)	212.44
56	2	20	1	0	1, 8	-	1.38
56	3	30	1	0	1, 8, 25	-	59.29
56	4	35	1	1	1, 22	2(1), 20(1)	226.86
54	3	30	1	0	1, 8, 23	-	46.76
54	4	40	1	0	1, 7, 22, 23	-	169.9
54	5	45	1	1	1, 12, 23	5(1), 13(1)	414.73

Table 7.3: Results of R-R-S Model on CAB Data Set (Atlanta (1), $30 \leq T \leq 52$)

T (hours)	p	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
52	3	30	1	0	1, 7, 22	-	81.09
52	4	40	1	0	1, 9, 19, 23	-	143.92
52	5	45	1	1	1, 19, 23	5(1), 9(1)	510.26
50	3	30	1	0	1, 12, 22	-	42.17
50	4	40	1	1	1, 12, 22	19(12)	216.78
50	5	45	1	1	1, 8, 22	2(1), 25(1)	516.55
48	3	30	1	0	1, 19, 23	-	43.48
48	4	40	1	0	1, 19, 21, 22	-	183.44
48	5	45	1	1	1, 8, 23	13(1), 21(1)	516.25
46	3	30	1	0	1, 8, 22	-	36.34
46	4	40	1	0	1, 8, 19, 22	-	322.32
46	5	45	1	1	1, 7, 22	13(1), 21(1)	480.5
44	4	40	1	0	1, 17, 19, 22	-	59.3
44	5	50	1	0	1, 3, 8, 12, 23	-	935.78
44	6	55	1	1	1, 18, 19, 22	2(18), 17(18)	10955.61
42	4	50	2	0	1, 6, 19, 23	-	68
42	5	50	1	0	1, 12, 15, 17, 23	-	521.94
42	6	60	1	0	1, 3, 13, 19, 23, 25	-	5485.41
40	4	50	2	0	1, 5, 19, 23	-	47.87
40	5	50	1	0	1, 8, 12, 20, 23	-	371.91
40	6	60	1	0	1, 3, 4, 8, 12, 23	-	6222.19
38	5	50	1	0	1, 8, 12, 20, 23	-	286.75
38	6	60	1	0	1, 6, 8, 19, 22, 23	-	7120.39
36	5	50	1	0	1, 8, 9, 12, 23	-	349.86
36	6	60	1	0	1, 9, 11, 12, 19, 23	-	9627.26
34	5	50	1	0	1, 8, 9, 12, 23	-	251.33
34	6	60	1	0	1, 6, 8, 11, 12, 23	-	3024.32
32	6	70	2	0	1, 6, 11, 12, 13, 23	-	2956.26
30	7	80	2	0	1, 8, 10, 11, 12, 17, 23	-	9966.96
≤22	25	infeasible					

Varying T and p values also affects the locations of the airport hubs and ground hubs. For the loose time bounds, such as between 58 and 72 hours, all of the airport hubs are opened in the west side of the country. These are Denver (8), Los Angeles (12), Phoenix (19), San Francisco (22) and Seattle (23). For 58 hours or less, in addition to airport hubs

in the west side, some of them are opened in the east side in order to cover all cities in the country. On the other hand, ground hubs are opened in the cities which are closer to the airport hubs and they are allocated to those airport hubs. Generally, this airport hub is the central airport hub, which is Atlanta.

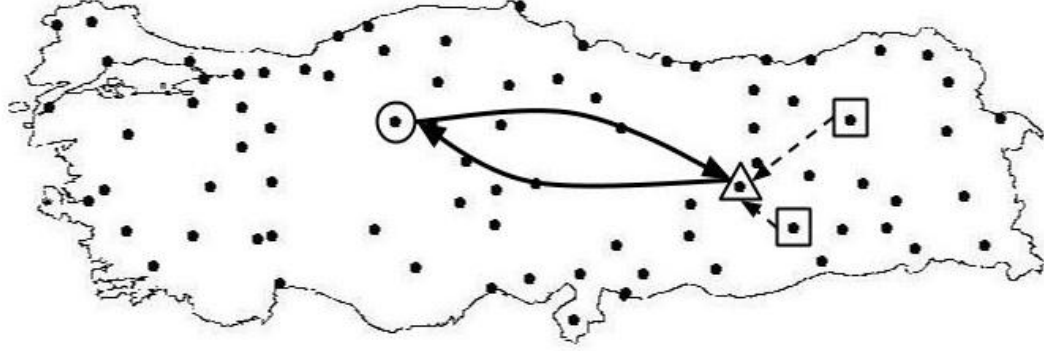
When we look at the CPU time requirement, we can see that increasing the time bound and decreasing the number of hubs to be established causes the high CPU times, which is the same effect as in the TR data set. Also, p value has a greater impact on the CPU time. As you can see from Table 7.3, if p is equal to 6 or 7, the CPU time start to increase.

7.2 Comparison of the Solutions of the R-S-S and R-R-S Models

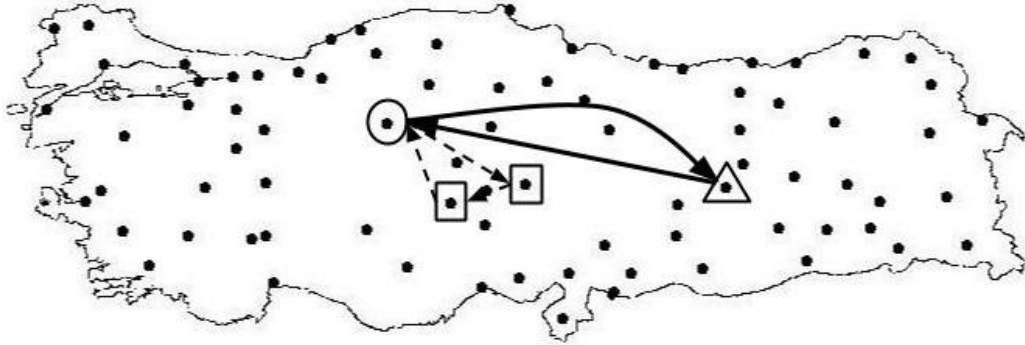
In this section, we compare the results of the R-S-S and R-R-S models under the same T - p settings. We use some instances of TR network for this analysis.

One such instance is for $T = 22$ and $p = 4$. If we consider the R-S-S model, 1 airplane and 2 big trucks are required for 2 airport and 2 ground hubs. The locations of airport hubs are Ankara (6) and Elazığ (23) and the locations of ground hubs are Diyarbakır (21) and Erzurum (25) (Figure 7.1(a)).

When the R-R-S model is solved, 1 airplane and 1 big truck are enough to cover Turkey within 22 hours. Again, 2 airport and 2 ground hubs are used. The locations of airport hubs do not change. The locations of ground hubs change to Kayseri (38) and Aksaray (68) (Figure 7.1(b)).



(a) The Outputs of R-S-S Model

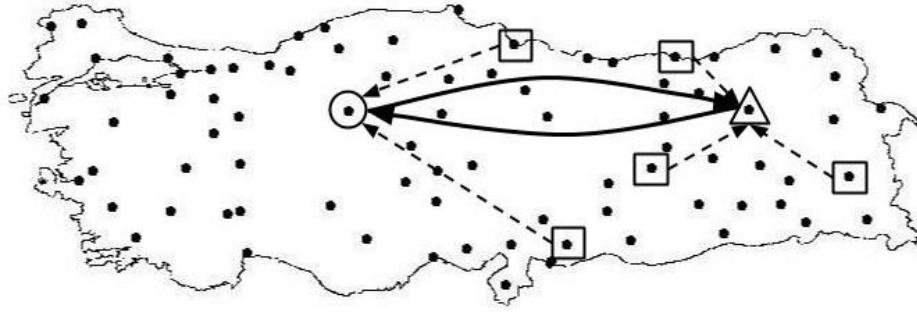


(b) The Outputs of R-R-S Model

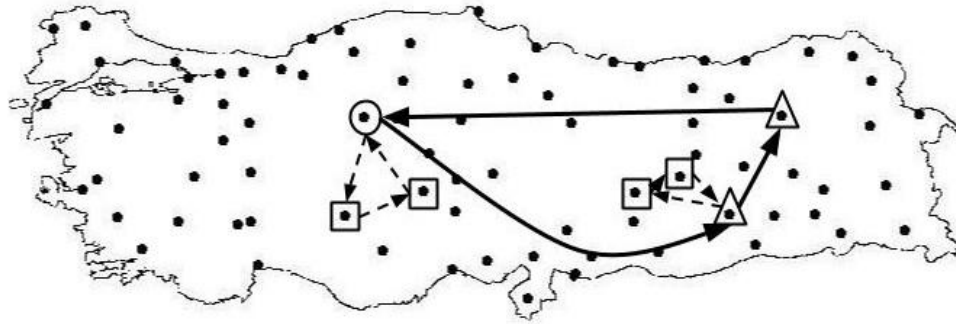
Figure 7.1: Results with $T = 22$, $p = 4$

For the next instance, T and p are equal to 22 and 7, respectively. If we solve the R-S-S model, then 1 airplane and 5 big trucks are required. 2 airport and 5 ground hubs are established. In Ankara (6) and Erzurum (25), airport hubs are opened. In Elazığ (23), Gaziantep (27), Samsun (55), Trabzon (61) and Van (65), ground hubs are located (Figure 7.2(a)).

When the R-R-S model is solved for the same instance, 1 airplane and 2 big trucks are enough to serve all cities in Turkey. Based on the solution, 3 airport hubs, which are Ankara (6), Diyarbakır (21) and Erzurum (25), are opened and 4 ground hubs, which are Elazığ (23), Konya (42), Malatya (44) and Aksaray (68), are established (Figure 7.2(b)). In this solution, there is an addition airport hub, which is Diyarbakır, compared to the solution of the first problem. Also, the locations of most of the ground hubs change. The new locations are much closer to airport hubs.



(a) The Outputs of R-S-S Model



(b) The Outputs of R-R-S Model

Figure 7.2: Results with $T = 21$, $p = 7$

All these comparisons indicate that the number of vehicles, especially big trucks, can be reduced by considering ring(s)-ring(s)-star network because highway segments are also minimized in the objective function of the R-R-S model.

7.3 The Effects of Different Central Airport Hubs on the Solutions

We now consider the effect of different locations for the central airport hub for TR data set; these locations are again, İstanbul and İzmir. The results for İstanbul case are summarized in Appendix 8. In this case, more vehicles are used compared to Ankara case, because İstanbul is located in the north-west of Turkey. In order to cover Turkey, more vehicles are needed. When we look at the locations of airport hubs, generally they are in the east side of the country and similar to Ankara case, the locations of ground hubs are closer to the allocated airport hubs. Also, the CPU time increases compared to Ankara case, since İstanbul is far away from the center of Turkey compared to Ankara. The results for İzmir case can be found in Appendix 9. When the location of central airport hub is İzmir, then the number of airplanes increases and the number of big trucks decreases. Since İzmir also is far away from the center of the country, airplanes are more effective than big trucks in order to serve cities in the east regions. The locations of airport and ground hubs are very similar to Ankara and İstanbul cases. Finally, the CPU time requirements are similar to İstanbul case.

We also analyze the effects of the different central airport hub locations on the results for CAB data set. To be consistent with the R-S-S models, we again select New York, Los Angeles and Kansas City as the central airport hub. The results for New York case are summarized in Appendix 10. When we compared with the results of Atlanta case, they are very similar in terms of number of vehicles. Since Atlanta is more centric than New York, for tight time bound, the objective function values for New York case are

generally bigger. In these two cases, the locations of the hubs and also the CPU times are usually similar because both of them are located in the eastern side of the country. The computational results for Los Angeles case can be found in Appendix 11. For loose time bound, the objective function value and the number of vehicles are similar compared to Atlanta case. When we tighten up the time bound, the objective function value and the number of vehicles are bigger in Los Angeles case. The locations of the airport hubs are not similar to Atlanta and New York cases because Los Angeles is located in the western side. Therefore, generally, airport hubs are opened in the eastern regions of USA. Again, the locations of ground hubs are closer to their allocated airport hubs. Finally, solving problems takes much longer time compared to Atlanta and New York cases. The results for Kansas City case can be seen in Appendix 12. For the loose time bound such as 72 hours, objective function value and the number of vehicles are smaller compared to other three cities since Kansas City is located in the center of the United States. For less than 72 hours, the results are usually similar to other cases. When the time bound is not strict, airport hubs are generally opened in the western side. If they are tightened up, then they are established both western and eastern side of the country. The CPU times are bigger compared to Atlanta case due to the high number of feasible solutions.

7.4 Analysis of the Effects of the Discount Factor of Time (α)

In this section, we analyze the influence of the different discount factor for time (α) on the R-R-S network. TR data set is used. The results are summarized in Table 7.4. On this analysis, α is varied between 0.2 and 0.8.

Table 7.4: Results with Different Discount Factor of Time (α)

T (hours)	p	α	Objective Function	Number of Airplanes/Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
20	6	0,8	55	1/1	6, 25, 27, 65	26(6), 81(6)	4490.73
20	6	0,6	50	1/1	6, 21, 25	26(6), 3(6), 81(6)	472.76
20	6	0,4	50	1/2	6, 21	38(6), 81(6), 61(21), 25(21)	739.09
20	6	0,2	35	0/2	6	25(6), 27(6), 44(6), 61(6), 81(6)	257.08
17	7	0,8	80	2/0	6, 16, 25, 27, 35, 44, 65	-	47885.56
17	7	0,6	70	1/3	6, 25, 27, 65	16(6), 34(6), 3(6)	24093.92
17	7	0,4	60	1/2	6, 25, 65	16(6), 27(6), 35(6), 81(6)	6681.15
17	7	0,2	45	0/3	6	21(6), 25(6), 38(6), 65(6), 3(6), 81(6)	985.26

We test two T - p pairs with different discount factor values. When we decrease the discount factor from 0.8 to 0.2, the objective function value reduces because instead of airline segments, highway segments between ground hubs are used. By reducing the discount factor, we increase the speed of the big trucks. Since the big trucks serve faster, we do not need airplanes as before, so the number airplanes decreases and the number of big trucks generally increases. Therefore, when we decrease α , the number of airport hubs declines and the number of ground hubs increases. Finally, decreasing α reduces CPU time requirement.

Chapter 8

A Heuristic Approach to Solve Large Problems

In this chapter, we propose a heuristic solution approach. In Section 8.1 we present the structure of the proposed heuristic. In Section 8.2 computational studies for this heuristic on R-S-S model are carried out. Section 8.3 analyzes the results of the heuristic applied to the R-R-S model.

8.1 The Heuristic Algorithm

When the time bound is tight and the number of hubs to be opened is high, solving the R-S-S and R-R-S models may take long CPU times. In order to solve the larger-sized problems, we now propose an efficient heuristic algorithm.

The main idea of the heuristic is fixing some airport hubs in addition to the central airport hub. We propose to use this heuristic when the number of hubs to be located exceeds a threshold value (r). Selecting these fixed airport hubs is very critical. Therefore, we propose to create a set called “Critical” which is an ordered set of the potential airport hubs. The set “Critical” is an ordered set with respect to the distances to the central airport hub (farthest towards nearest). We additionally give a lower bound (> 1) for the number of airplanes to be used, again, to decrease the solution time of the models. When the time bound is less than a threshold value K , we propose to operate at least t airplanes. The threshold values r and K are dependent on the data set. Also, the number of airport hubs to be fixed (f) and the minimum number of airplanes to operate (t) are determined according to the data set. In order to decide the threshold values r and K , we conducted some preliminary analysis from the results obtained in Chapter 7 and 8. Based on this analysis, For TR data set, r and K are 5 and 18. We propose f as 1 or 2 and t as 2. We include the following additional constraints to the models and solve the resulting models again using Gurobi 5.0.2. The required constraints are as follows:

$$y_{ss} = 1 \quad \begin{array}{l} s = \text{Critical}[1] \text{ if } f = 1 \\ s = \text{Critical}[1], \text{Critical}[2] \text{ if } f = 2 \end{array} \quad (8.1)$$

$$\sum_{l \in A \setminus \{0\}} u_{0l} \geq t \quad (8.2)$$

where $\text{Critical}[i]$ represents the i^{th} node of the set Critical for $i = 1$ and 2. Constraint (8.1) ensures that the farthest node(s) to the central airport hub are selected as airport hubs. Constraint (8.2) puts a lower bound for the number of airplanes.

The flow chart of the proposed heuristic approach is depicted in Figure 8.1. First of all, we calculate the distance between the central airport hub and every possible airport hub. After that, we sort the possible airport hubs in a non-increasing order of their distances to the central airport hub. Then, if the number of hubs to be located is more than or equal

to the threshold value r , the first f airport hub(s) from the ordered list are considered as fixed. Also, when the time bound is less than or equal to threshold value K , we put a lower bound for the number of airplanes to t value. Finally, we solve the resulting model using Gurobi 5.0.2. Due to the inclusion of (8.1) and (8.2), we expect shorter CPU times.

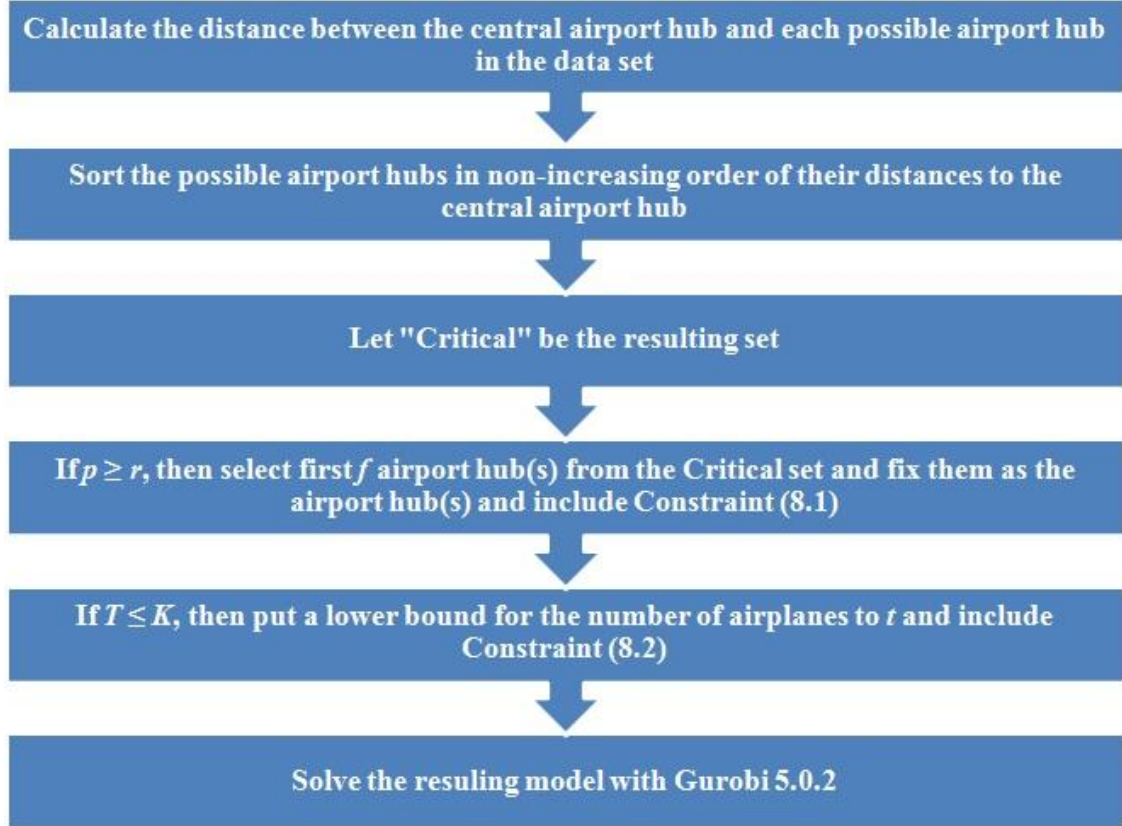


Figure 8.1: Flow Chart of the Heuristic Approach

8.2 Performance of the Proposed Heuristic Algorithm on the R-S-S Problem

Based on this heuristic approach, we conduct a computational study. On this study, we use the Turkish network and the same settings as it explained in Chapter 5. The central airport hub is Ankara.

First; the distances between the central airport hub Ankara and other 18 possible airport hubs are calculated. Then, we sort the cities in terms of these distance values in a non-increasing order (Table 8.1).

Table 8.1: Sorted Distances between Ankara and Other Possible Airport Hubs

City Numbers	City	Distance to Ankara (km)
65	VAN	1232
21	DIYARBAKIR	910
25	ERZURUM	871
23	ELAZIĞ	757
61	TRABZON	747
27	GAZİANTEP	671
44	MALATYA	659
35	İZMİR	579
7	ANTALYA	544
1	ADANA	490
20	DENİZLİ	477
34	İSTANBUL	453
55	SAMSUN	414
16	BURSA	382
5	AMASYA	334
42	KONYA	258
26	ESKİŞEHİR	233

Based on the features of the TR data set, r value is set to 5. In other words, if the number of hubs to be opened is 5 or more, then first f airport hub(s) will be fixed based on Table 8.1. For f , we consider two cases. In the first one, f is equal to 1 and so only Van (65) will be fixed as the additional airport hub. In the second case, f is equal to 2, so Van (65) and Diyarbakır (21) will be assigned as the additional airport hub(s). Also, K and t are set to be 18 and 2 for this data set, respectively. Thus, when the time bound is less than or equal to 18 hours, the lower bound for the number of airplanes will be 2.

In the first case, one additional airport hub, which is Van (65), is fixed. The results for the heuristic approach with Van as the additional airport hub are summarized in

Appendix 13. Also, the optimal results of the R-S-S and the results of the heuristic models are compared in Table 8.2.

Table 8.2: The Comparison between the R-S-S and Heuristic ($f = 1$) Models on TR Data Set

T (hours)	p	R-S-S Model			Heuristic Model			Optimality Gap (%)	CPU Improvement (%)
		Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)		
20	5	3	1	1	3	1	0.79	0	21
20	6	3	1	1.24	3	1	1.12	0	9.68
20	7	3	1	1.33	3	1	0.75	0	43.61
20	8	3	1	1.44	3	1	0.76	0	47.22
20	9	3	1	1.12	3	1	0.85	0	24.11
19	5	5	2	9.59	6	2	1.59	16.67	83.42
19	6	4	1	23.49	6	2	13.31	33.33	43.34
19	7	4	1	20.71	5	1	11.2	20	45.92
19	8	4	1	12.33	5	1	4.82	20	60.91
19	9	4	1	31.29	5	1	33.41	20	-6.35
19	10	4	1	18.02	5	1	10.06	20	44.17
18	6	6	2	45.59	6	2	1.35	0	97.04
18	7	6	2	87.49	6	2	0.99	0	98.87
18	8	6	2	177.87	6	2	1.26	0	99.29
18	9	6	2	408.78	6	2	1.93	0	99.53
18	10	6	2	177.3	6	2	1.72	0	99.03
18	11	6	2	483.98	6	2	1.86	0	99.62
17	6	7	2	94.44	7	2	13.47	0	85.74
17	7	7	2	559.84	7	2	72.47	0	87.06
17	8	7	2	2282.25	7	2	146.7	0	93.57
16	6	9	4	59.17	9	4	28.43	0	51.95
16	7	9	4	2382.76	9	3	329.73	0	86.16
16	8	8	3	8509.38	8	3	379.32	0	95.54
15	8	10	3	4510.63	10	3	1699.42	0	62.32
14	8	11	4	3633.69	11	4	1176.91	0	67.61
14	9	10	3	38645.65	10	3	3340	0	91.36

When we compare the R-S-S model and heuristic algorithm, generally the objective function value and the number of airplanes are the same except for the instances when $T = 19$. This time bound is very critical because when Van is fixed as the second airport

hub, some of the cities between Ankara and Van cannot be covered by these two cities. Therefore at least two other airport hubs such as Elazığ (23) or Malatya (44) and also Trabzon (61), are needed to cover these cities. Furthermore, in order to cover cities located in west side of Turkey, Bursa (16) or İstanbul (34) must be opened as the airport hub (Appendix 13). Therefore, the objective function of the heuristic model is more than that of the R-S-S model. On the other hand, when we look at the CPU times of these two models, heuristic algorithm with one additional airport hub is much faster than the original model for all instances except one instance. As you can see from the Table 8.2, the CPU time improvements are very high. The average CPU time improvement for these 26 instances is 66.6%. Especially, for the hard instances CPU improvement is more pronounced. For example, for $T = 14$ and $p = 9$, the original R-S-S model requires approximately 11 hours whereas with the heuristic, the optimal solution is achieved within an hour.

We also want to test the performance of the heuristic when we fix two additional airport hubs. The results for the heuristic approach with Van and Diyarbakır as the additional airport hubs can be found in Appendix 14. Also, the comparison of the R-S-S and heuristic models is depicted in Table 8.3.

Table 8.3: The Comparison between the R-S-S and Heuristic ($f = 2$) Models on TR Data Set

T (hours)	p	R-S-S Model			Heuristic Model			Optimality Gap (%)	CPU Improvement (%)
		Objective Function	Number of Airplanes	CPU (sec)	Objective Function	Number of Airplanes	CPU (sec)		
20	5	3	1	1	4	1	0.52	25	48
20	6	3	1	1.24	4	1	0.69	25	44.36
20	7	3	1	1.33	4	1	2.26	25	-41.15
20	8	3	1	1.44	4	1	2.75	25	-47.64
20	9	3	1	1.12	4	1	0.96	25	14.29
19	5	5	2	9.59	infeasible		0.59		
19	6	4	1	23.49	6	2	8.45	33.33	64.03
19	7	4	1	20.71	6	2	15.77	33.33	23.85
19	8	4	1	12.33	6	2	19.54	33.33	-36.9
19	9	4	1	31.29	6	2	20.57	33.33	34.26
19	10	4	1	18.02	6	2	13.88	33.33	22.98
18	6	6	2	45.59	infeasible		8.99		
18	7	6	2	87.49	7	2	1.79	14.29	97.95
18	8	6	2	177.87	7	2	2.45	14.29	98.62
18	9	6	2	408.78	7	2	3.83	14.29	99.06
18	10	6	2	177.3	7	2	3.88	14.29	97.81
18	11	6	2	483.98	7	2	2.1	14.29	99.57
17	6	7	2	94.44	infeasible		8.21		
17	7	7	2	559.84	8	2	56.81	12.5	89.85
17	8	7	2	2282.25	8	2	134.12	12.5	94.12
16	6	9	4	59.17	infeasible		9.13		
16	7	9	4	2382.76	9	3	220.81	0	90.73
16	8	8	3	8509.38	8	2	157.96	0	98.14
15	8	10	3	4510.63	10	3	246.25	0	94.54
14	8	11	4	3633.69	11	4	193.39	0	94.68
14	9	10	3	38645.65	10	3	378.93	0	99.02

When we consider the heuristic approach with Van and Diyarbakır as the additional airport hubs, 4 out of 26 instances become infeasible. For these instances, either Van or Diyarbakır is opened as the airport hub in the R-S-S model, but both of them are not opened at the same time. Locating airport hubs in both of these locations causes the infeasibility. Also, generally, the objective function values for these two models are

different because fixing the location of an additional airport hub can cause redundant airline segments. As can be seen from the Table 8.3, optimality gap for this case is higher than the gap of the first case (heuristic with one additional airport hub). On the other hand, when the time bound is tight ($T = 14, 15, 16$), the heuristic approach gives the optimal solution. When we look at the CPU times for both models, except 4 instances, heuristic model gives lower CPU times. The average CPU time improvement for the 22 instances is 58.19%. The CPU time improvement in the second case is lower compared to the first case, because fixing one more airport hub causes to delay getting a feasible solution.

Based on our analysis with $f = 1$ and $f = 2$, we choose to continue with $f = 1$. The CPU times to solve TR data set with $f = 1$ seems satisfactory. Next, we analyze the performance of the same heuristic over R-R-S problem.

8.3 Performance of the Proposed Heuristic Algorithm on the R-R-S Problem

We also apply the same heuristic algorithm to the R-R-S problem. The settings in Section 8.2 are considered in this section, too. Again, we use the same Critical sets and r and K thresholds as 5 and 18, respectively, in this analysis.

Firstly, we consider $f = 1$, i.e. Van (65) is fixed as the additional airport hub. The results for this heuristic approach are summarized in Appendix 15. Also, the optimal results of the R-R-S and the results of the heuristic models are compared in Table 8.4.

Table 8.4: The Comparison between the R-R-S and Heuristic ($f = 1$) Models on TR Data Set

T (hours)	P	R-R-S Model			Heuristic Model			Optimality Gap (%)	CPU Improvement (%)
		Objective Function	Number of Airplanes/ Trucks	CPU (sec)	Objective Function	Number of Airplanes/ Trucks	CPU (sec)		
24	5	40	1/1	255.33	45	1/1	98.54	11.11	61.41
24	6	50	1/1	1021.7	50	1/1	231.43	0	77.35
23	5	40	1/1	317.92	45	1/1	141.39	11.11	55.53
23	6	50	1/1	2814.18	50	1/1	335.58	0	88.08
22	5	45	1/1	803.42	45	1/1	88.48	0	88.99
22	6	50	1/2	889.15	55	1/1	667.5	9.09	24.93
21	5	45	1/1	268.23	45	1/1	121.52	0	54.7
21	6	55	1/1	5391.56	55	1/1	549.85	0	89.8
21	7	60	1/2	15427.06	60	1/2	4114.62	0	73.33
20	5	45	1/1	201.13	50	1/1	40.86	10	79.69
20	6	55	1/1	3533.38	55	1/1	281.8	0	92.03
20	7	60	1/2	12959.27	65	1/2	3583.71	7.69	72.35
19	5	60	2/0	179.31	60	2/0	128.53	0	28.32
19	6	60	1/0	3031.87	60	1/0	1822.41	0	39.89
19	7	70	1/0	23306.42	70	1/0	4772.4	0	79.52
18	6	70	2/0	4681.88	70	2/0	222.58	0	95.25
18	7	80	2/0	46406.62	80	2/1	1938.46	0	95.82
17	6	70	2/0	1920.52	70	2/0	357.92	0	81.36
17	7	80	2/0	46523.09	80	2/0	4197.97	0	90.98
16	6	90	4/0	1801.65	90	4/0	822.9	0	54.33
16	7	90	3/0	10258.93	90	3/0	7158.82	0	30.22

When we consider the solutions of the R-R-S model and proposed heuristic algorithm, usually the objective function value and the number of vehicles (airplanes and big trucks) are the same except for a few instances. In these instances, Van is not considered as the airport hub in the solution of the R-R-S model, so fixing Van as an airport hub in the heuristic algorithm increases the objective function value. Furthermore, when the CPU times of these two solution approaches are compared, heuristic algorithm is faster than the R-R-S model for all 21 instances in Table 8.4. As it can be seen from this table, the minimum CPU time improvement is approximately 35% and the average CPU time improvement for all instances 69.23%. For instance, when we consider $T = 18$ and $p = 7$

case, the R-R-S model requires approximately 13 hours. On the other hand, with the heuristic algorithm, this problem is solved within half an hour.

We also want to observe the performance of the heuristic algorithm when two additional airport hubs are fixed. The results for the heuristic algorithm can be seen in Appendix 16. Also, the comparison of the R-R-S model and heuristic approach is summarized in Table 8.5.

Table 8.5: The Comparison between the R-R-S and Heuristic ($f = 2$) Models on TR Data Set

T (hours)	p	R-R-S Model			Heuristic Model			Optimality Gap (%)	CPU Improvement (%)
		Objective Function	Number of Airplanes/ Trucks	CPU (sec)	Objective Function	Number of Airplanes/ Trucks	CPU (sec)		
24	5	40	1/1	255.33	45	1/1	38.87	11.11	84.78
24	6	50	1/1	1021.7	55	1/1	172.95	9.09	83.07
23	5	40	1/1	317.92	50	1/0	34.61	20	89.11
23	6	50	1/1	2814.18	55	1/1	197.48	9.09	92.98
22	5	45	1/1	803.42	50	1/1	31.59	10	96.07
22	6	50	1/2	889.15	55	1/1	174.98	9.09	80.32
21	5	45	1/1	268.23	50	1/1	31.08	10	88.41
21	6	55	1/1	5391.56	55	1/1	173.68	0	96.78
21	7	60	1/2	15427.06	65	1/1	3070.02	7.69	80.1
20	5	45	1/1	201.13	50	1/1	9.6	0.1	95.23
20	6	55	1/1	3533.38	55	1/1	80.96	0	97.71
20	7	60	1/2	12959.27	65	1/2	1291.81	7.69	90.03
19	5	60	2/0	179.31	infeasible		5.44		
19	6	60	1/0	3031.87	60	1/0	105.64	0	96.52
19	7	70	1/0	23306.42	70	1/0	2005.56	0	91.4
18	6	70	2/0	4681.88	infeasible		81.69		
18	7	80	2/0	46406.62	80	2/0	304.62	0	99.34
17	6	70	2/0	1920.52	infeasible		75.35		
17	7	80	2/0	46523.09	80	2/0	385.13	0	99.17
16	6	90	4/0	1801.65	infeasible		70.57		
16	7	90	3/0	10258.93	90	3/0	2152.57	0	79.02

When we compare the results of these two solution approaches, generally the objective function values differ from each other, especially for the loose time bounds ($20 \leq T \leq 24$). When we consider the tight time bounds ($16 \leq T \leq 19$), the objective function values

are the same unless the solution of the heuristic algorithm is infeasible. For 4 out of 21 instances, heuristic algorithm has no feasible solution. For these instances, either Van or Diyarbakır is considered as an airport hub in the solution of R-R-S model. Fixing both cities as the additional airport hubs causes infeasibility. When the CPU times of the R-R-S model and heuristic algorithm are considered, the heuristic algorithm solves the problem much faster compared to R-R-S model for all instances. The average CPU time improvement for 17 instances is 90.59%, which is higher than the average CPU time improvement of the first heuristic case with one additional airport hub (69.23%).

When we compare the heuristic algorithms with $f = 1$ and $f = 2$, we choose to continue with the heuristic approach with one additional airport hub. Although the CPU time to solve TR data set with $f = 2$ is lower, the optimality gap differences and infeasibility of some instances can be considered the crucial drawbacks of the heuristic algorithm with two additional airport hubs, i.e. $f = 2$.

Chapter 9

Model Variation: (R-R-R Case)

In this chapter, a possible extension for our study is presented. In Section 9.1 a new hierarchical hub network is proposed and based on this network, the hierarchical hub location problem on a ring(s)-ring(s)-ring(s) (R-R-R) network is defined. Also, the mathematical formulation of this problem is provided. Finally, a computational study for R-R-R model is conducted.

9.1 The Hierarchical Hub Location Problem on a R-R-R Network

In this network, ring structure(s) concept is considered at the third layer as well in order to decrease the number of the pickup trucks (Figure 9.1). This topology is referred to as Ring(s)-Ring(s)-Ring(s) (R-R-R) network. With that configuration, when ring structure is considered on the third layer, routing and scheduling decisions are included at that

layer, too. Therefore, in this setting, VRPs are considered for top, second and third layer of this hierarchical network.

For this problem, a linear mixed integer mathematical model is proposed. Given the node set, potential ground hub and air hub locations, the model outputs the network configuration with ground hubs, airport hubs, the allocations of demand points to the ground or airport hubs and the allocations of ground hubs to the airport hubs, and the required airline and highway (both for second and third layer) segments with the minimum number of airline and highway links while obeying the time bound.

The parameter of our mathematical model for this problem is the same as the parameters of the mathematical model of the R-S-S and R-R-S problems.

Also, the decision variables of the R-S-S and R-R-S problems are used again in this problem (Figure 9.1). The additional parameters and decision variables are;

δ = coefficient for ground segments between hubs and demand nodes

$v_{ij}^k = 1$ if there is a directed link between demand node $i \in D$ and demand node $j \in D$

and these two demand nodes are allocated to the same hub $k \in H$

$r_i^{\text{pickuptruck}}$ = the earliest time that pickup truck departs from demand node $i \in D$ towards other demand nodes

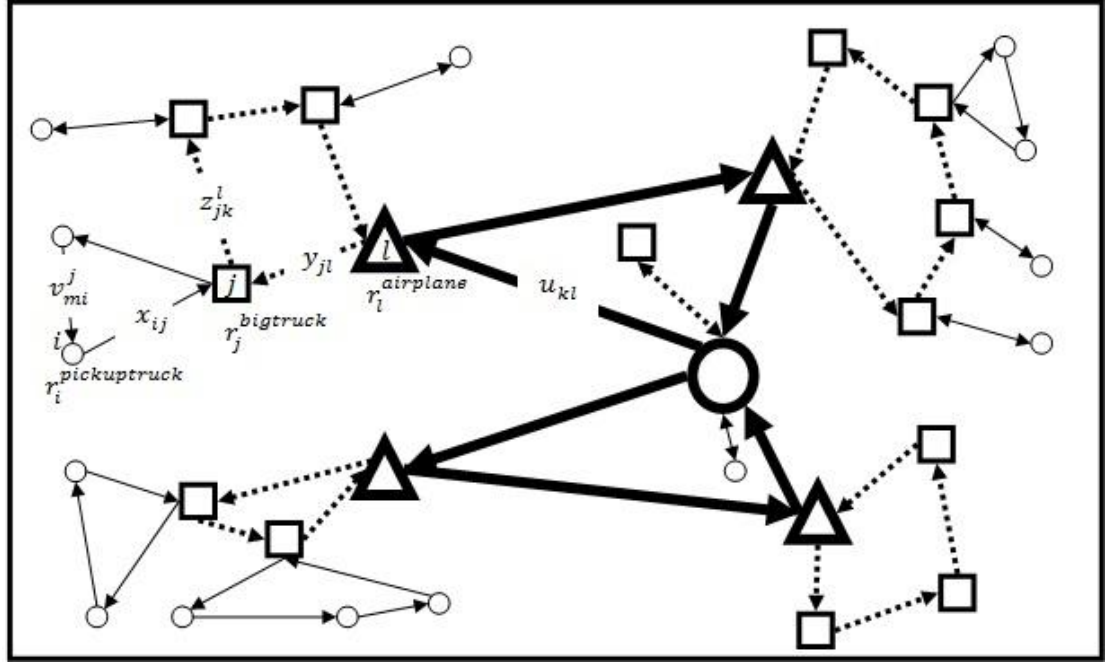


Figure 9.1: Ring(s)-Ring(s)-Ring(s) Network

The mixed integer programming formulation of the proposed problem is as follows;

$$\text{Minimize } \beta \sum_{k \in A} \sum_{l \in A \setminus \{k\}} u_{kl} + \gamma \sum_{j \in H} \sum_{k \in H \setminus \{j\}} \sum_{l \in A} z_{jk}^l + \quad (7.1)$$

$$\delta \sum_{i \in D} \sum_{j \in D \setminus \{i\}} \sum_{k \in H} v_{ij}^k$$

subject to

$$\sum_k x_{ik} = 1 \quad \forall i \quad (3.3)$$

$$\sum_k x_{kk} = p \quad (3.4)$$

$$x_{ik} \leq x_{kk} \quad \forall i, k \quad (3.6)$$

$$\sum_{l \in A} y_{jl} = x_{jj} \quad \forall j \in H \quad (4.2)$$

$$y_{jl} \leq y_{ll} \quad \forall j \in H, l \in A \quad (4.3)$$

$$y_{jj} \leq x_{jj} \quad \forall j \in A \quad (4.4)$$

$$y_{00} = 1 \quad (4.5)$$

$$\sum_{l \in A \setminus \{k\}} u_{kl} = y_{kk} \quad \forall k \in A \quad (4.6)$$

$$\sum_{l \in A \setminus \{k\}} u_{lk} = y_{kk} \quad \forall k \in A \quad (4.7)$$

$$\sum_{l \in A \setminus \{0\}} u_{0l} = \sum_{l \in A \setminus \{0\}} u_{l0} \quad (4.8)$$

$$\sum_{j \in H \setminus \{k\}} z_{jk}^l = y_{kl} \quad \forall k \in H, l \in A \setminus \{k\} \quad (4.20)$$

$$\sum_{j \in H \setminus \{k\}} z_{kj}^l = y_{kl} \quad \forall k \in H, l \in A \setminus \{k\} \quad (4.21)$$

$$\sum_{j \in H \setminus \{l\}} z_{jl}^l = \sum_{j \in H \setminus \{l\}} z_{lj}^l \quad \forall l \in A \quad (4.22)$$

$$\sum_{i \in D \setminus \{j\}} v_{ij}^k = x_{jk} \quad \forall j \in D, k \in H \setminus \{j\} \quad (7.2)$$

$$\sum_{i \in D \setminus \{j\}} v_{ji}^k = x_{jk} \quad \forall k \in H, l \in A \setminus \{k\} \quad (7.3)$$

$$\sum_{i \in D \setminus \{j\}} v_{ij}^j = \sum_{i \in D \setminus \{j\}} v_{ji}^j \quad \forall j \in H \quad (7.4)$$

$$r_k^{\text{airplane}} - r_l^{\text{airplane}} + T u_{kl} \leq T - (t_{kl}^{\text{air}} + m_l) u_{kl} \quad \forall k \in A \setminus \{0\}, l \in A \setminus \{k\} \quad (4.11)$$

$$r_k^{\text{airplane}} \geq (t_{0k}^{\text{air}} + m_k) u_{0k} \quad \forall k \in A \setminus \{0\} \quad (4.12)$$

$$r_j^{\text{bigtruck}} - r_k^{\text{bigtruck}} + T z_{jk}^l \leq T - \alpha z_{jk}^l t_{jk} \quad \forall l \in A, j \in H \setminus \{l\}, k \in H \setminus \{j\} \quad (4.23)$$

$$r_j^{\text{bigtruck}} \geq \alpha t_{lj} z_{lj}^l \quad \forall j \in H, l \in A \setminus \{j\} \quad (4.24)$$

$$r_k^{\text{airplane}} \geq r_k^{\text{bigtruck}} + m_k \quad \forall k \in A \quad (4.26)$$

$$\begin{aligned} r_i^{pickuptruck} - r_j^{pickuptruck} + T v_{ij}^k & \leq T - v_{ij}^k t_{ij} & \forall k \in H, i \in D \setminus \{k\}, j \in D \setminus \{i\} \end{aligned} \quad (7.5)$$

$$r_i^{pickuptruck} \geq t_{ki} v_{ki}^k \quad \forall i \in D, k \in H \setminus \{i\} \quad (7.6)$$

$$r_j^{bigtruck} \geq r_j^{pickuptruck} \quad \forall j \in H \quad (7.7)$$

$$2r_0^{airplane} \leq T \quad (4.13)$$

$$x_{ik} \geq 0 \quad \forall i, k \quad (3.5)$$

$$y_{jl} \in \{0,1\} \quad \forall j \in H, l \in A \quad (4.14)$$

$$u_{kl} \in \{0,1\} \quad \forall k \in A, l \in A \setminus \{k\} \quad (4.15)$$

$$z_{jk}^l \in \{0,1\} \quad \forall j \in H, k \in H \setminus \{j\}, l \in A \quad (4.27)$$

$$v_{ij}^k \in \{0,1\} \quad \forall D \in H, j \in D \setminus \{i\}, k \in H \quad (7.8)$$

$$r_l^{airplane} \geq 0 \quad \forall l \in A \quad (4.16)$$

$$r_l^{bigtruck} \geq 0 \quad \forall l \in H \quad (4.28)$$

$$r_i^{pickuptruck} \geq 0 \quad \forall i \in D \quad (7.9)$$

In this mathematical model, the objective function (7.1) minimizes the weighted sum of the number of airline segments between airport hubs and highway segments among airport hubs, ground hubs and demand nodes ($\delta < \gamma < \beta$).

Constraints (3.3)-(3.6); (4.2)-(4.8) and (4.11)-(4.16) are from the R-S-S model. Also, constraints (4.20)-(4.24); (4.26)-(4.28) are from the R-R-S model. Constraints (7.2) and (7.3) construct the ring structure(s) for the demand nodes (third layer of the hierarchical hub network). Constrains (7.4) allows to the structure with more than one ring for one hub. It means that more than one pickup truck can be used, if necessary.

Constraint (7.5) ensures that the earliest time that a pickup truck departs from any demand nodes is within the predetermined time bound. Also, remark that Constraint (7.5) acts as sub-tour breaking constraints for the pickup truck tours. Constraint (7.6)

calculates the earliest time that a pickup truck departs from the demand hub, which has a directed link from its allocated airport or ground hub. We compute this time separately in order to complete ring structure(s) for the third layer. Constraint (7.7) guarantees that a big truck departs from the hub, after the arrival of all demands from its demand nodes via the pickup trucks.

Constraints (7.8) and (7.9) are the domain constraints for the additional decision variables.

This mathematical formulation is a mixed binary programming formulation with $O(n^3)$ binary variables, $O(n)$ non-negative variables, and $O(n^3)$ constraints.

Finally, we remark here that; although we change the star structure to ring(s) for the third layer, two valid inequalities from the R-S-S model can be used for this model, too because of the triangular inequality. So, Constraints (4.18) and (4.19) are also used for this model.

For the R-R-R model, we conduct a computational study over the CAB data set. Since the problem is too complicated, the CAB data set with 25 nodes cannot be solved optimally. Therefore, we consider the first 10 nodes from the CAB data set. Being in the 10 node set again, Atlanta is assigned as the central airport hub. Also, other computational settings are the same as before. For R-R-R model, coefficients β , γ and δ in the objective functions are taken as 10, 5 and 2, respectively. The results are summarized in Table 9.1.

Table 9.1: Results of R-R-R Model on CAB Data Set (Atlanta (1))

T (hours)	p	Objective Function	Number of Airplanes/Big Trucks/Pickup Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	Demand Nodes(allocated Hubs)	CPU (sec)
48	5	66	1/0/3	1, 2, 5, 7, 8	-	3(2), 4(5), 6(5), 9(5), 10(7)	83.19
48	6	69	1/1/3	1, 2, 8, 10	5(2), 6(2)	3(2), 4(6), 9(6), 7(10)	159.66
48	7	75	1/1/2	1, 3, 6, 7, 8	2(6), 9(6)	4(6), 5(6), 7(10)	163.87
48	8	78	1/1/2	1, 3, 7, 8, 9	4(9), 5(9), 6(9)	2(3), 10(7)	306.55
24	9	104	2/0/1	1, 2, 3, 4, 5, 7, 8, 9, 10	-	6(9)	98.44

Based on these results, for 2-day delivery, one airplane, at most one big truck and at most three pick-up trucks are required. For the next day delivery, the number of airplanes increases and also, the number big and pick-up trucks decrease. For all instances, Denver (8) is opened as an airport hub, since it is the farthest city from the central airport hub Atlanta among 10 cities. When we compare the 2-day and next day deliveries, next-day delivery needs more airport hubs in order to cover 10 cities of USA within 24 hours. Also, increasing p value increases the CPU time.

We analyze one instance in detail and the result of this instance on USA map can be seen Figure 9.2. In this instance, the time bound is 48 hours and the number of hubs to be opened is 6. In this instance, 4 airport and 2 ground hubs are opened. Also, one airplane, one big truck and 3 pick-up trucks are used to serve 10 cities of USA within 48 hours. As can be seen from the map, in each layer, there are ring structures. At the top layer, airplane travels along the path Atlanta (1)-Houston (10)-Denver (8)-Baltimore (2)-Atlanta (1). At the second layer, big truck travels along the path Baltimore (2)-Cincinnati (5)-Cleveland (6)-Baltimore (2). Finally, at the third layer, pick-up truck travels along the path Cleveland (6)-Chicago (4)-Detroit (9)-Cleveland (6).

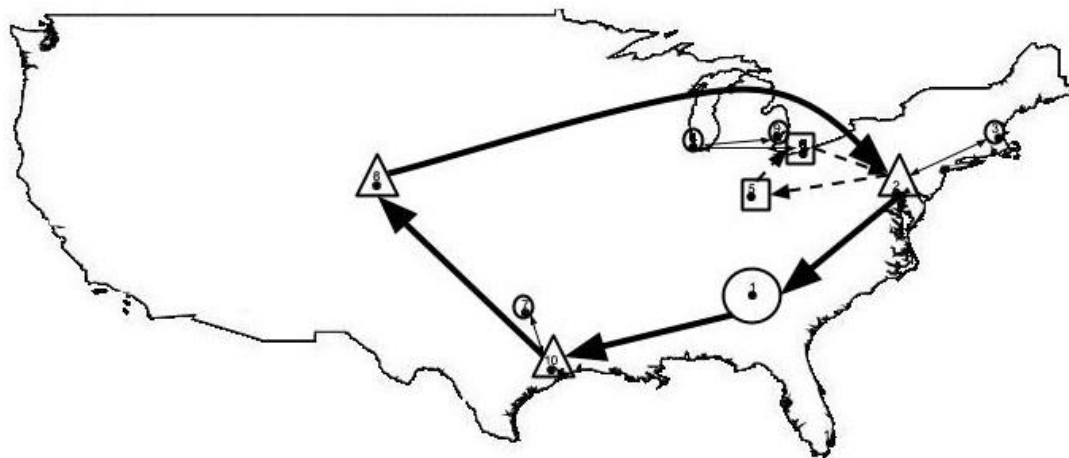


Figure 9.2: Result of the R-R-R Model on USA map ($T = 48, p = 6$)

Chapter 10

Conclusion and Future Research

In this study, we introduce the hierarchical multimodal hub covering problem over different service network configurations. The aim of this research is to design a three level network that serves all origin-destination pairs in a predetermined time bound and also to minimize the number of segments and vehicles.

Since the main objective is to reduce the number of segments and vehicles, we consider a different network structure such as ring(s). First of all, the ring structure(s) is used at the top layer. Airplanes at that layer pickup and deliver the cargoes with tour(s) between airport hubs. Therefore, in addition to scheduling decisions, routing decisions are also included in this problem. Secondly, we consider the ring structure(s) at the second layer, too. At that layer, big trucks also serve via circle(s) between hubs.

Two mixed integer programming formulations are developed and some valid inequalities are proposed. Comprehensive computational studies for the R-S-S and R-R-

S models are conducted on both Turkish network and CAB data set. These two problems are solved to optimality using the optimization software Gurobi 5.0.2.

Based on the computational results of the R-S-S model, we conclude that for the same service level, using a ring structure(s) rather than a star structure at the top layer of the hierarchy decrease the number of airplanes and also the number of airline segments (flights). As it stated earlier the aim of the study is to cover all origin-destination pairs in a given time bound (T). According to our analysis, most of the origin-destination pairs are covered within a bound far less than time bound T . Also, when we compare the different locations for the central airport hub for the R-S-S model, more centric location in the country are more favorable in terms of the number of airplanes and airline segments.

When we consider the results of the R-R-S model, for the tight time bounds, the importance of the big trucks and ground hubs vanishes due to the ring structure(s) at the second layer. On the other hand, a ring structure(s) instead of a star structure at that layer reduces the number of big trucks and the number of highway segments among hubs. Finally, similar to the results of R-S-S model, more centric location for the central airport hub is more advantageous in terms of the objective function and the number of vehicles.

In this thesis, also a heuristic approach is proposed in order to solve R-S-S and R-R-S models over larger data set. Based on this heuristic algorithm, computational studies are carried out on TR data set.

For the heuristic solutions of the R-S-S model, the average optimality gap of 26 instances is 5%. On the other hand, the average CPU time improvement for the same instances is 66.6%. When we consider the heuristic solutions of the R-R-S model, the

average optimality gap of 21 instances 2.33% and the average CPU time improvement is 69.23%. This result shows the efficiency of the proposed heuristic approach.

In this research, we introduce a new hub location problem over a hierarchical and multimodal network. Since the proposed mathematical model structure is generic, we can consider different versions of mathematical model such as R-S-S and R-R-S. Finally, we can solve the big sized network such as Turkish data set in reasonable times.

As possible future directions for our research, flow and cost issues can be included into our problem settings. By considering the flow and cost data, we can observe their effects on the solutions. Also, the capacity of the vehicles can be added into the problem if flow is considered. With the capacity constraint, more vehicles can be required to deliver the cargos within the time bound. In addition to this, cargo delivery with “pick and deliver together” service can be considered. Therefore, we can decrease the delivery time for cargos.

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APPENDIX

Appendix 1: Results of TR Data Set (Ankara (6)) on the S-S-S Network

T (hours)	p	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	2	2	1	6, 25	-	0.06
24	3	2	1	6, 23	61(6)	0.19
24	4	2	1	6, 23	25(6), 44(23)	0.2
24	5	2	1	6, 23	21(23), 25(23), 61(6)	0.19
24	6	2	1	6, 23	21(23), 42(6), 61(6), 65(6)	0.2
23	2	2	1	6, 25	-	0.06
23	3	2	1	6, 23	3(6)	0.18
23	4	2	1	6, 21	5(6), 61(6)	0.18
23	5	2	1	6, 21	25(21), 26(6), 61(6)	0.2
23	6	2	1	6, 65	5(6), 23(6), 25(65), 61(6)	0.19
22	2	2	1	6, 23	-	0.06
22	3	2	1	6, 23	61(23)	0.19
22	4	2	1	6, 23	27(23), 61(23)	0.2
22	5	2	1	6, 25	21(25), 23(6), 65(25)	0.2
22	6	2	1	6, 23	5(6), 44(23), 55(6), 61(6)	0.2
21	3	4	2	6, 21, 25	-	0.09
21	4	2	1	6, 25	27(6), 65(25)	0.2
21	5	2	1	6, 25	5(6), 38(6), 65(25)	0.22
21	6	2	1	6, 25	21(25), 38(6), 61(25), 65(25)	0.19
21	7	2	1	6, 25	16(6), 21(25), 38(6), 61(25), 65(25)	0.19
20	4	4	2	6, 21, 25	81(6)	0.18
20	5	4	2	6, 21, 25	61(25), 81(6)	0.24
20	6	4	2	6, 21, 25	1(6), 34(6), 65(25)	0.22
20	7	4	2	6, 21, 25	7(6), 27(6), 34(6), 65(61)	0.21
20	8	4	2	6, 21, 25	23(21), 27(21), 34(6), 61(25), 65(21)	0.21
19	5	6	3	6, 21, 25, 34	27(21)	0.21
19	6	6	3	6, 21, 25, 26	27(21), 61(25)	0.24
19	7	6	3	6, 21, 25, 26	7(6), 27(21), 61(25)	0.24
19	8	6	3	6, 16, 21, 25	7(6), 27(21), 65(25), 3(6)	0.23
19	9	6	3	6, 21, 25, 26	16(26), 27(21), 44(6), 61(25), 65(25)	0.22
18	6	8	4	6, 16, 23, 25, 65	20(6)	0.19
18	7	8	4	6, 16, 23, 25, 65	20(6), 81(6)	0.24
18	8	8	4	6, 16, 23, 61, 65	20(6), 25(23), 34(6)	0.26

18	9	8	4	6, 16, 23, 25, 65	20(6), 34(6), 55(6), 61(23)	0.23
18	10	8	4	6, 16, 23, 25, 65	20(6), 44(23), 55(6), 61(25), 68(6)	0.23
17	6	10	5	6, 16, 20, 25, 44, 65	20(26)	0.2
17	7	10	5	6, 16, 25, 26, 27, 65		0.25
17	8	10	5	6, 16, 25, 27, 35, 65		0.57
17	9	10	5	6, 16, 20, 44, 61, 65		0.61
17	10	10	5	6, 7, 16, 25, 44, 65		0.61
16	6	10	5	6, 7, 16, 44, 61, 65	-	0.18
16	7	10	5	6, 16, 27, 35, 61, 65	7(6)	0.22
16	8	10	5	6, 16, 35, 44, 61, 65	7(6), 23(44)	0.38
16	9	10	5	6, 16, 35, 44, 61, 65	23(44), 27(44), 3(6)	0.19
16	10	10	5	6, 16, 35, 44, 61, 65	7(6), 21(44), 26(6), 27(44)	0.22
15	8	14	7	6, 20, 21, 25, 34, 44, 55, 65	-	0.16
15	9	14	7	6, 20, 21, 25, 27, 34, 61, 65	35(20)	0.16
15	10	14	7	6, 20, 21, 25, 27, 34, 61, 65	35(20), 81(6)	0.16
15	11	14	7	6, 20, 21, 25, 27, 34, 61, 65	35(20), 3(34), 81(6)	0.16
15	12	14	7	6, 20, 21, 25, 27, 34, 61, 65	26(20), 35(20), 3(34), 81(6)	0.16
14	8	14	7	6, 1, 20, 21, 25, 34, 61, 65	-	0.06
14	9	14	7	6, 20, 21, 25, 27, 34, 61, 65	1(27)	0.15
14	10	14	7	6, 20, 21, 25, 27, 34, 61, 65	55(6), 81(0)	0.15
14	11	14	7	6, 20, 21, 25, 27, 34, 61, 65	1(27), 7(20), 35(20)	0.15
14	12	14	7	6, 1, 20, 21, 25, 34, 61, 65	7(20), 27(1), 35(20), 81(6)	0.15
13	9	16	8	6, 1, 5, 20, 21, 25, 34, 61, 65	-	0.15
13	10	16	8	6, 1, 20, 21, 25, 34, 55, 61, 65	2(55)	0.15
13	11	16	8	6, 5, 20, 21, 25, 27, 34, 61, 65	7(20), 16(6)	0.15
13	12	16	8	6, 5, 20, 21, 25, 27, 34, 61, 65	7(20), 35(20), 55(0)	0.15

13	13	16	8	6, 1, 5, 20, 21, 28, 34, 61, 65	16(34), 27(1), 35(20), 55(0)	0.15
≤ 12	22	infeasible				

Appendix 2: Results of CAB Data Set (Atlanta (1)) on the S-S-S Network

T (hours)	p	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	2	1	1, 22	-	0.03
72	3	2	1	1, 19	22(19)	0.05
72	4	2	1	1, 8	2(1), 3(1)	0.09
70	2	2	1	1, 22	-	0.02
70	3	2	1	1, 19	22(19)	0.04
70	4	2	1	1, 8	2(1), 3(1)	0.09
68	2	2	1	1, 22	-	0.05
68	3	2	1	1, 12	22(12)	0.1
68	4	2	1	1, 22	12(22), 23(22)	0.09
66	2	2	1	1, 22	-	0.05
66	3	2	1	1, 8	12(8)	0.09
66	4	2	1	1, 12	2(1), 23(12)	0.09
64	2	2	1	1, 19	-	0.05
64	3	2	1	1, 12	2(1)	0.08
64	4	2	1	1, 22	19(22), 23(22)	0.08
62	2	2	1	1, 22	-	0.04
62	3	2	1	1, 22	19(22)	0.06
62	4	2	1	1, 22	12(22), 13(1)	0.06
60	2	2	1	1, 22	-	0.04
60	3	2	1	1, 22	19(22)	0.06
60	4	2	1	1, 22	3(1), 19(22)	0.06
58	2	2	1	1, 22	-	0.03
58	3	2	1	1, 22	23(22)	0.06
58	4	2	1	1, 8	12(8), 22(8)	0.08
56	2	2	1	1, 8	-	0.02
56	3	2	1	1, 22	9(1)	0.04
56	4	2	1	1, 8	5(1), 9(1)	0.08
54	3	2	1	1, 8	23(8)	0.03
54	4	2	1	1, 12	3(1), 23(12)	0.07
54	5	2	1	1, 12	3(1), 18(1), 23(12)	0.08
52	3	2	1	1, 8	23(8)	0.03
52	4	2	1	1, 12	3(1), 23(12)	0.08
52	5	2	1	1, 22	3(1), 8(1), 20(1)	0.07
50	3	4	2	1, 7, 22	-	0.04
50	4	2	1	1, 8	22(8), 23(8)	0.07
50	5	2	1	1, 8	12(8), 22(8), 23(8)	0.07
48	3	4	2	1, 4, 22	-	0.04
48	4	4	2	1, 8, 23	4(1)	0.06
48	5	4	2	1, 21, 22	2(1), 11(21)	0.06
46	3	4	2	1, 8, 22	-	0.05
46	4	4	2	1, 11, 22	19(22)	0.05
46	5	4	2	1, 11, 22	19(22), 23(22)	0.05
44	4	4	2	1, 21, 22	3(1)	0.07
44	5	4	2	1, 21, 22	3(1), 12(22)	0.08
44	6	4	2	1, 21, 22	12(22), 14(1), 18(1)	0.07

42	4	6	3	1, 19, 20, 23	-	0.1
42	5	4	2	1, 19, 23	3(1), 15(1)	0.11
42	6	4	2	1, 21, 22	3(1), 19(22), 23(22)	0.1
40	4	6	3	1, 9, 19, 23	-	0.1
40	5	6	3	1, 5, 19, 23	15(1)	0.1
40	6	6	3	1, 5, 19, 23	12(19), 15(1)	0.1
38	5	6	3	1, 19, 20, 23	22(19)	0.1
38	6	6	3	1, 19, 20, 23	14(1), 22(19)	0.1
38	7	6	3	1, 19, 20, 23	12(19), 14(1), 22(19)	0.1
36	5	8	4	1, 11, 12, 20, 23	-	0.1
36	6	8	4	1, 12, 15, 20, 23	8(15)	0.1
36	7	8	4	1, 6, 12, 15, 23	8(15), 22(12)	0.1
34	5	8	4	1, 6, 11, 12, 23	-	0.1
34	6	8	4	1, 11, 12, 20, 23	17(20)	0.1
34	7	8	4	1, 6, 11, 12, 23	9(11), 24(1)	0.11
32	6	8	4	1, 11, 12, 23, 25	10(1)	0.11
32	7	8	4	1, 11, 12, 23, 25	10(1), 22(12)	0.11
32	8	8	4	1, 11, 12, 23, 25	10(1), 19(12), 22(12)	0.11
30	7	8	4	1, 11, 12, 18, 23	8(11), 10(1)	0.11
30	8	8	4	1, 11, 12, 23, 25	8(11), 10(1), 18(25)	0.1
30	9	8	4	1, 11, 12, 18, 23	3(18), 8(11), 10(1), 19(12)	0.11
28	8	10	5	1, 11, 12, 16, 20, 23	8(11), 24(1)	0.11
28	9	10	5	1, 11, 12, 13, 23, 25	2(25), 8(11), 24(1)	0.11
28	10	10	5	1, 7, 11, 12, 23, 25	2(25), 8(11), 20(25), 24(1)	0.11
26	9	14	7	1, 8, 10, 11, 18, 19, 22, 23	14(1)	0.11
26	10	12	6	1, 8, 10, 11, 12, 18, 23	14(1), 19(12), 22(12)	0.11
26	11	12	6	1, 8, 12, 13, 15, 23, 25	14(1), 19(12), 22(12), 24(1)	0.12
24	10	18	9	1, 4, 8, 10, 12, 15, 17, 19, 22, 23	-	0.1
24	11	18	9	1, 2, 4, 8, 10, 12, 14, 19, 22, 23	3(2)	0.12
24	12	18	9	1, 4, 8, 10, 12, 14, 19, 22, 23, 25	2(25), 6(25)	0.11
≤22	25	infeasible				

Appendix 3: Results of TR Data Set (İstanbul (34)) on the R-S-S Network

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	2	2	1	34, 23	-	0.17
24	3	2	1	34, 23	44(23)	0.42
24	4	2	1	34, 23	25(23), 44(23)	1.51
24	5	2	1	34, 23	21(23), 25(23), 44(23)	2.37
24	6	2	1	34, 23	21(23), 35(34), 44(23), 81(34)	2.99
23	4	3	1	34, 5, 21	35(34)	5.7
23	5	2	1	34, 23	21(23), 35(34), 3(34)	1.97
23	6	2	1	34, 23	20(34), 21(23), 65(23), 3(34)	1.71
23	7	2	1	34, 23	1(23), 20(34), 21(23), 25(23), 42(34)	4.39
23	8	2	1	34, 23	16(34), 20(34), 21(23), 26(34), 35(34), 38(34)	1.68
22	4	4	1	34, 6, 21, 25	-	3.73
22	5	3	1	34, 25, 38	35(34), 65(25)	35.67
22	6	3	1	34, 25, 44	35(34), 42(34), 65(25)	30.32
22	7	3	1	34, 25, 38	20(34), 21(25), 42(34), 65(25)	31.45
22	8	3	1	34, 25, 44	20(34), 21(25), 23(44), 42(34), 65(25)	2.51
21	5	4	1	34, 21, 25, 42	55(34)	50.1
21	6	4	1	34, 6, 21, 25	27(21), 3(6)	48.25
21	7	4	1	34, 21, 25, 42	6(42), 27(21), 55(42)	32.59
21	8	4	1	34, 6, 21, 25	1(6), 27(21), 44(25), 3(6)	44.97
21	9	4	1	34, 21, 25, 42	23(25), 44(21), 55(42), 65(25), 68(42)	34.24
20	5	6	2	34, 21, 42, 61, 65	-	24.45
20	6	5	2	34, 6, 21, 25	20(6), 27(21)	48.26
20	7	5	2	34, 6, 21, 25	20(6), 27(21), 61(25)	1075.54
20	8	5	2	34, 6, 21, 25	20(6), 23(25), 27(21), 42(6)	736.47
20	9	5	2	34, 6, 21, 25	20(6), 27(21), 38(6), 68(6), 81(34)	46.75
19	6	6	2	34, 26, 27, 61, 65	55(61)	464.23
19	7	6	2	34, 27, 42, 61, 65	20(42), 55(61)	1079.97
19	8	6	2	34, 21, 42, 61, 65	1(42), 20(42), 55(61)	541.37
19	9	6	2	34, 23, 42, 61, 65	1(42), 20(42), 27(23), 55(61)	1060.42
19	10	6	2	34, 26, 44, 61, 65	1(44), 23(44), 27(44), 42(26), 55(61)	600.59

18	6	7	2	34, 1, 25, 26, 55, 65	-	220.11
18	7	7	2	34, 6, 20, 25, 27, 65	3(6)	1648.95
18	8	7	2	34, 5, 25, 26, 27, 65	20(25), 61(5)	3578.53
18	9	7	2	34, 1, 5, 25, 26, 65	21(25), 38(1), 3(26)	5552.61
18	10	7	2	34, 5, 20, 25, 27, 65	1(27), 38(5), 42(20), 61(5)	2145.72
17	6	9	3	34, 5, 7, 25, 27, 65	-	677.19
17	7	8	2	34, 1, 20, 21, 25, 55, 65	-	3749.69
17	8	8	2	34, 1, 20, 21, 25, 55, 65	42(1)	6763.82
16	7	9	3	34, 1, 20, 21, 25, 55, 65	-	1963.95
15	8	10	3	34, 1, 5, 20, 21, 25, 61, 65	-	9610.25
≤13	22	infeasible				

Appendix 4: Results of TR Data Set (İzmir (35)) on the R-S-S Network

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	3	3	1	35, 6, 23	-	0.49
24	4	3	1	35, 5, 23	25(23)	4.31
24	5	3	1	35, 23, 55	25(23), 65(23)	8.69
24	6	3	1	35, 5, 23	21(23), 25(23), 44(23)	4.94
24	7	3	1	35, 25, 38	23(25), 27(38), 61(25), 65(25)	6.08
23	3	4	2	35, 5, 21	-	0.48
23	4	3	1	35, 21, 55	68(35)	8.8
23	5	3	1	35, 21, 38	5(38), 61(35)	7.28
23	6	3	1	35, 21, 38	44(38), 61(38), 65(21)	4.24
23	7	3	1	35, 21, 38	1(21), 23(21), 25(21), 61(38)	24.36
22	4	4	1	35, 6, 21, 25	-	6.01
22	5	4	1	35, 6, 21, 25	23(21)	64.59
22	6	4	1	35, 6, 21, 25	27(6), 68(6)	53.65
22	7	4	1	35, 6, 21, 25	23(21), 44(25), 68(6)	22.68
22	8	4	1	35, 21, 25, 38	1(38), 5(38), 55(38), 65(21)	64.98
21	4	5	2	35, 6, 21, 25	-	20.56
21	5	4	1	35, 6, 21, 25	27(21)	35.35
21	6	4	1	35, 25, 38, 65	61(38), 81(35)	49.59
21	7	4	1	35, 25, 38, 65	21(65), 68(38), 81(35)	35.34
21	8	4	1	35, 21, 25, 38	5(38), 23(21), 3(35), 81(35)	75.66
20	5	5	2	35, 6, 21, 25	27(21)	40.99
20	6	5	1	35, 5, 25, 27, 65	1(27)	54.31
20	7	5	2	35, 6, 21, 25	27(21), 65(25), 68(6)	673.28
20	8	5	2	35, 6, 21, 25	1(6), 23(21), 27(21), 55(6)	645.91
20	9	5	1	35, 5, 25, 27, 65	1(27), 44(25), 55(5), 61(25)	477.69
19	5	6	2	35, 6, 25, 44, 65	-	74.95
19	6	6	2	35, 5, 27, 61, 65	1(27)	1244.5
19	7	6	2	35, 5, 25, 27, 65	21(25), 42(35)	852.99
19	8	6	2	35, 1, 6, 25, 65	27(1), 42(6), 44(25)	753.61
19	9	6	2	35, 5, 25, 44, 65	1(44), 38(5), 42(35), 61(5)	1128.39
18	5	7	3	35, 6, 27, 61, 65	-	23.31
18	6	7	2	35, 6, 25, 44, 61, 65	-	576.77

18	7	7	2	35, 6, 21, 25, 27, 65	81(6)	3473.75
18	8	7	2	35, 6, 21, 27, 61, 65	25(61), 68(6)	8058.78
18	9	7	2	35, 6, 25, 27, 61, 65	5(6), 38(6), 55(6)	8119.15
17	7	8	2	35, 6, 21, 25, 27, 61, 65	-	2388.25
16	8	9	2	35, 1, 5, 16, 21, 25, 61, 65	-	17182.61
≤14	22	infeasible				

Appendix 5: Results of CAB Data Set (New York (17)) on the R-S-S Network

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	2	1	17, 19	-	0.1
72	3	2	1	17, 12	8(17)	0.54
72	4	2	1	17, 19	18(17), 12(19)	3.3
70	2	2	1	17, 19	-	0.09
70	3	2	1	17, 19	23(19)	0.33
70	4	2	1	17, 8	12(8), 23(8)	1.53
68	2	2	1	17, 19	-	0.08
68	3	2	1	17, 12	18(17)	0.27
68	4	2	1	17, 22	14(17), 12(22)	1.69
66	2	2	1	17, 19	-	0.08
66	3	2	1	17, 19	8(19)	0.32
66	4	2	1	17, 19	25(17), 8(19)	5.21
64	2	2	1	17, 19	-	0.09
64	3	2	1	17, 8	12(8)	0.37
64	4	2	1	17, 8	3(17), 10(17)	6.56
62	2	2	1	17, 8	-	0.08
62	3	2	1	17, 19	23(19)	0.35
62	4	2	1	17, 8	7(8), 22(8)	6.59
60	2	2	1	17, 8	-	0.09
60	3	2	1	17, 19	23(19)	0.3
60	4	2	1	17, 19	8(19), 23(19)	2.2
58	2	2	1	17, 8	-	0.08
58	3	2	1	17, 8	7(8)	0.27
58	4	2	1	17, 8	7(8), 23(8)	1.99
56	3	2	1	17, 8	23(8)	0.23
56	4	2	1	17, 8	12(8), 23(8)	1.38
56	5	2	1	17, 8	10(8), 19(8), 23(8)	1.87
54	3	3	1	17, 11, 22	-	0.29
54	4	2	1	17, 8	16(17), 23(8)	8.07
54	5	2	1	17, 8	16(17), 19(8), 23(8)	2.66
52	3	3	1	17, 13, 22	-	0.24
52	4	3	1	17, 13, 22	19(22)	3.67
52	5	2	1	17, 8	1(17), 22(8), 23(8)	2.05
50	3	3	1	17, 13, 22	-	1.02
50	4	3	1	17, 13, 22	14(17)	5.73
50	5	3	1	17, 13, 22	14(1), 23(22)	9.01
48	3	3	1	17, 13, 22	-	0.53

48	4	3	1	17, 13, 22	24(13)	4.99
48	5	3	1	17, 13, 22	14(17), 19(22)	7.58
46	4	4	2	17, 13, 22	8(13)	4.07
46	5	4	2	17, 13, 22	5(13), 8(13)	26.19
46	6	3	1	17, 13, 22	8(13), 19(22), 23(22)	60.25
44	5	4	1	17, 13, 19, 23	14(13)	46.29
44	6	4	1	17, 13, 19, 23	24(17), 14(13)	60.06
44	7	4	1	17, 14, 21, 22	13(21), 19(22), 23(22)	107.35
42	5	5	1	17, 12, 21, 23, 24	-	20.79
42	6	4	1	17, 13, 19, 23	14(13), 22(19)	160.88
42	7	4	1	17, 13, 19, 23	12(19), 14(13), 22(19)	144.77
40	5	5	1	17, 11, 12, 16, 23	-	28.47
40	6	5	1	17, 1, 11, 12, 23	7(11)	73.33
40	7	5	1	17, 11, 12, 16, 23	19(12), 22(12)	525.65
38	5	5	1	17, 1, 11, 12, 23	-	20.93
38	6	5	1	17, 1, 11, 12, 23	14(1)	884.52
38	7	5	1	17, 11, 12, 16, 23	14(16), 21(16)	620.98
36	6	5	1	17, 1, 11, 12, 23	10(1)	962.02
36	7	5	1	17, 1, 11, 12, 23	10(1), 19(12)	687.05
36	8	5	1	17, 1, 11, 12, 23	5(17), 10(1), 22(12)	643.6
34	6	6	2	17, 11, 12, 23, 24	10(11)	1037.68
34	7	6	2	17, 11, 12, 23, 24	10(11), 21(11)	457.6
34	8	6	2	17, 1, 11, 12, 23	10(11), 13(11), 19(12)	2066.58
32	7	7	2	17, 10, 11, 12, 23, 24	8(11)	2924.36
32	8	7	2	17, 11, 12, 16, 23, 24	8(11), 14(24)	6219.87
32	9	7	2	17, 7, 11, 12, 23, 24	4(17), 8(11), 22(12)	18224.9 1
30	7	8	3	17, 10, 11, 12, 23, 24	8(11)	417.09
30	8	7	2	17, 11, 12, 14, 16, 23	1(16), 8(11)	3702.79
30	9	7	2	17, 11, 12, 13, 23, 24	8(11), 10(13), 22(12)	10032.5 6
≤24	25	infeasible				

Appendix 6: Results of CAB Data Set (Los Angeles (12)) on the R-S-S Network

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	2	1	12, 20	-	0.3
72	3	2	1	12, 18	17(18)	4.79
72	4	2	1	12, 18	2(18), 17(18)	13.91
70	2	2	1	12, 6	-	0.26
70	3	2	1	12, 17	5(17)	3.75
70	4	2	1	12, 6	13(6), 25(6)	11.79
68	2	2	1	12, 6	-	0.26
68	3	2	1	12, 25	18(25)	5.33
68	4	2	1	12, 6	9(6), 14(6)	9.17
66	2	2	1	12, 4	-	0.26
66	3	2	1	12, 11	9(11)	3.53
66	4	2	1	12, 18	11(12), 25(18)	8.28
64	2	2	1	12, 20	-	0.21
64	3	2	1	12, 5	22(12)	5.06
64	4	2	1	12, 4	1(4), 19(12)	11.65
62	2	2	1	12, 13	-	0.2
62	3	2	1	12, 20	10(12)	3.01
62	4	2	1	12, 1	7(1), 10(12)	9.89
60	2	2	1	12, 21	-	0.19
60	3	2	1	12, 21	5(21)	5.25
60	4	2	1	12, 21	10(12), 11(12)	8.95
58	2	2	1	12, 5	-	0.19
58	3	2	1	12, 13	17(13)	2.84
58	4	2	1	12, 5	14(5), 24(5)	10.78
56	2	2	1	12, 5	-	0.19
56	3	2	1	12, 1	22(12)	2.37
56	4	2	1	12, 21	6(21), 14(21)	29.24
54	3	2	1	12, 5	1(5)	2.98
54	4	2	1	12, 5	1(5), 4(5)	11.61
54	5	2	1	12, 5	1(5), 2(5), 6(5)	10.58
52	3	2	1	12, 5	24(5)	1.71
52	4	2	1	12, 5	14(5), 20(5)	10.45
52	5	2	1	12, 5	6(5), 10(5), 24(5)	11.89
50	3	3	1	12, 3, 13	-	1.33
50	4	2	1	12, 5	10(5), 14(5)	42.42
50	5	2	1	12, 5	10(5), 14(5), 16(5)	14.8
48	3	3	1	12, 1, 5	-	0.68
48	4	3	1	12, 5, 13	14(13)	14.31

48	5	3	1	12, 13, 18	21(13), 24(13)	16.62
46	4	3	1	12, 9, 16	23(12)	4.69
46	5	3	1	12, 1, 5	23(12), 24(1)	10.59
46	6	3	1	12, 2, 23	23(12), 24(13), 25(13)	12.53
44	4	3	1	12, 1, 9	23(12)	3.63
44	5	3	1	12, 1, 9	23(12), 25(1)	37.45
44	6	3	1	12, 9, 16	3(9), 20(9), 23(12)	9.24
42	4	4	2	12, 9, 16	-	3.18
42	5	3	1	12, 6, 16	15(6), 23(12)	10.73
42	6	3	1	12, 6, 16	2(6), 15(6), 23(12)	16.92
40	5	5	1	12, 1, 3, 11, 23	-	31.15
40	6	5	1	12, 11, 14, 18, 23	13(11)	194.35
40	7	5	1	12, 6, 21, 23, 24	10(21), 20(6)	162.9
38	5	5	1	12, 2, 11, 23, 24	-	35.87
38	6	5	1	12, 11, 23, 24, 25	16(11)	57.15
38	7	5	1	12, 1, 11, 17, 23	5(11), 14(1)	269.99
36	6	6	2	12, 2, 11, 23, 24	10(11)	526.79
36	7	6	2	12, 11, 23, 24, 25	10(11), 16(24)	797.28
36	8	5	1	12, 2, 11, 23, 24	9(11), 10(11), 16(24)	240.6
34	6	7	2	12, 11, 13, 23, 24, 25	-	428.32
34	7	7	2	12, 11, 14, 16, 18, 23	1(16)	3345.58
34	8	7	2	12, 7, 11, 20, 23, 24	3(20), 13(11)	14843.61
32	7	7	2	12, 11, 16, 23, 24, 25	8(11)	3370.75
32	8	7	2	12, 11, 13, 23, 24, 25	8(11), 17(25)	11633.91
32	9	7	2	12, 2, 11, 13, 23, 24	5(2), 8(11), 20(2)	12382.06
30	7	8	2	12, 4, 8, 16, 18, 23, 24	-	2516.86
30	8	8	2	12, 4, 8, 16, 17, 23, 24	18(17)	52590.29
≤24	25	infeasible				

Appendix 7: Results of CAB Data Set (Kansas City (11)) on the R-S-S Network

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	1	0	0	11	-	0.01
72	2	0	0	11	1(11)	0.08
72	3	0	0	11	19(11), 20(11)	0.11
68	2	2	1	11, 23	-	0.16
68	3	0	0	11	22(11), 23(11)	0.1
68	4	0	0	11	17(11), 22(11), 23(11)	0.1
64	2	2	1	11, 23	-	0.16
64	3	0	0	11	22(11), 23(11)	0.1
64	4	0	0	11	17(11), 22(11), 23(11)	0.1
60	2	2	1	11, 8	-	0.15
60	3	2	1	11, 23	22(23)	0.67
60	4	2	1	11, 8	12(11), 23(8)	0.8
56	3	3	1	11, 20, 22	-	0.31
56	4	2	1	11, 23	3(11), 14(11)	0.5
56	5	2	1	11, 8	9(11), 12(8), 14(11)	1.18
52	3	3	1	11, 22, 25	-	0.53
52	4	3	1	11, 8, 25	14(25)	5.87
52	5	3	1	11, 1, 8	3(1), 19(8)	18.05
48	4	3	1	11, 5, 22	14(5)	2.25
48	5	3	1	11, 20, 22	14(20), 23(22)	7.19
48	6	3	1	11, 5, 22	6(5), 9(5), 24(5)	27.62
44	4	4	1	11, 2, 22, 24	-	2.44
44	5	4	1	11, 14, 28, 22	23(22)	13.27
44	6	3	1	11, 5, 22	14(5), 19(22), 23(22)	19.44
40	5	4	1	11, 14, 22, 25	23(22)	5.54
40	6	4	1	11, 2, 14, 22	10(11), 23(22)	23.84
40	7	4	1	11, 14, 17, 22	2(17), 19(22), 23(22)	166.4
36	5	5	1	11, 1, 12, 20, 23	-	25.7
36	6	5	1	11, 1, 6, 12, 23	24(1)	83.32
36	7	5	1	11, 1, 5, 12, 23	3(5), 22(12)	674.74
32	5	6	2	11, 12, 18, 23, 24	-	29.33
32	6	6	2	11, 12, 23, 24, 25	22(12)	1325.35
32	7	6	2	11, 12, 20, 23, 24	1(11), 16(11)	1321.58
28	6	7	2	11, 2, 12, 13, 23, 24	-	13.05
28	7	7	2	11, 12, 13, 23, 24,	10(11)	276.36

28	8	7	2	25 11, 12, 13, 23, 24, 25	10(11), 17(25)	1545.65
≤ 12	25	infeasible				

Appendix 8: Results of TR Data Set (İstanbul (34)) on the R-R-S Network

T (hours)	p	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	2	20	1	0	34, 23	-	0.74
24	3	30	1	1	34, 23	21(23)	23.6
24	4	35	1	1	34, 23	21(23), 44(23)	59.76
24	5	40	1	1	34, 23	16(34), 26(34), 81(34)	347.33
24	6	50	1	2	34, 23	16(34), 21(23), 26(34), 81(34)	6207.4
23	4	40	1	0	34, 6, 21, 55	-	52.52
23	5	45	1	1	34, 5, 21	16(34), 26(34)	384.04
23	6	50	1	1	34, 5, 21	16(34), 26(34), 81(34)	7223.94
22	4	40	1	0	34, 6, 21, 25	-	102.53
22	5	50	1	0	34, 6, 21, 25, 27	-	446.18
22	6	55	1	1	34, 21, 25, 26	42(26), 3(26)	5361.16
21	5	50	1	0	34, 21, 42, 61, 65	-	739.76
21	6	60	1	0	34, 16, 23, 25, 38, 65	-	6289.91
21	7	65	1	1	34, 25, 26, 27, 65	6(26), 3(26)	45147.47
20	5	60	2	0	34, 23, 42, 61, 65	-	301.91
20	6	60	1	0	34, 23, 25, 42, 55, 65	-	7982.21
19	6	70	2	0	34, 1, 6, 25, 35, 65	-	4597.47
18	6	70	2	0	34, 6, 7, 25, 27, 65	-	4504
≤13	22	infeasible					

Appendix 9: Results of TR Data Set (İzmir (35)) on the R-R-S Network

T (hours)	p	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	3	30	1	0	35, 23, 55	-	27.98
24	4	40	1	0	35, 21, 25, 42	-	132.25
24	5	45	1	1	35, 23, 55	21(23), 44(23)	544.1
23	3	40	1	0	35, 21, 55	-	14.19
23	4	40	1	0	35, 25, 38, 65	-	47.22
23	5	45	1	1	35, 21, 55	20(35), 3(35)	540.23
22	4	40	1	0	35, 27, 55, 65	-	96.86
22	5	50	1	0	35, 6, 21, 23, 25	-	653.05
22	6	55	1	1	35, 5, 23, 65	20(35), 3(35)	5490.49
21	4	50	2	0	35, 6, 21, 25	-	119.17
21	5	50	1	1	35, 25, 38, 65	6(38)	1444.83
21	6	60	1	0	35, 6, 21, 23, 25, 65	-	7882.49
20	5	50	1	0	35, 6, 25, 27, 65	-	552.13
20	6	60	1	0	35, 6, 21, 25, 27, 65	-	6990.01
19	5	60	2	0	35, 6, 25, 44, 65	-	1373.68
19	6	70	2	0	35, 26, 27, 55, 61, 65	-	16071.04
18	5	70	2	0	35, 6, 25, 44, 65	-	417.93
18	6	70	2	0	35, 1, 6, 21, 25, 65	-	8423.82
≤14	22	infeasible					

Appendix 10: Results of CAB Data Set (New York (17)) on the R-R-S Network

T (hours)	P	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	20	1	0	17, 19	-	2.73
72	3	30	1	0	17, 23, 25	-	62.32
72	4	35	1	1	17, 8	6(17), 18(17)	212.57
68	2	20	1	0	17, 8	-	1.76
68	3	30	1	0	17, 23, 25	-	54.4
68	4	35	1	1	17, 8	3(17), 20(17)	219.83
64	2	20	1	0	17, 8	-	1.36
64	3	30	1	0	17, 8, 10	-	52.73
64	4	35	1	1	17, 8	1(17), 25(17)	183.81
60	2	20	1	0	17, 8	-	1.12
60	3	30	1	0	17, 8, 25	-	93.11
60	4	35	1	1	17, 8	5(17), 6(17)	203.99
56	3	30	1	0	17, 8, 23	-	24.25
56	4	40	1	0	17, 8, 22, 24	-	351.54
56	5	45	1	1	17, 10, 22	3(17), 6(17)	642.76
52	3	30	1	0	17, 13, 22	-	19.18
52	4	40	1	0	17, 1, 21, 22	-	342.58
52	5	45	1	1	17, 21, 22	5(21), 9(21)	515.33
48	3	30	1	0	17, 13, 22	-	11.76
48	4	40	1	0	17, 5, 13, 22	-	76.3
48	5	45	1	1	17, 13, 22	11(13), 21(13)	503.88
44	5	50	1	0	17, 1, 8, 22, 23	-	722.68
44	6	60	1	0	17, 11, 14, 19, 20, 23	-	6899.64
40	5	50	1	0	17, 1, 11, 12, 23	-	633.85
40	6	60	1	0	17, 8, 13, 14, 22, 23	-	6263.29
36	6	70	2	0	17, 11, 12, 13, 23, 24	-	9088.5
≤24	25	infeasible					

Appendix 11: Results of CAB Data Set (Los Angeles (12)) on the R-R-S Network

T (hours)	p	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	2	20	1	0	12, 25	-	4.23
72	3	30	1	0	12, 19, 25	-	86.22
72	4	35	1	1	12, 2	1(2), 20(2)	3070.07
68	2	20	1	0	12, 25	-	4.18
68	3	30	1	0	12, 8, 17	-	138.13
68	4	35	1	1	12, 9	6(9), 20(9)	4274.31
64	2	20	1	0	12, 13	-	3.72
64	3	30	1	0	12, 8, 25	-	133.04
64	4	35	1	1	12, 21	1(21), 13(21)	4939.83
60	2	20	1	0	12, 21	-	2.93
60	3	30	1	0	12, 13, 21	-	90.96
60	4	35	1	1	12, 21	5(21), 6(21)	1109.74
56	2	20	1	0	12, 1	-	3.46
56	3	30	1	0	12, 1, 19	-	113.1
56	4	35	1	1	12, 5	2(5), 25(5)	618.27
52	3	30	1	0	12, 1, 20	-	79.66
52	4	40	1	0	12, 4, 16, 24	-	274.55
52	5	45	1	1	12, 13, 18	2(18), 6(18)	1223.85
48	3	30	1	0	12, 1, 6	-	49.99
48	4	40	1	0	12, 8, 14, 17	-	227.09
48	5	45	1	1	12, 1, 6	2(6), 18(6)	1827.1
44	4	40	1	0	12, 6, 16, 23	-	60.3
44	5	50	1	0	12, 1, 9, 22, 23	-	812.75
40	5	50	1	0	12, 1, 11, 20, 23	-	784.51
40	6	60	1	0	12, 6, 11, 16, 23, 24	-	17833.52
36	6	70	2	0	12, 10, 11, 20, 22, 24	-	7636.5
≤24	25	infeasible					

Appendix 12: Results of CAB Data Set (Kansas City (11)) on the R-R-S Network

T (hours)	p	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
72	1	0	0	0	11	-	0.07
72	2	10	0	1	11	21(11)	4.19
72	3	15	0	1	11	4(11), 5(11)	4.88
68	2	20	1	0	11, 23	-	2.89
68	3	30	1	1	11, 23	8(11)	39.56
68	4	35	1	1	11, 22	8(11), 21(11)	207.79
64	2	20	1	0	11, 22	-	2.8
64	3	30	1	0	11, 22, 23	-	111.91
64	4	35	1	1	11, 23	5(11), 9(11)	127.97
60	2	20	1	0	11, 12	-	2.73
60	3	30	1	0	11, 12, 23	-	137.92
60	4	35	1	1	11, 12	7(11), 21(11)	100.23
56	3	30	1	0	11, 22, 25	-	5.05
56	4	40	1	0	11, 12, 20, 23	-	5304.25
56	5	45	1	1	11, 18, 22	2(18), 17(18)	818.08
52	3	30	1	0	11, 2, 22	-	9.84
52	4	40	1	0	11, 2, 22, 23	-	8650.09
52	5	45	1	0	11, 2, 22	6(2), 25(2)	12670.43
48	4	40	1	0	11, 5, 22, 24	-	96.44
48	5	50	1	0	11, 13, 14, 22, 25	-	10227.28
48	6	55	1	1	11, 6, 14, 22	20(6), 25(6)	24306.17
44	4	40	1	0	11, 2, 22, 24	-	73.53
44	5	50	1	0	11, 3, 12, 23, 24	-	585.66
44	6	55	1	1	11, 14, 17, 22	2(17), 18(17)	7117.67
40	5	50	1	0	11, 18, 19, 23, 24	-	375.97
40	6	60	1	1	11, 12, 23, 24, 25	20 (25)	11530.13
36	5	50	1	0	11, 1, 12, 20, 23	-	284.06
36	6	60	1	0	11, 1, 9, 19, 22, 23	-	4335.23
32	5	60	2	0	11, 12, 23, 24, 25	-	366.63
32	6	70	2	0	11, 1, 6, 12, 14, 23	-	5990.27
28	6	70	2	0	11, 12, 13, 23, 24, 25	-	92.69
28	7	80	2	0	11, 3, 6, 12, 13, 23, 24	-	10116.79
≤12	25	infeasible					

Appendix 13: Results of the Heuristic Algorithm ($f = 1$) on R-S-S Network (Van (65))

T (hours)	p	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
20	5	3	1	6, 23, 65	34(6), 61(23)	0.79
20	6	3	1	6, 23, 65	25(23), 34(6), 61(23)	1.12
20	7	3	1	6, 23, 65	21(23), 25(23), 61(23), 81(6)	0.75
20	8	3	1	6, 23, 65	5(6), 34(6), 44(23), 61(23), 68(6)	0.76
20	9	3	1	6, 23, 65	1(6), 25(23), 27(23), 34(6), 44(23), 61(23)	0.85
19	5	6	2	6, 16, 44, 61, 65	-	1.59
19	6	6	2	6, 34, 44, 61, 65	23(65)	13.31
19	7	5	1	6, 23, 34, 61, 65	25(23), 26(6)	11.2
19	8	5	1	6, 23, 34, 61, 65	1(23), 25(23), 26(6)	4.82
19	9	5	1	6, 23, 34, 61, 65	7(6), 16(6), 25(23), 42(6)	33.41
19	10	5	1	6, 23, 34, 61, 65	7(6), 21(65), 25(23), 26(6), 44(23)	10.06
18	6	6	2	6, 23, 25, 26, 65	34(26)	1.35
18	7	6	2	6, 23, 34, 61, 65	20(6), 25(23)	0.99
18	8	6	2	6, 16, 23, 25, 65	20(6), 27(23), 61(25)	1.26
18	9	6	2	6, 16, 23, 25, 65	20(6), 26(16), 55(6), 61(25)	1.93
18	10	6	2	6, 26, 44, 61, 65	1(44), 20(6), 23(44), 25(61), 34(26)	1.72
18	11	6	2	6, 34, 44, 61, 65	16(6), 20(6), 21(44), 25(61), 55(61), 3(6)	1.86
17	6	7	2	6, 16, 25, 27, 35, 65	-	13.47
17	7	7	2	6, 16, 20, 25, 27, 65	34(16)	72.47
17	8	7	2	6, 16, 20, 25, 27, 65	35(16), 61(25)	146.7
16	6	9	4	6, 20, 34, 44, 61, 65	-	28.43
16	7	9	3	6, 16, 20, 23, 27, 61, 65	-	329.73
16	8	8	3	6, 26, 27, 34, 61, 65	20(26), 44(27)	379.32
15	8	10	3	6, 20, 21, 25, 27, 34, 61, 65	-	1699.42
14	8	11	4	6, 20, 21, 25, 27, 34, 61, 65	-	1176.91
14	9	10	3	6, 20, 21, 25, 27, 34, 61, 65	16(34)	3340

Appendix 14: Results of the Heuristic Algorithm with ($f = 2$) on R-S-S Network (Van (65) and Diyarbakır (21))

T (hours)	P	Objective Function	Number of Airplanes	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
20	5	4	1	6, 21, 25, 65	81(6)	0.52
20	6	4	1	6, 21, 23, 65	34(6), 61(23)	0.69
20	7	4	1	6, 21, 61, 65	1(6), 25(61), 34(6)	2.26
20	8	4	1	6, 21, 61, 65	1(6), 25(61), 44(21), 81(6)	2.75
20	9	4	1	6, 21, 61, 65	25(21), 34(6), 44(21), 3(6), 68(6)	0.96
19	5	infeasible				0.59
19	6	6	2	6, 21, 34, 61, 65	27(21)	8.45
19	7	6	2	6, 21, 25, 26, 65	27(21), 61(25)	15.77
19	8	6	2	6, 21, 34, 61, 65	23(21), 25(21), 27(21)	19.54
19	9	6	2	6, 21, 25, 35, 65	20(6), 27(21), 34(6), 61(25)	20.57
19	10	6	2	6, 21, 34, 61, 65	1(6), 23(21), 25(61), 27(21), 42(6)	13.88
18	6	infeasible				8.99
18	7	7	2	6, 21, 25, 27, 34, 65	20(6)	1.79
18	8	7	2	6, 16, 21, 44, 61, 65	27(21), 35(16)	2.45
18	9	7	2	6, 16, 21, 25, 27, 65	20(6), 61(25), 81(6)	3.83
18	10	7	2	6, 21, 25, 26, 27, 65	20(6), 34(26), 44(6), 55(6)	3.88
18	11	7	2	6, 21, 25, 26, 27, 65	20(6), 34(26), 44(6), 3(6), 68(6)	2.1
17	6	infeasible				8.21
17	7	8	2	6, 16, 20, 21, 25, 27, 65	-	56.81
17	8	8	2	6, 7, 16, 21, 25, 27, 65	35(16)	134.12
16	6	infeasible				9.13
16	7	9	3	6, 20, 21, 27, 34, 61, 65		220.81
16	8	8	2	6, 7, 16, 21, 25, 34, 65	55(6)	157.96
15	8	10	3	6, 20, 21, 25, 27, 34, 61, 65	-	246.25
14	8	11	4	6, 20, 21, 25, 27, 34, 61, 65	-	193.39
14	9	10	3	6, 1, 20, 21, 25, 34, 61, 65	16(34)	378.93

Appendix 15: Results of the Heuristic Algorithm with ($f = 1$) on R-R-S Network (Van (65))

T (hours)	p	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	5	45	1	1	6, 55, 65	3(6), 42(6)	98.54
24	6	50	1	1	6, 23, 65	16(6), 26(6), 81(6)	231.43
23	5	45	1	1	6, 25, 65	26(6), 42(6)	141.39
23	6	50	1	1	6, 44, 65	3(6), 42(6), 68(6)	335.58
22	5	45	1	1	6, 23, 65	21(23), 44(23)	88.48
22	6	55	1	1	6, 27, 55, 65	3(6), 26(6)	667.5
21	5	45	1	1	6, 23, 65	42(6), 68(6)	121.52
21	6	55	1	1	6, 27, 61, 65	26(6), 81(6)	549.85
21	7	60	1	2	6, 21, 25	23(21), 42(6), 44(21), 68(6)	4114.62
20	5	50	1	1	6, 27, 61, 65	81(6)	40.86
20	6	55	1	1	6, 27, 61, 65	26(6), 81(6)	281.8
20	7	65	1	2	6, 27, 55, 65	5(6), 26(6), 81(6)	3583.71
19	5	60	2	0	6, 25, 26, 44, 65	-	128.53
19	6	60	1	0	6, 21, 25, 26, 38, 65	-	1822.41
19	7	70	1	0	6, 21, 25, 26, 44, 61, 65	-	4772.4
18	6	70	2	0	6, 16, 23, 26, 61, 65	-	222.58
18	7	80	2	1	6, 23, 25, 34, 35, 65	21(23)	1938.46
17	6	70	2	0	6, 1, 16, 20, 25, 65	-	357.92
17	7	80	2	0	6, 16, 25, 27, 35, 44, 65	-	4197.97
16	6	90	4	0	6, 20, 27, 34, 61, 65	-	822.9
16	7	90	3	0	6, 1, 16, 20, 21, 61, 65	-	7158.82

Appendix 16: Results of the Heuristic Algorithm with ($f = 2$) on R-R-S Network (Van (65) and Diyarbakır (21))

T (hours)	P	Objective Function	Number of Airplanes	Number of Big Trucks	Airport Hubs	Ground Hubs(allocated Airport Hubs)	CPU (sec)
24	5	45	1	1	6, 21, 65	5(6), 55(6)	38.87
24	6	55	1	1	6, 21, 25, 35	3(6), 81(6)	172.95
23	5	50	1	0	6, 7, 21, 61, 65	-	34.61
23	6	55	1	1	6, 21, 61, 65	3(6), 68(6)	197.48
22	5	50	1	1	6, 21, 25, 65	44(21)	31.59
22	6	55	1	1	6, 21, 25, 65	3(6), 26(6)	174.98
21	5	50	1	1	6, 21, 23, 65	44(23)	31.08
21	6	55	1	1	6, 21, 25, 65	3(6), 42(6)	173.68
21	7	65	1	1	6, 7, 21, 61, 65	23(21), 44(21)	3070.02
20	5	50	1	1	6, 21, 61, 65	81(6)	9.6
20	6	55	1	1	6, 21, 61, 65	26(6), 81(6)	80.96
20	7	65	1	2	6, 21, 61, 65	38(6), 68 (6), 81(6)	1291.81
19	5	infeasible					5.44
19	6	60	1	0	6, 21, 25, 26, 38, 65	-	105.64
19	7	70	1	0	6, 21, 25, 26, 38, 44, 65	-	2005.56
18	6	infeasible					81.69
18	7	80	2	0	6, 1, 21, 34, 35, 61, 65	-	304.62
17	6	infeasible					75.35
17	7	80	2	0	6, 16, 20, 21, 27, 61, 65	-	385.13
16	6	infeasible					70.57
16	7	90	3	0	6, 7, 16, 21, 27, 61, 65	-	2152.57