

ANKARA YILDIRIM BEYAZIT UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED
SCIENCES



APPLICATION OF MAXIMUM COVERAGE
CAPACITATED FACILITY LOCATION PROBLEM
WITH RANGE CONSTRAINED DRONES: A PILOT
STUDY

M.Sc. Thesis by

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Department of Industrial Engineering

August, 2020

ANKARA

**APPLICATION OF MAXIMUM COVERAGE
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WITH RANGE CONSTRAINED DRONES: A PILOT
STUDY**

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**APPLICATION OF MAXIMUM COVERAGE CAPACITATED FACILITY LOCATION PROBLEM WITH RANGE CONSTRAINED DRONES: AMAZON PRIME AIR IN THE CITY OF ANKARA**” completed by **Wael Khatib** under the supervision of **ASSIST. PROF. DR. ABDULLAH YILDIZBAŞI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Wael KHATIB

APPLICATION OF MAXIMUM COVERAGE CAPACITATED FACILITY LOCATION PROBLEM WITH RANGE CONSTRAINED DRONES: A PILOT STUDY

ABSTRACT

Logistics and cargo companies have been seeking ways and methods to minimize delivery times. Drones are used as a contemporary solution for these issues. Many of the most recent studies show methods and applications of the Drone delivery system in the Last Mile Delivery. In this thesis a real-world case of integrating Amazon's Prime Air drones into the Turkish National Postal Service (PTT) delivery system in Ankara Province will be presented and solved to explore the efficiency of deploying drones to the last mile delivery for Light Cargo Delivering System. Deciding on the depot location and number of drones needed for maximum coverage, as well as assigning drones and demands to depots, all will be accomplished by applying the Maximum Coverage Facility Location Problem with Drones (MCFLPD) model. The application of the model will provide a drone delivery system with maximum demand coverage and minimum time of service to all customers. Lastly, a comparison with truck delivery system using Traveling Salesman Problem (TSP) is presented for the evaluation.

Keywords: Drone shipment, last mile delivery, maximum coverage facility location problem, optimization, integer linear programming.

MAXIMUM KAPSAMA KAPASİTELİ TESİS KONUM PROBLEMİ İLE KAPSAM SINIRLI İNSANSIZ HAVA ARAÇLARI: PİLOT ÇALIŞMASI

ÖZ

Lojistik ve kargo şirketleri teslimat sürelerini en aza indirmenin yollarını ve yöntemlerini aramaktadır. Drone'lar bu sorunlar için çağdaş bir çözüm olarak kullanılmaktadır. Son dönemde yürütülen çalışmaların çoğu, Last Mile Delivery sistemindeki drone yöntemlerini ve uygulamalarını ele almaktadır. Bu tez, Amazon Prime yayınında drone larını Ankara'daki Posta ve Telgraf Teşkilatı (PTT)'ndeki dağıtım sistemine entegre edilmesi konusunda gerçek dünyadan bir vaka olarak sunmayı ve drone'ların Son Mil Teslimatındaki dağıtımının verimliliğini araştırarak bir çözüm sunmayı hedeflemektedir. Depo yeri ve maksimum kapsama alanı için gereken drone sayısına karar vermek, Drone ve depolara talep oluşturmak için Drone'larla Maksimum Kapsama Tesis Yer Seçim Problemi (DMKTYSP) modeli uygulanmıştır. Drone Teslimat Sistemi, modelin uygulanmasıyla müşterilerin taleplerinin minimum sürede maksimum alanı kapsayarak temin edilmesini sağlayacaktır. Son olarak Gezgin Satıcı Problemi (TSP) yöntemi ile kamyon teslim sistemi karşılaştırılarak bir değerlendirme sunulmuştur.

Anahtar Kelimeler: Drone sevkiyatı, son nokta teslimat, drone'larla maksimum kapsama tesis yer seçim problemi, optimizasyon, tamsayı doğrusal programlama.

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NOMENCLATURE

Roman Letter Symbols

| | |
|----------|---|
| I | Set of all demand locations |
| J | Set of all potential facility locations |
| K | Set of available fully charged drones at each open facility |
| E | Drone flying endurance |
| d_{ij} | Travel distance between demand point $i \in I$ and facility $j \in J$ |
| P | Maximum number of facilities |
| U | Capacity of each located depot |
| w_i | Demand for resource at location $i \in I$ |

Decision variables

| | |
|-----------|---|
| x_{ijk} | 1, if customer i is served by the k^{th} drone of plant $j \in J$, and 0, otherwise |
| y_j | 1, if the facility is located at $j \in J$, and 0, otherwise |
| z_{jk} | 1, if the k^{th} drone is assigned to facility $j \in J$, and 0, otherwise |

Subscripts

| | |
|-------|---------|
| max | Maximum |
|-------|---------|

Acronyms

| | |
|--------|--|
| MCFLPD | Maximum Coverage Facility Location Problem with Drones |
| TSP | Traveling Salesman Problem |

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CHAPTER 1

INTRODUCTION

Nowadays, delivery systems are associated with the operations, the methods, the services and the components of the system to achieve efficient distribution. To accomplish that, companies started developing methods, procedures and new efficient tools [1]. This is where drones took place in the market, as E-commerce boomed over the past few years drone delivery systems and the use of drones in deliveries have expanded to various fields in life [2].

Many Companies have been searching for new methods or technologies to improve their last mile delivery systems by achieving less time delivery and more cost-efficient shipments [3]. Companies such as Google with Project Wing in 2014 [4], DHL with Parcelcopter in 2013 [5], and Amazon with Prime Air Project in 2013, which completed their first parcel delivery with a drone on December 7, 2016. [6].

According to The Turkish Statistical Institute [34], 84.049.236 parcels and 913.831.948 postal items were delivered between regional directorates in year 2017 by the Turkish National Postal Service (PTT). As most of the cargo delivery systems in Turkey the PTT delivery system consists of regional main hubs, demand centers and the delivery nodes. A group of nodes are linked to the demand centers which are linked to the regional hubs. Parcel deliveries are conducted using trucks which travel from the demand centers that cover the delivery nodes [13].

We chose this study, which is addressed to the cargo companies using traditional methods, and by traditional methods we mean trucks, as an attempt to demystify the implementation of the Drone Delivery Systems in the last mile delivery, give an example of Light Cargo Delivering System and provide companies with a more comprehensive understanding that will encourage them to improve their systems and keep up with the constantly evolving technology in the industry.

Delivering with a drone have many advantageous features when compared to other delivery methods, starting from being unmanned and having no need for a human pilot, which can be quite costly, having an automated navigation system, and the ability to fly over jammed roads directly to the customer through the shortest and fastest path possible [3]. Drones also have a green effect, they can be more environmentally friendly than trucks as they can reduce the CO₂ emissions when there is smaller number of delivery points or if the delivery points are closer to the depot, conversely, Trucks would have CO₂ advantage over drones if the delivery points were both many and they were of a big distance from the depot [7]. Drones have a significantly smaller payload carrying capacities and ranges compared to trucks, for instance, Amazon Prime Air can carry a package with a maximum weight of 5 pounds (2.25 kg), while flying at a speed of 50 mph [6].

The use of Drones in the last mile delivery is promising to take the logistics industry to a whole new level of performance, while other studies suggest that the use of a combination system of Truck and Drone together can be more efficient compared to only Drone systems [6, 7, 8].

Drones applications have expanded to humanitarian and post disaster logistics, in which models finding optimal locations for distribution centers were developed [9,10].

As all the Cargo Delivery systems in Turkey use traditional truck delivery systems, they consider speed as the main factor for an efficient delivery [13], such as the Turkish National Postal Service (PTT). It is the cargo institution with the most branches, with 5000 postal offices around Turkey, 304 of which are located in the center, Ankara Province [14].

The location of the depots is very essential yet can be costly to construct. To eliminate the cost of depot construction, the current service centers will be considered as potential depots.

We chose this study which is addressed to the cargo companies using traditional methods, and by traditional methods we mean trucks, as an attempt to demystify the implementation of the Drone Delivery Systems in the last mile delivery and to provide

companies with a a better understanding that will encourage them to improve their systems and keep up with the constantly evolving technology in the industry.

The Maximum Coverage Facility Location Problem with Drones (MCFLPD) [15] seemed to be the perfect fit for our thesis to achieve maximum coverage since the selected area for the study is entirely a customer area. After reviewing the literature, here is our approach for the system:

In our adopted Drone Delivery System, depots will be dividing the center of Ankara city into circles of the center "depot", with a radius that equals the endurance of Amazon's Prime Air Drone, which is 10 miles (16.09 km), as shown in Figure 1. 1. These depots or distribution centers will be the starting and end points of the drones. Drones will fly from the depot to reach the delivery points directly without having the need to visit any recharge station. The Euclidean distance is considered between depots and delivery points, and the shortest path algorithm will be applied to calculate this route [16] as shown in Figure 1. 2.



a) Amazon Prime Air's first operating drone



b) Amazon Prime Air's newest delivery drone

Figure 1. 1 Amazon Prime Air's drones (source: amazon.com)

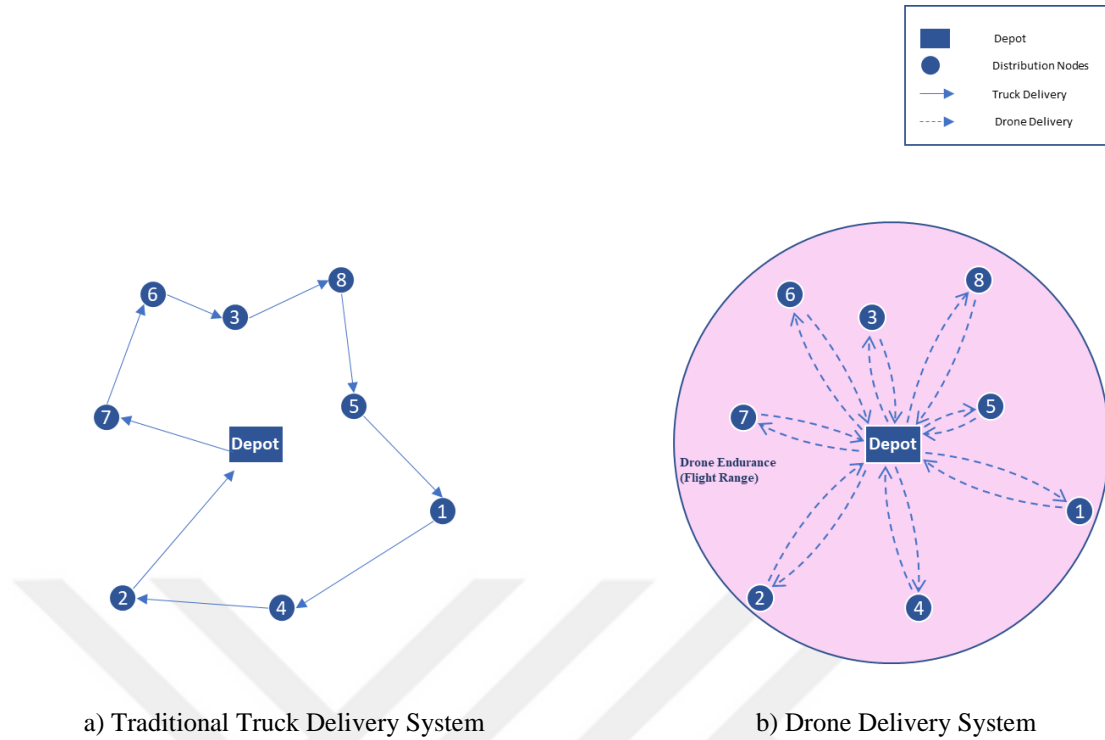


Figure 1. 2 Delivery systems and their routes

This study aims to provide a real-world case of the integration of drones in traditional truck parcel delivery system in the last-mile delivery. It investigates the efficiency of the drone delivery system when compared to truck delivery system. Discussing the possible locations for depots and number of drones needed to assure maximal coverage. The objective is to investigate the Drone Delivery Systems and propose a system that will facilitate this integration. This thesis is, to the best of the author's knowledge, the first to investigate this potential across Turkey. The main contribution of the thesis is that the results of this study could be considered a possible integration method to be applied in other cities or by other companies to evaluate their systems with the proposed system, and as a reference for the drone last mile delivery systems in Turkey to be developed by other authors.

In CHAPTER 2, a literature review mainly covering drones in the last mile delivery. A description and formulation represented in a real-world case application for drone deliveries in Ankara, Turkey will be presented in CHAPTER 3. In CHAPTER 4 a solution for the problem will be proposed and discussed with mathematical models

and a heuristic approach. Numerical analysis and the outcomes of the study will be provided in CHAPTER 5. Followed by the conclusion in CHAPTER 6.



CHAPTER 2

LITERATURE REVIEW

Our primary focus was to identify and gain an understanding about Last Mile Delivery Drone Shipment/Delivery. There has been a significant increase in the literature and academic search concerning Drone delivery, hubs and depot allocations and the applications regarding drones using Linear Programming Models. Many academic papers and novelty discuss drone shipment and provide new studies and methodologies to deal with them.

Table 2. 1 List of abbreviations

| Category | Abbreviation | Details |
|-------------|--|--|
| Method | MCLP | Maximal covering location problem |
| | MCFLPD | Maximum coverage capacitated facility location problem |
| | HLRP | The hub location and routing problem |
| | LAHCP | Latest arrival hub covering problem |
| | GCHLRP | Green city hub location routing problem |
| | P-hub M | p-hub median problem |
| | UAV-R | UAV Routing model |
| | TSP | Traveling salesman |
| | TSP-D | Traveling salesman with Drone |
| | TSP-MD | Traveling salesman with Multiple Drones |
| | TSPLIB | A traveling salesman problem library |
| | mTSPD | Multiple Traveling Salesman with Drones |
| | FSTSP | The flying sidekick TSP The |
| | PDSTSP | The parallel drone scheduling TSP |
| | DDP | Drone delivery problem |
| | MT-DDP | Minimum time drone delivery problem |
| | MC-DDP | Minimum cost drone delivery problem |
| | FLP | Facility location problem |
| | HFLP | Hierarchical facility location problem |
| | DRM | Drone Routing Model |
| | DDRLM | Drone delivery recharging location model |
| | SDDP | Stochastic Drone delivery problem |
| | DDP | Drone delivery problem |
| | LA | Location-allocation problem |
| | A | Analytical framework/model |
| | DTRC | Drone Truck Route Construction |
| | LNS | Large Neighborhood Search |
| | STRPD | Simultaneous Traveling Repairman Problem with Drones |
| | TDRA | Truck and Drone Routing Algorithm To |
| | RPD | Drone routing problem |
| VRP | Vehicle routing problem | |
| VRP-D | Vehicle routing problem with drone (truck-drone) | |
| FH | Fast Heuristic | |
| RRLS | Random restart local search | |

Table 2. 1 (continued): List of abbreviations.

| | CA 2EVRPD | Continuous approximation Two Echelon Vehicle Routing Problems with Drones |
|-------------------------|-----------------------------|---|
| Contribution | M H T C L CS | Mathematical Modeling Heuristic development or application Theoretical Study Cost analysis Literature review Case Studies, thesis, empirical studies, computational studies, experiments |
| Vehicle Characteristics | D TD DV DTV | Drone Truck & drone Drone & other vehicles Different types of vehicles |

Table 2. 2 Summary of surveyed papers

| Reference | Method | Objective | Vehicle Characteristics | Contribution |
|------------------|-----------------------------|--|--------------------------------|---------------------|
| [17] | A | Examine labor-saving technology of the drone system | D | C |
| [3] | TSP-D | Optimizing a truck-drone delivery system | TD | M, H |
| [10] | FSTSP, PDSTSP | Optimizing a truck-drone delivery system | TD | M, H |
| [18] | P-hub M UAV-R | UAV Hub location and routing problem | D | M |
| [19] | LA | Costly efficient integration of drones in the last mile delivery | D | M |
| [9] | TSP, K-means clusters | Investigating the effectiveness of truck-drone delivery network | TD | M |
| [20] | A | Analyzing the energy emissions efficiency of UAV's | DV | CS |
| [21] | MT-DDP MC-DDP | Cost and time minimization models for Drone delivery | D | L |
| [7] | A | Analyzing the environmental impact of drone in the delivery system | TD | CS |
| [22] | TSP-MD | Costly efficient integration of drones in the last mile delivery | TD | M |
| [16] | HFLP | Cost minimization, locations and allocations of drone stations. | D | CS, H |
| [23] | TSP, K-means clusterin g | Finding optimal truck-drone delivery route for minimum delivery time | TD | M |
| [12] | DRM | Drone fleet model for humanitarian logistics | D | M |
| [24] | DDRLM | Extending drone coverage area by optimizing recharging station locations | D | M |
| [25] | DRM | Finding optimal drone delivery route for minimum delivery cost | TD | CS |

Table 2. 2 (continued): Summary of surveyed papers

| | | | | |
|------|--|---|----------|----------|
| [15] | MCFLP D | Finding optimal locations for drone depots and drone assignment for maximum demand coverage | D | M |
| [26] | mTSPD K-means clusterin g | Minimizing arrival times for truck-drone delivery system by finding the shortest route | TD | M, H |
| [27] | DDP, SDDP | Green location and routing problems with conventional vehicles and drones | D | CS |
| [28] | dynamic allocatio n methods using LUISA platform | Estimating the location of drone-beehives based on economic viability criterion in European cities. | D | CS |
| [2] | 2EVRPD , DTRC, LNS | Truck-Drone delivery route optimization | TD | H |
| [8] | STRPD, TRDA | Truck-Drone system with minimum customer waiting time | TD | M, H |
| [29] | RPD, VRP, VRP-D | Addressing the problems of VRP by comparing it to drone deliveries | T, D, TD | CS |
| [30] | VRPD | Truck-Drone delivery route with minimum duration | TD | CS |
| [31] | PDSTSP, FH, RRLS | Truck-Drone delivery route optimization | TD | M, H |
| [11] | CA | Finding optimal locations for drone depots and minimizing the overall delivery cost | TD | CS |

Table 2. 1 (continued): List of abbreviations.

| | CA 2EVRPD | Continuous approximation Two Echelon Vehicle Routing Problems with Drones |
|-------------------------|-----------------------------|---|
| Contribution | M H T C L CS | Mathematical Modeling Heuristic development or application Theoretical Study Cost analysis Literature review Case Studies, thesis, empirical studies, computational studies, experiments |
| Vehicle Characteristics | D TD DV DTV | Drone Truck & drone Drone & other vehicles Different types of vehicles |

Table 2. 2 represents a summary of reviewed papers on drone shipment. Through the table it is clear that TSP and VRP variant models are the most commonly used models

for drone routing problems. [29] addressed the problems of not using drones by comparing the three different systems VRP with trucks only, RPD with only drones and VRP-D which consists of trucks equipped with one drone. [30] provided several worst-case theoretical bounds on the benefits of using drones for the VRP, by using existing solution algorithms for VRP and TSP variants to solve VRPD in a system where drones are carried on trucks and dispatch to make a delivery then back to the truck. A similar system was developed by [10] using TSP as the flying sidekick traveling salesman problem (FSTSP), where deliveries are completed by coordinated trucks and drones, a drone dispatches from the truck at a certain point to make a delivery, while the truck proceed to another point to make a delivery then the drone is collected by the truck at that node or another. The model was solved by a developed Simulated annealing metaheuristic. [10] also presented the parallel drone scheduling PDSTSP model where no synchronization between drones and trucks exist, as each makes deliveries solely.

[3] presented a very similar model to the FSTSP called TSP-D, several route-first cluster second heuristics was developed to be faster and provide a better solution.

[9] used K-means clustering algorithm to solve TSP with tandem delivery of truck and drones, the algorithm finds the launching locations for optimal delivery time. [23] proposed finding shift-weights with k-means clustering to help make wider drone delivery areas with shorter truck routes, which can minimize total delivery time by moving the centers of clusters further away from the depots.

Drone applications also took part in humanitarian logistics, [11] developed a model for disaster-affected regions by trucks and drones. The model finds the optimal locations for the distribution centers and minimizes the total distribution cost. [12] Proposed a similar model for remote locations of disaster-affected regions, the model depends on drones only with an objective of also minimizing the overall distribution cost. [19] applied LA model or incapacitated facility location problem on drone delivery system to find the optimal locations for charging stations. [16] provided a case study on the application HFLP, the delivery system consisted of drones only with the objective of finding the optimal locations for depots and charging stations while minimizing the total cost of the system.

[24] developed drone delivery recharging location model (DDRLM) based on maximal covering location problem MCLP, which was developed by [32], the models maximize demand covered by finding the best locations for depots and charging stations, greedy and interchange heuristics were developed to solve the model. A more complicated variant of MCFLP was presented by [15] and named it MCFLPD. The model consists of drones only and has an objective of maximizing the demand covered by allocating the number of depots with drone range constraints as well as allocating the number of drones to each demand to ensure meeting all demands. We provided two heuristic methods that include greedy and three stage heuristic. Furthermore, we adopted the model with greedy heuristic for this thesis with alterations in the parameters and constraints from battery to distance.

CHAPTER 3

PROBLEM DESCRIPTION AND PROPOSED SYSTEM

3.1. Problem Description

According to our research, delivery speed, delivery costs and environmental factors are essential for a delivery system to be operating efficiently. When compared to trucks, Drones are faster, this is due to the fact that drones do not have to follow a certain road, they can fly directly to the delivery point, using the shortest path possible over congested and jammed roads while maintaining their speed. The delivery cost of a drone is less than that of a truck, additionally, drones are more environmentally friendly, causing less CO₂ emissions. All in all, the problem is established by demonstrating the delivery system model; (Drone Delivery System) then applying the system on the Turkish National Postal Service (PTT) to integrate drones into the current system, which is a parcel delivery system of traditional trucks. In the proposed systems we will discuss the location of the depots, demand locations and drone assignment.

3.1.1. PTT System (Distribution System and Characteristics)

PTT Ankara has several service operation-centers in each of the following 25 districts:

Akyurt, Altındağ, Ayaş, Bala, Beypazarı, Çamlıdere, Çankaya, Çubuk, Elmadağ, Etimesgut, Evren, Gölbaşı, Güdül, Haymana, Kalecik, Kazan, Keçiören, Kızılcihamam, Mamak, Nallıhan, Polatlı, Pursaklar, Sincan, Şereflikoçhisar and Yenimahalle.

PTT has many service centers at each of the districts. In our proposed solution, some of the centers will be used as depots.

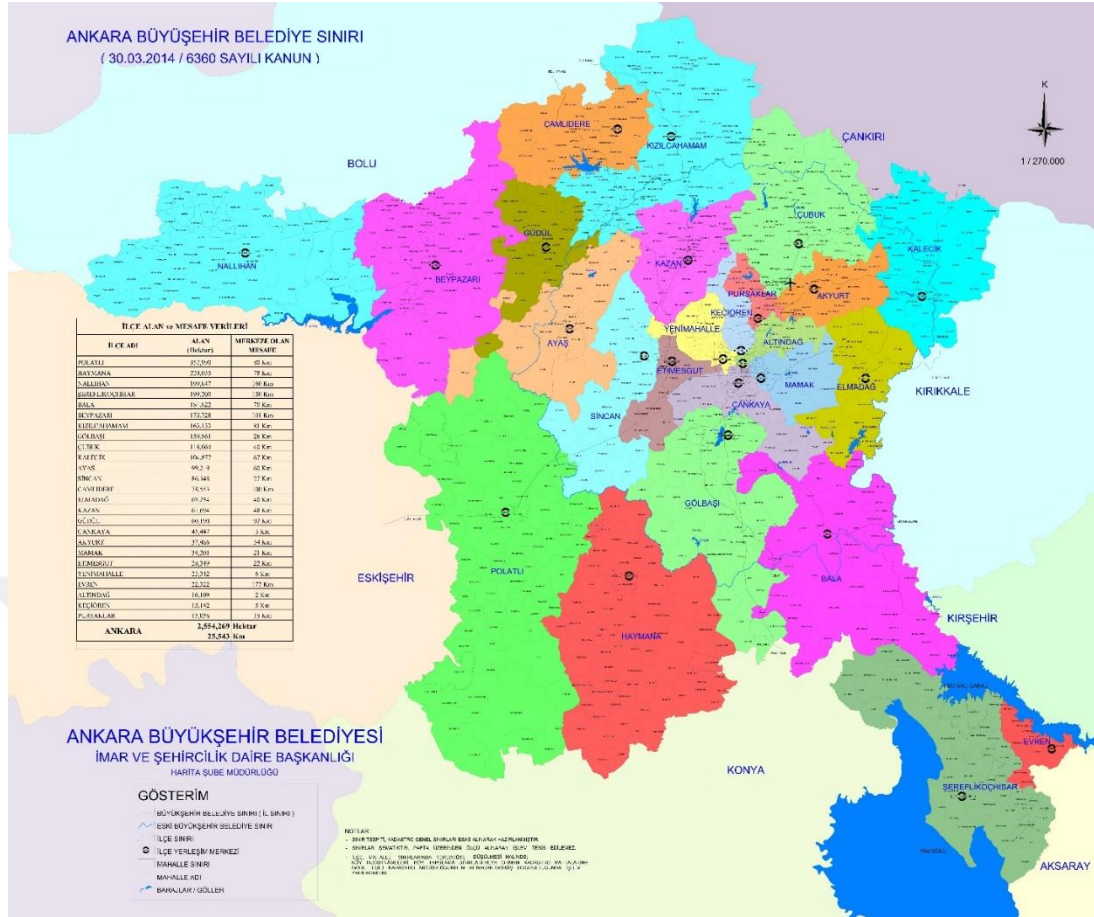


Figure 3.1 Ankara province map and districts

The PTT delivery is executed via regional main hubs (operation centers), districtal hubs (demand centers) and the delivery points (nodes). A group of nodes are linked to the districtal hubs which are linked to the main hubs. A parcel would travel with a truck from the main hub to the districtal hub that covers the area of the parcel destination node. Then another truck would travel from the districtal hub to all the nodes that are served by that hub [13]. The Manhattan distance in the route of all deliveries is used as in Figure 1. 2.

3.2. Proposed System

3.2.1. Drone Delivery System

This system is the perfect fit for companies that work with light parcels. When there is a cargo that needs to be delivered on a single day, the cargo units would be shipped

by old means (trucks) to the depot that covers the parcel's destination node. Light parcels are shipped with drones. The drones considered in the system are Amazon Prime Air's drones. A parcel is considered light cargo when it doesn't exceed the weight capacity of the drone.

3.2.2. Amazon Prime Air's Drone

The weight of an Amazon Prime Air's drone is around 55 pounds, it can fly at a speed of 50 mph (50 miles per 60 mins, 10 miles per 12 minutes), while carrying a package with a maximum weight of 5 pounds (2.25 kg), with a radius of 10 miles (16.9 km) and an altitude of 400 feet from the ground [6]. This means, a drone completes the round trip within 24 mins + 6 mins of loading and unloading the package, acceleration and deceleration [17].

3.2.3. How the System Works

When there is light cargo that needs to be delivered on a single day from a depot, drones would fly directly from the depot to the delivery node to complete the delivery of light cargos and come back to the depot to get prepared for another delivery.

Drone Route: Deliveries by drones will follow a route that considers the Euclidean distance in the shortest path algorithm. As illustrated in Figure 1. 2.

We consider that a given route is linked to a certain day, this is a reasonable assumption because a group of customers covered by one route is, very likely, only relevant for that one day of the horizon. The routes will be changing daily. Each drone can make several trips from depot to a single demand point and back until the travelled distance range is met, a total travelled distance of 16.09 km by each drone in multiple trips. Short term planning period (one day) is considered so that the recharging of the drones is not considered.

Location of depots: The selected area will be divided into circles of the radius (16.09 km). A single depot will be located at the center of each of the circles which represent the range of the drone. An example will be provided in chapter 4. The depots will be

chosen from the existing districtial hubs of PTT. Therefore, the fixed cost of opening a new facility is disregarded.

Number of drones needed: the number of drones needed for each facility will be calculated by dividing the total distance travelled from each open facility to the demand points allocated to it by the drone endurance.



CHAPTER 4

SOLUTION APPROACH

4.1. Overview

The optimal location of the depots is found by applying the Maximum Coverage Facility Location Problem with Drones (MCFLPD) introduced by [15]. Although the model provides a solution for the problem, we found the need for some modifications. The current model uses the drone battery capacity, but we want to solve the model according to travelled distance between depots and demand points, so the battery capacity was changed to distance capacity, modifying the other constraints and heuristic method accordingly.

4.2. Problem Formulation

The integer linear formulation for the MCFLPD is provided in this section. A demand w_i of the demand location $i: i \in I$ is given. The parcels are to be delivered from depot $j: j \in J$ to demand location i , using the k^{th} drone: $k \in K$, located at each depot. where $i \in I$ is the set demand locations, J is the set of possible locations, and K is the set of available charged drones that will be assigned to each located depot. The aim of the model is maximizing the demand served by locating P depots. The maximum amount of the demand w_i that can be served by each depot in a time period is denoted by $U = \frac{\sum_{i \in I} w_i}{0.8 P}$; the capacity of each located depot which is generated as [33] where the average utilization of the facilities is equal to 80 percent of the total available capacity. The capacity has a limiting factor which arises from the maximum mass of w_i that can be stored at each located depot. As in any facility location model, costs of transportation of parcels and drones from warehouse to the located depots are not considered and are assumed to be constant regardless of the allocation of depots. It is assumed that drones are recharged either over night or in-between deliveries. Figure 5. 1 shows the potential depot locations used in this study.

4.3. Mathematical Model

Nomenclature

Assumptions

Drone flying endurance $E = 10$ miles = 16.09 km

The distance parameter d_{ij} is Euclidean distance

Sets

I Set of all demand locations

J Set of all potential facility locations

K Set of available fully charged drones at each open facility

Indices

$i \in I$

$j \in J$

$k \in K$

Parameters

E Drone flying endurance

d_{ij} Travel distance between demand point $i \in I$ and facility $j \in J$

P Maximum number of facilities

U Capacity of each located depot

w_i Demand for resource at location $i \in I$

Decision variables

x_{ijk} 1, if customer i is served by the k^{th} drone of plant $j \in J$, and 0, otherwise

y_j 1, if the facility is located at $j \in J$, and 0, otherwise

z_{jk} 1, if the k^{th} drone is assigned to facility $j \in J$, and 0, otherwise

Objective function;

$$\max \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} w_i \cdot x_{ijk} \quad (4.1)$$

Seeks to maximize the demand served

S.t.

$$\sum_{j \in J} \sum_{k \in K} x_{ijk} \leq 1, \quad \forall i \in I \quad (4.2)$$

Guarantees that each demand location is visited once at most.

$$\sum_{j \in J} y_j \leq P \quad (4.3)$$

Ensures the number of depots that will be located to be less than or equal to the maximum number of depots that should be opened P.

$$\sum_{i \in I} d_{ij} \cdot x_{ijk} \leq E \cdot z_{jk}, \quad \forall j \in J, k \in K \quad (4.4)$$

Enforces Drone Endurance constraints on all the drones and demand nodes.

$$\sum_{j \in J} \sum_{k \in K} w_i \cdot x_{ijk} \leq U \cdot y_j, \quad \forall j \in J \quad (4.5)$$

Restricts the demand served by each located depot to be less than or equal to the capacity of the depot.

$$z_{jk} \leq y_j, \quad \forall j \in J, k \in K \quad (4.6)$$

Ensures that drones are assigned to the located depots only.

$$\sum_{j \in J} z_{jk} \leq 1, \quad \forall k \in K \quad (4.7)$$

Guarantees that each drone is assigned to one open depot at most.

$$x_{ijk}, x_{ijt}, y_j, z_{jk} \in \{0,1\}, \quad \forall i \in I, j \in J, k \in K \quad (4.8)$$

corresponds to decision variable definitions to be all binary.

4.4. Greedy Heuristic:

The MCFLP is considered to be a more complicated variant of the maximum coverage capacitated facility location model which is known to be an NP-Hard problem. [15] has presented a greedy heuristic for this model but we want to solve the model with a different approach that depends on distance traveled rather than battery parameters. This required some modifications. The modified greedy heuristic still has the main headlines of the steps as the original one as: creating a sorted weight matrix, allocating demand to open facilities, allocating drones to open facilities and the assignment of demand to drones. Define s_{ij} as an indicator variable, which takes value 1 if a demand location i is assigned to an open facility j and 0 otherwise. s_{ij} is initially set to 0 for all potential facilities and demand locations.

Step 1. Defining a weight matrix wt_{ij} , which is calculated as: $wt_{ij} = \frac{w_i}{d_{ij}}$ if $d_{ij} \leq E$ and 0 otherwise, $\forall i \in I, j \in J$

A facility location of the highest weight at a demand location has a higher chance of being opened at that demand location. A demand location with the shortest distance from a facility has the priority to be assigned to a facility. The weights are sorted in Decreasing order and distances are sorted in Increasing Order and each sorted in a weight array and distance array respectively. Each element in the weight array has a potential facility location j associated with each demand location i . The sorted arrays are traversed sequentially, and the following demand allocation measures are applied to each element.

Step 2. Allocation of facilities and demand: If facility j is not opened, find maximum weight from the sorted weight array and open facility j if number of open facilities is less than P , $wt_{ij} > 0$ and set $s_{ij} = 1$, and start assigning demand locations to the opened facility from the sorted distance array as long as $d_{ij} < 16.09$ and facility j has residual capacity available to serve w_i of each assigned demand location i . Move to the next element of the sorted weight matrix to open another facility and continue with the following demand allocation: If a demand i is not assigned to an open facility, check if the facility j associated with it, is open or not, if it is open, assign it and set

$s_{ij} = 1$ as long as $wt_{ij} > 0$, $d_{ij} < 16.09$ and facility j has residual capacity available to serve w_i . if demand i is already assigned to an open facility, move to the next element of the sorted distance array. Continue demand allocations until all capacities of opened facilities are met.

Step 3. Allocation of drones to open facilities: Define \hat{J} to be the set of all open facilities. Sort demand locations of each open facility in Increasing order of d_{ij} , start from the first entry of the sorted demand locations array and select a group of demand locations that meets $\sum_{i \in I} d_{ij} \leq E$. Sort the new distances in a new array \hat{J} . let \bar{d}_j be the average distance travelled at an open facility $j \in \hat{J}$. The number of drones required to serve all demands assigned is calculated for each open facility as:

$$ND_j = \left\lceil \sum_{i \in I} \frac{d_{ij}s_{ij}}{\bar{d}_j} \right\rceil \quad \forall j \in \hat{J}, \quad (4.9)$$

Let J_0 represent the open facilities sorted in decreasing order of ND_j . Traverse the set J_0 and assign one drone to each open facility sequentially. Assign one drone to each open facility sequentially and go back to the first facility in the sorted J_0 and continue the assignment of drones to demand locations at each facility. When the number of assigned drones to a facility reaches ND_j , delete that facility from the sorted J_0 and then continue the assignment of drones. Stop assigning when ND_j of each facility is met or when all the available K drones are assigned.

Step 4. Assignment of drones to demand nodes: For each facility in the sorted distance array \hat{J} , assign the first group of demand locations of which $\sum_{i \in I} d_{ij} \leq E$ to the first drone. A single fully charged drone can perform multiple deliveries as long as the total travelled distance of all deliveries is less than the drone endurance E. In other words, more than one demand point in the sorted demand array can be assigned to a single fully charged drone if the sum of their traveling distances is less than 16.09. Repeat until all demands associated with that facility are assigned to drones or until it is not possible to assign any more demands to the final drone for that facility without violating the drone range constraint. Repeat the process for all facilities.

Demand coverage percentage is calculated by adding the demands for all of the locations which have been served by drones and divide it by the total number of demands.



CHAPTER 5

NUMERICAL ANALYSIS

5.1. Data Set

The proposed system is applied on Ankara Province. The current facilities of The National Postal Service PTT are treated as demand locations/delivery nodes and as potential facility locations. The optimal locations and number of facilities to be opened are to be found mainly. We have a total of 304 facilities and 304 demand locations. All coordinates of the locations were taken from google maps and can be found in Appendix A – Locations and Demands.

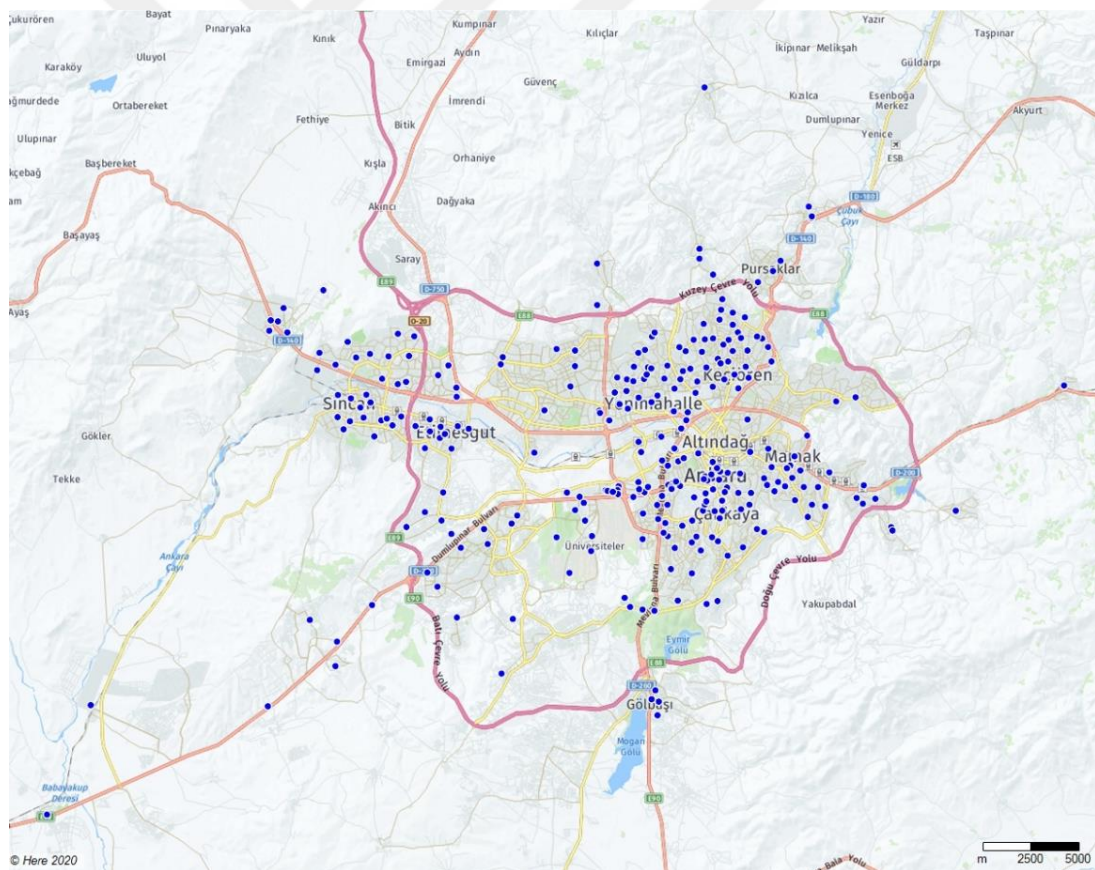


Figure 5. 1 Potential facility locations and demand locations

The application of the proposed system will be executed at the districts forming the city center of Ankara province, which are the most populated districts Figure 3.1. According to The Turkish Statistical Institute [34], these districts are: **Çankaya, Etimesgut, Gölbaşı, Keçiören, Mamak, Pursaklar, Sincan and Yenimahalle**. See Appendix E – Districts and population information of Ankara Province. for population numbers, maps and more detailed info.

Using a discrete uniform distribution, we generate the demands for recourse at a location with the range 0.1 kg to 2.25 kg, since we are dealing with light cargo payloads. The sum of all demands is 370.0249367. The capacity of each opened facility will change according to P the number of opened facilities. And the Euclidean distance is considered as the traveling distance of the drone since drones fly directly from the depot to the delivery node. After collecting all coordinates for all locations, the ‘haversine’ formula was used to calculate the great-circle distance between two point coordinates, that is the shortest distance over the earth’s surface. From that, the distance matrix was calculated.

5.2. Application and Results

By applying the greedy heuristic on Python, we obtained multiple cases by opening different numbers of depots. The following table shows the number of opened facilities with the average utilization of the open facilities.

We start the solution by opening one extra facility in each round starting by 1 facility and compare the results to select the optimal number of facilities to open for maximal coverage. Table 5. 2 Shows the code result. This is the result of steps 1 and 2 of greedy heuristic.

Table 5. 1 shows comparison results between the number of uncovered demand nodes according to the number of open facilities and open facility utilization level.

Table 5. 1 Capacity utilization and uncovered demand nodes

| Number of Uncovered Demand Nodes | | | |
|---|---------------------------------|---------------------------------|----------------------------------|
| P | 80% Capacity Utilization | 90% Capacity Utilization | 100% Capacity Utilization |
| 1 | 57 | 57 | 57 |
| 2 | 54 | 103 | 117 |
| 3 | 66 | 73 | 7 |
| 4 | 6 | 24 | 30 |
| 5 | 6 | 13 | 47 |
| 6 | 8 | 5 | 30 |
| 7 | 5 | 13 | 21 |
| 8 | 3 | 4 | 8 |
| 9 | 1 | 6 | 22 |
| 10 | 2 | 16 | 21 |

Using 80% of average utilization of the total available capacity provides the best results when compared to using 90% and 100%. In which it covers more demand with less facilities. However, the 80% utilization is a level of utilization that is noticed in real life systems [33].

According to the uncovered demand results, opening 9 facilities seems to be the optimal solution with only 1 uncovered demand location. While opening 4 and 5 facilities have 6 uncovered demands. On the other hand, opening 5 more facilities to only cover 5 more demand locations is not feasible when we consider the cost of opening a new facility. Relatively opening 4 facilities with 80% capacity utilization is the best case with our proposed greedy.

Table 5. 2 Facilities and demand points allocation

| Open Facility ID | 11 | | | 110 | | | 142 | 160 | | |
|-------------------------|-----------|----|----|------------|-----|-----|------------|------------|-----|-----|
| Assigned Demand ID | 1 | 44 | 83 | 104 | 237 | 285 | 7 | 77 | 190 | 229 |
| | 2 | 45 | 84 | 106 | 238 | 286 | 10 | 145 | 192 | 230 |
| | 3 | 46 | 85 | 107 | 239 | 287 | 28 | 146 | 193 | 256 |
| | 4 | 47 | 86 | 115 | 240 | 289 | 35 | 147 | 194 | 299 |
| | 5 | 48 | 87 | 117 | 241 | 290 | 37 | 148 | 195 | |
| | 6 | 49 | 88 | 118 | 242 | 291 | 39 | 149 | 196 | |
| | 8 | 50 | 89 | 119 | 243 | 293 | 41 | 151 | 197 | |
| | 9 | 51 | 90 | 120 | 244 | 294 | 63 | 153 | 198 | |
| | 12 | 52 | 91 | 121 | 245 | 295 | 70 | 155 | 199 | |
| | 13 | 53 | 93 | 122 | 246 | 296 | 72 | 156 | 200 | |
| | 14 | 54 | 94 | 123 | 247 | 300 | 92 | 157 | 201 | |
| | 15 | 55 | 96 | 126 | 248 | 301 | 95 | 158 | 202 | |

Table 5. 2 (continued) Facilities and demand points allocation

| | | | | | | | | | |
|--|----|----|-----|-----|-----|-----|-----|-----|-----|
| | 16 | 56 | 97 | 127 | 249 | 302 | 100 | 159 | 203 |
| | 17 | 57 | 98 | 128 | 250 | 303 | 105 | 161 | 204 |
| | 18 | 58 | 99 | 130 | 252 | 304 | 108 | 162 | 205 |
| | 19 | 59 | 101 | 131 | 253 | | 109 | 163 | 206 |
| | 20 | 60 | 102 | 134 | 254 | | 111 | 165 | 207 |
| | 21 | 61 | 103 | 135 | 255 | | 112 | 166 | 208 |
| | 22 | 62 | 259 | 138 | 257 | | 113 | 167 | 209 |
| | 23 | 64 | 262 | 150 | 258 | | 114 | 168 | 210 |
| | 24 | 65 | 265 | 152 | 260 | | 116 | 169 | 213 |
| | 25 | 66 | 266 | 154 | 261 | | 124 | 170 | 214 |
| | 26 | 67 | 267 | 164 | 263 | | 125 | 171 | 215 |
| | 27 | 68 | 271 | 173 | 264 | | 129 | 172 | 216 |
| | 29 | 69 | 272 | 177 | 268 | | 132 | 174 | 217 |
| | 30 | 71 | 273 | 180 | 269 | | 133 | 175 | 218 |
| | 31 | 73 | 274 | 181 | 270 | | 136 | 176 | 219 |
| | 32 | 74 | 275 | 182 | 276 | | 137 | 178 | 220 |
| | 33 | 75 | 280 | 188 | 277 | | 139 | 179 | 221 |
| | 34 | 76 | 288 | 191 | 278 | | 140 | 183 | 222 |
| | 36 | 78 | 292 | 231 | 279 | | 141 | 184 | 223 |
| | 38 | 79 | 297 | 232 | 281 | | 143 | 185 | 224 |
| | 40 | 80 | 298 | 234 | 282 | | | 186 | 225 |
| | 42 | 81 | | 235 | 283 | | | 187 | 226 |
| | 43 | 82 | | 236 | 284 | | | 189 | 227 |

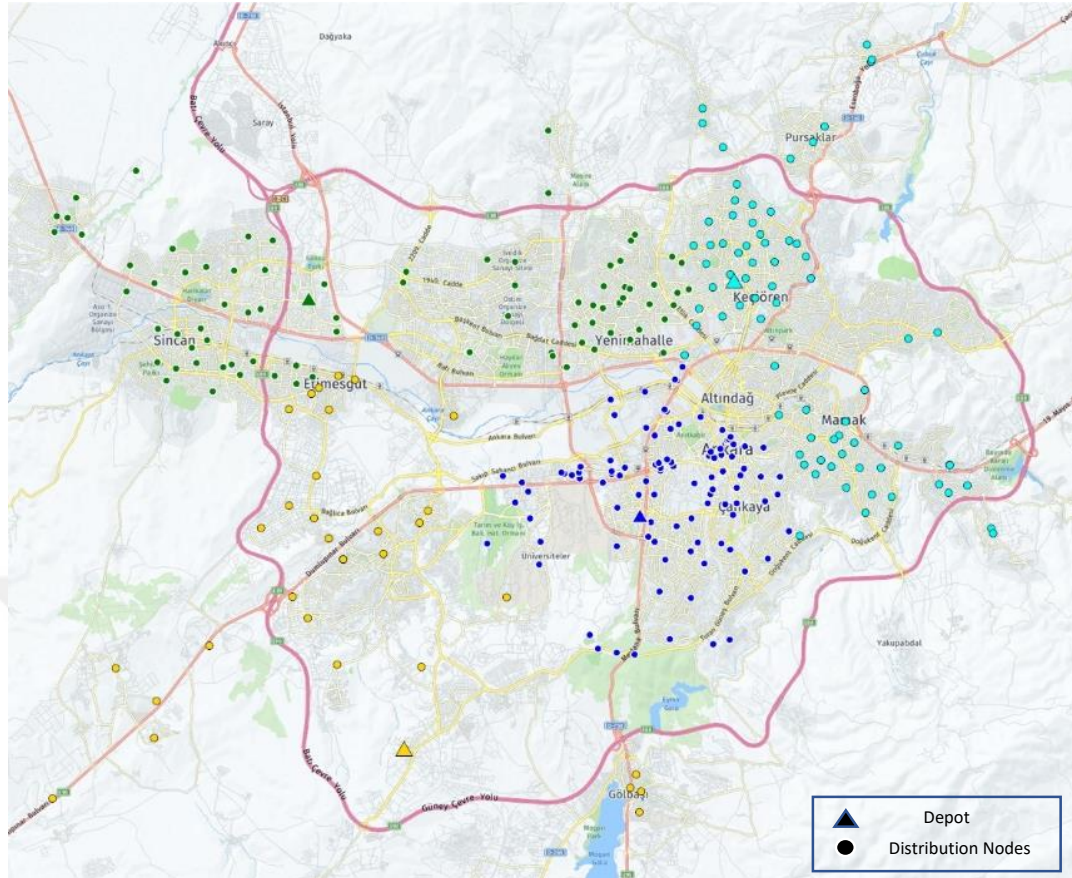


Figure 5. 2 Allocated drone depots and assigned distribution nodes (demand points)

Allocated depots and their allocated demand nodes are plotted on the map in Figure 5. 2. Allocated depots are demonstrated as triangles and demand nodes as circles of the same color for the assigned depot. Depot 11 is represented in Blue, 110 in Green, 142 in Yellow and 160 in Turkuaz. Coordinates, IDs and demands of the points can be found in Appendix A – Locations and Demands

By applying steps 3 and 4 of greedy heuristic, we obtain the results shown in Table 5. 3 for allocated depot 110. Firstly, the demand points were sorted in increasing order of distance from the assigned depot, then the sorted distance array is divided into groups of demand locations with a sum of travelling distance less than 16.09 for each group. The average distance of the grouped demand locations is found to be 12.78 km. The total traveled distance is then divided by that average to obtain the number of drones needed for the depot. $741.05/12.78 = 58$ drones are needed for depot 110.

Table 5. 3 Drone assignment to distribution points at depot 110, K=160.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|--|------------------|---------------------------|-------------------|--|------------------|---------------------------|-------------------|
| 104 | 0.90797 | | | 285 | 8.872008 | 8.872007 | 17 |
| 128 | 1.408823 | | | 235 | 9.104503 | 9.104502 | 18 |
| 134 | 1.811454 | | | 242 | 9.992435 | 9.992435 | 19 |
| 122 | 2.085668 | | | 276 | 10.51955 | 10.51955 | 20 |
| 106 | 2.228222 | | | 277 | 10.60014 | 10.60013 | 21 |
| 123 | 2.632298 | | | 231 | 10.74267 | 10.74266 | 22 |
| 126 | 2.835145 | 13.90957 | 1 | 236 | 10.7722 | 10.77220 | 23 |
| 130 | 2.861748 | | | 283 | 11.08282 | 11.08282 | 24 |
| 117 | 2.912718 | | | 255 | 11.1332 | 11.13319 | 25 |
| 135 | 3.294408 | | | 257 | 11.21877 | 11.21876 | 26 |
| 127 | 3.384857 | | | 237 | 11.22873 | 11.22873 | 27 |
| 120 | 3.532965 | 15.98669 | 2 | 304 | 11.28828 | 11.28827 | 28 |
| 119 | 3.552484 | | | 291 | 11.3133 | 11.31330 | 29 |
| 118 | 3.577964 | | | 300 | 11.41748 | 11.41747 | 30 |
| 131 | 3.619225 | | | 282 | 11.71372 | 11.71371 | 31 |
| 121 | 3.680577 | 14.43025 | 3 | 284 | 12.03506 | 12.03505 | 32 |
| 261 | 4.051787 | | | 268 | 12.04994 | 12.04994 | 33 |
| 264 | 4.279239 | | | 289 | 12.27992 | 12.27992 | 34 |
| 115 | 4.281891 | 12.61291 | 4 | 301 | 12.3817 | 12.38170 | 35 |
| 138 | 4.326118 | | | 287 | 12.45072 | 12.45071 | 36 |
| 253 | 4.550675 | | | 286 | 12.49338 | 12.49338 | 37 |
| 107 | 4.629469 | 13.50626 | 5 | 295 | 12.84169 | 12.84169 | 38 |
| 246 | 4.646023 | | | 269 | 12.86139 | 12.86138 | 39 |
| 239 | 4.74219 | | | 279 | 13.13106 | 13.13105 | 40 |
| 241 | 5.351957 | 14.74017 | 6 | 278 | 13.14904 | 13.14903 | 41 |
| 232 | 5.365815 | | | 181 | 13.28351 | 13.28350 | 42 |
| 238 | 5.470537 | 10.83635 | 7 | 290 | 13.29647 | 13.29647 | 43 |
| 250 | 5.641463 | | | 263 | 13.38892 | 13.38892 | 44 |
| 248 | 5.750791 | 11.39225 | 8 | 294 | 13.59377 | 13.59376 | 45 |
| 249 | 5.75626 | | | 270 | 13.70899 | 13.70899 | 46 |
| 240 | 6.147876 | 11.90413 | 9 | 182 | 13.85914 | 13.85914 | 47 |
| 234 | 6.347012 | | | 303 | 14.04315 | 14.04314 | 48 |
| 244 | 6.51285 | 12.85986 | 10 | 191 | 14.0687 | 14.06869 | 49 |
| 252 | 6.573138 | | | 173 | 14.42268 | 14.42267 | 50 |
| 247 | 6.944124 | 13.51726 | 11 | 152 | 14.62828 | 14.62827 | 51 |
| 245 | 6.946054 | | | 150 | 15.09271 | 15.09270 | 52 |
| 302 | 7.136667 | 14.08272 | 12 | 258 | 15.18604 | 15.18604 | 53 |
| 260 | 7.170328 | | | 180 | 15.44742 | 15.44741 | 54 |
| 254 | 7.703616 | 14.87394 | 13 | 188 | 15.48189 | 15.48189 | 55 |
| 243 | 7.723026 | | | 177 | 15.60538 | 15.60538 | 56 |
| 281 | 7.733709 | 15.45673 | 14 | 164 | 15.85598 | 15.85598 | 57 |
| 293 | 8.468322 | 8.468322 | 15 | 154 | 16.08596 | 16.08595 | 58 |
| 296 | 8.747954 | 8.747954 | 16 | | | | |
| Total traveled distance = 741.05 km | | | | average distance of the grouped demands | | | |
| ND₁₁₀ = 58 | | | | | | | |

One drone is assigned to either a group of demand points with total distance less than 16.09 or to a single demand point that cannot be grouped with other points because of drone endurance constraint. As can be seen in the table, demand points 104, 128, 134,

122, 106, 123 and 126 are treated as one group and are therefore assigned to the same drone. If we assign one drone to each demand point, this will lead to the use of more drones, which is costly. To avoid this, we group the demand points in the sorted array as mentioned earlier and assign a single drone to them because a fully charged drone can travel up to 16.09 km from the depot and back. This process is repeated with all other open depots. Firstly, the number of needed drones is identified for all open depots, then sorted in a decreasing order of ND_j , and finally, the process mentioned above (as in step 4) is applied for drone assignment. Table 5. 4, Table 5. 5 and Table 5. 6 show the results of steps 3 and 4 from greedy heuristic for the other three depots.

Table 5. 4 Drone assignment to distribution points at depot 160, K=160.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 145 | 0.33213116 | | | 230 | 6.7611290 | | |
| 185 | 0.49320315 | | | 168 | 6.8065256 | 13.567654 | 66 |
| 169 | 0.94793972 | | | 203 | 7.1926552 | | |
| 171 | 1.05110944 | | | 192 | 7.3809002 | 14.573555 | 67 |
| 161 | 1.09974084 | | | 156 | 7.4204611 | | |
| 166 | 1.13623628 | | | 226 | 7.5701915 | 14.990652 | 68 |
| 146 | 1.20636867 | | | 213 | 7.5784643 | | |
| 157 | 1.39517090 | | | 200 | 7.7578918 | 15.336356 | 69 |
| 158 | 1.57544027 | | | 193 | 7.8409536 | | |
| 174 | 1.58455232 | | | 196 | 7.8876685 | 15.728622 | 70 |
| 178 | 1.61859053 | | | 220 | 7.9139431 | 7.9139431 | 71 |
| 176 | 1.6570744 | | | 202 | 8.3087708 | 8.3087708 | 72 |
| 184 | 1.82491150 | 15.9224 | 59 | 215 | 8.4152929 | 8.4152929 | 73 |
| 165 | 1.88905152 | | | 214 | 8.5184729 | 8.5184729 | 74 |
| 155 | 1.89620359 | | | 217 | 8.6158864 | 8.6158864 | 75 |
| 183 | 1.95332384 | | | 210 | 8.8583926 | 8.8583926 | 76 |
| 149 | 2.01175009 | | | 198 | 8.8586099 | 8.8586099 | 77 |
| 175 | 2.07241341 | | | 194 | 8.8759415 | 8.8759415 | 78 |
| 163 | 2.26336922 | | | 219 | 9.5116178 | 9.5116178 | 79 |
| 159 | 2.28314652 | 14.36925 | 60 | 221 | 9.8221043 | 9.8221043 | 80 |
| 167 | 2.46878629 | | | 208 | 9.9395466 | 9.9395466 | 81 |
| 162 | 2.57617255 | | | 195 | 10.046819 | 10.046819 | 82 |
| 151 | 2.73646178 | | | 201 | 10.743153 | 10.743153 | 83 |
| 186 | 2.78800590 | | | 227 | 10.924310 | 10.924310 | 84 |

Table 5. 4 (continued): Drone assignment to distribution points at depot 160, K=160.

| | | | | | | | |
|--|------------|----------|----|--|-----------|-----------|----|
| 148 | 2.88175611 | 13.45118 | 61 | 229 | 11.022319 | 11.022319 | 85 |
| 147 | 3.08121512 | | | 77 | 11.126026 | 11.126026 | 86 |
| 190 | 3.20222468 | | | 216 | 11.267486 | 11.267486 | 87 |
| 189 | 3.24581192 | | | 199 | 11.300561 | 11.300561 | 88 |
| 153 | 3.31526600 | 12.84451 | 62 | 225 | 11.456524 | 11.456524 | 89 |
| 187 | 3.31990456 | | | 204 | 11.969496 | 11.969496 | 90 |
| 179 | 3.411813 | | | 205 | 11.996819 | 11.996819 | 91 |
| 299 | 3.76394666 | | | 222 | 12.207173 | 12.207173 | 92 |
| 256 | 3.97156926 | 14.46723 | 63 | 223 | 12.746902 | 12.746902 | 93 |
| 172 | 4.08978930 | | | 209 | 13.117186 | 13.117186 | 94 |
| 170 | 5.67577125 | | | 206 | 15.087638 | 15.087638 | 95 |
| 224 | 5.69664441 | 15.46220 | 64 | 207 | 15.300734 | 15.300734 | 96 |
| 197 | 5.96119152 | | | 206 | 15.087638 | 15.087638 | 97 |
| 218 | 6.23881423 | 12.20000 | 65 | 207 | 15.300734 | 15.300734 | 98 |
| Total traveled distance = 481.25 km | | | | average distance of the grouped demands | | | |
| ND₁₆₀ = 40 drones | | | | = 12.03 km | | | |

Table 5. 5 Drone assignment to distribution points at depot 11, K=160.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 1 | 1.029566 | | | 22 | 4.21707 | | |
| 20 | 0.524885 | | | 265 | 4.247246 | | |
| 40 | 0.900927 | | | 34 | 4.256479 | 12.72079 | 109 |
| 99 | 0.940558 | | | 90 | 4.263515 | | |
| 21 | 1.087386 | | | 2 | 4.307967 | | |
| 36 | 1.253029 | | | 26 | 4.363264 | 12.93474 | 110 |
| 64 | 1.496949 | | | 266 | 4.408615 | | |
| 76 | 1.601259 | | | 267 | 4.411255 | | |
| 38 | 1.61672 | | | 62 | 4.432775 | 13.25264 | 111 |
| 17 | 1.919824 | | | 273 | 4.561889 | | |
| 83 | 2.099707 | 14.470809 | 99 | 275 | 4.562862 | | |
| 67 | 2.120453 | | | 89 | 4.585734 | 13.71048 | 112 |
| 16 | 2.130334 | | | 280 | 4.624107 | | |
| 292 | 2.151641 | | | 30 | 4.632552 | | |
| 13 | 2.151691 | | | 56 | 4.667124 | 13.92378 | 113 |
| 52 | 2.176357 | | | 97 | 4.746332 | | |
| 79 | 2.218029 | | | 65 | 4.832982 | | |
| 86 | 2.249855 | 15.198360 | 100 | 25 | 4.856661 | 14.43597 | 114 |
| 50 | 2.271775 | | | 3 | 4.89077 | | |
| 32 | 2.380085 | | | 69 | 4.910395 | | |
| 85 | 2.534547 | | | 103 | 4.969545 | 14.77071 | 115 |
| 43 | 2.6136 | | | 101 | 4.98675 | | |

Table 5. 5 (continued): Drone assignment to distribution points at depot 11, K=160.

| | | | | | | | |
|--|----------|-----------|-----|---|----------|----------|-----|
| 42 | 2.627011 | | | 91 | 5.020215 | | |
| 94 | 2.655412 | 15.082429 | 101 | 81 | 5.036216 | 15.04318 | 116 |
| 6 | 2.670291 | | | 259 | 5.081307 | | |
| 98 | 2.682978 | | | 102 | 5.08965 | | |
| 48 | 2.685477 | | | 23 | 5.20663 | 15.37758 | 117 |
| 45 | 2.912317 | | | 274 | 5.263879 | | |
| 24 | 3.021209 | 13.972272 | 102 | 31 | 5.327678 | | |
| 68 | 3.1207 | | | 5 | 5.328138 | 15.91969 | 118 |
| 14 | 3.182903 | | | 78 | 5.32842 | | |
| 84 | 3.274413 | | | 75 | 5.36005 | | |
| 12 | 3.279858 | 12.857873 | 103 | 80 | 5.378673 | 16.06714 | 119 |
| 60 | 3.300198 | | | 4 | 5.46847 | | |
| 73 | 3.371415 | | | 29 | 5.706527 | 11.17499 | 120 |
| 82 | 3.383174 | | | 55 | 5.865756 | | |
| 58 | 3.446322 | 13.501109 | 104 | 88 | 5.866062 | 11.73181 | 121 |
| 44 | 3.460771 | | | 9 | 5.891173 | | |
| 51 | 3.630847 | | | 96 | 5.897646 | 11.78881 | 122 |
| 15 | 3.641069 | | | 297 | 5.945224 | | |
| 71 | 3.681489 | 14.414175 | 105 | 298 | 5.96371 | 11.90893 | 123 |
| 262 | 3.744627 | | | 87 | 5.978996 | | |
| 54 | 3.811444 | | | 46 | 6.058189 | 12.03718 | 124 |
| 57 | 3.872605 | | | 93 | 6.15515 | | |
| 18 | 3.906955 | 15.335631 | 106 | 74 | 6.2428 | 12.39794 | 125 |
| 59 | 3.933211 | | | 61 | 6.338937 | | |
| 49 | 3.984945 | | | 8 | 6.464507 | 12.80344 | 126 |
| 47 | 3.98871 | | | 271 | 6.559312 | | |
| 19 | 4.044734 | 15.951599 | 107 | 27 | 6.586132 | 13.14544 | 127 |
| 33 | 4.0706 | | | 272 | 6.912562 | | |
| 53 | 4.079912 | | | 288 | 6.94594 | 13.85850 | 128 |
| 66 | 4.126257 | 12.276767 | 108 | | | | |
| Total traveled distance = 412.06 km | | | | average distance of the grouped demands = 13.74 km | | | |
| ND₁₁ = 30 drones | | | | | | | |

Table 5. 6 Drone assignment to distribution points at depot 142, K=160.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 7 | 3.560428 | | | 139 | 10.32572 | 10.32571876 | 142 |
| 92 | 4.57816 | | | 114 | 10.50034 | 10.50033766 | 143 |
| 100 | 6.896885 | 15.03547228 | 129 | 137 | 10.62507 | 10.62506976 | 144 |
| 28 | 7.761518 | | | 136 | 10.71106 | 10.71105679 | 145 |
| 10 | 8.009987 | 15.771505 | 130 | 113 | 11.16093 | 11.16092895 | 146 |
| 35 | 8.319364 | 8.319363712 | 131 | 112 | 11.41348 | 11.41348028 | 147 |
| 63 | 8.44259 | 8.442590053 | 132 | 124 | 12.15728 | 12.15728474 | 148 |

Table 5. 6 (continued): Drone assignment to distribution points at depot 142, K=160.

| | | | | | | | |
|--|----------|-------------|-----|--|----------|-------------|-----|
| 39 | 8.443693 | 8.44369273 | 133 | 111 | 12.71769 | 12.71769278 | 149 |
| 70 | 9.296853 | 9.296853452 | 134 | 133 | 14.26204 | 14.26203951 | 150 |
| 41 | 9.361095 | 9.361094869 | 135 | 129 | 14.71819 | 14.71819437 | 151 |
| 116 | 9.482053 | 9.482052625 | 136 | 37 | 15.08 | 15.08000212 | 152 |
| 72 | 9.60406 | 9.604059993 | 137 | 108 | 15.19666 | 15.19665955 | 153 |
| 140 | 9.730231 | 9.730230996 | 138 | 109 | 15.55212 | 15.55211835 | 154 |
| 141 | 9.892243 | 9.892242516 | 139 | 132 | 15.72287 | 15.72287109 | 155 |
| 95 | 10.14738 | 10.14737611 | 140 | 125 | 15.77313 | 15.77312517 | 156 |
| 143 | 10.21158 | 10.21157947 | 141 | 105 | 16.04218 | 16.04217645 | 157 |
| Total traveled distance = 345.69 km | | | | average distance of the grouped demands | | | |
| ND₁₄₂ = 29 drones | | | | = 11.92 km | | | |

The assignment of drones was done starting with depot of the highest ND_j and proceeded sequentially as explained in the tables above. Table 5. 7 show the number of drones needed and number of demands point served by each depot, for a number of available fully charged drones K=160.

Table 5. 7 Number of drones needed, and number of demands point served by each depot, for K=160.

| Depot ID | ND _j | # demand points served |
|----------|-----------------|------------------------|
| 110 | 58 | 85 |
| 160 | 40 | 76 |
| 11 | 30 | 103 |
| 142 | 29 | 32 |

When the number of available drones K changes to be less than 160, there will be unserved demand points and unmet demand

Table 5. 8, this results in changes in the coverage percentage. We applied different numbers of K to see the impact on the coverage percentage. The coverage

Table 5. 9 shows the percentage of coverage by K number of drones for 4 opened facility and the demand locations assigned to it. Having $K = 160$ fully charged drones allows the system to cover all demands of all allocated demand points by drones allocated at the four opened facilities. Although the number of drones needed for depot 110, $ND_{110} = 58$, we are allowed to assign only 25 drones to it since we have a limited number of fully charged drones available $K=100$.



Table 5. 8 Drone assignment to distribution points at depot 110 with K=100.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|--|------------------|---------------------------|-------------------|--|------------------|---------------------------|-------------------|
| 104 | 0.90797 | | | 285 | 8.872008 | 8.872007 | 17 |
| 128 | 1.408823 | | | 235 | 9.104503 | 9.104502 | 18 |
| 134 | 1.811454 | | | 242 | 9.992435 | 9.992435 | 19 |
| 122 | 2.085668 | | | 276 | 10.51955 | 10.51955 | 20 |
| 106 | 2.228222 | | | 277 | 10.60014 | 10.60013 | 21 |
| 123 | 2.632298 | | | 231 | 10.74267 | 10.74266 | 22 |
| 126 | 2.835145 | 13.90957 | 1 | 236 | 10.7722 | 10.77220 | 23 |
| 130 | 2.861748 | | | 283 | 11.08282 | 11.08282 | 24 |
| 117 | 2.912718 | | | 255 | 11.1332 | 11.13319 | 25 |
| 135 | 3.294408 | | | 257 | 11.21877 | 11.21876 | |
| 127 | 3.384857 | | | 237 | 11.22873 | 11.22873 | |
| 120 | 3.532965 | 15.98669 | 2 | 304 | 11.28828 | 11.28827 | |
| 119 | 3.552484 | | | 291 | 11.3133 | 11.31330 | |
| 118 | 3.577964 | | | 300 | 11.41748 | 11.41747 | |
| 131 | 3.619225 | | | 282 | 11.71372 | 11.71371 | |
| 121 | 3.680577 | 14.43025 | 3 | 284 | 12.03506 | 12.03505 | |
| 261 | 4.051787 | | | 268 | 12.04994 | 12.04994 | |
| 264 | 4.279239 | | | 289 | 12.27992 | 12.27992 | |
| 115 | 4.281891 | 12.61291 | 4 | 301 | 12.3817 | 12.38170 | |
| 138 | 4.326118 | | | 287 | 12.45072 | 12.45071 | |
| 253 | 4.550675 | | | 286 | 12.49338 | 12.49338 | |
| 107 | 4.629469 | 13.50626 | 5 | 295 | 12.84169 | 12.84169 | |
| 246 | 4.646023 | | | 269 | 12.86139 | 12.86138 | |
| 239 | 4.74219 | | | 279 | 13.13106 | 13.13105 | |
| 241 | 5.351957 | 14.74017 | 6 | 278 | 13.14904 | 13.14903 | |
| 232 | 5.365815 | | | 181 | 13.28351 | 13.28350 | |
| 238 | 5.470537 | 10.83635 | 7 | 290 | 13.29647 | 13.29647 | |
| 250 | 5.641463 | | | 263 | 13.38892 | 13.38892 | |
| 248 | 5.750791 | 11.39225 | 8 | 294 | 13.59377 | 13.59376 | |
| 249 | 5.75626 | | | 270 | 13.70899 | 13.70899 | |
| 240 | 6.147876 | 11.90413 | 9 | 182 | 13.85914 | 13.85914 | |
| 234 | 6.347012 | | | 303 | 14.04315 | 14.04314 | |
| 244 | 6.51285 | 12.85986 | 10 | 191 | 14.0687 | 14.06869 | |
| 252 | 6.573138 | | | 173 | 14.42268 | 14.42267 | |
| 247 | 6.944124 | 13.51726 | 11 | 152 | 14.62828 | 14.62827 | |
| 245 | 6.946054 | | | 150 | 15.09271 | 15.09270 | |
| 302 | 7.136667 | 14.08272 | 12 | 258 | 15.18604 | 15.18604 | |
| 260 | 7.170328 | | | 180 | 15.44742 | 15.44741 | |
| 254 | 7.703616 | 14.87394 | 13 | 188 | 15.48189 | 15.48189 | |
| 243 | 7.723026 | | | 177 | 15.60538 | 15.60538 | |
| 281 | 7.733709 | 15.45673 | 14 | 164 | 15.85598 | 15.85598 | |
| 293 | 8.468322 | 8.468322 | 15 | 154 | 16.08596 | 16.08595 | |
| 296 | 8.747954 | 8.747954 | 16 | | | | |
| Total traveled distance = 741.05 km | | | | average distance of the grouped demands | | | |
| ND₁₁₀ = 58 | | | | = 12.78 | | | |

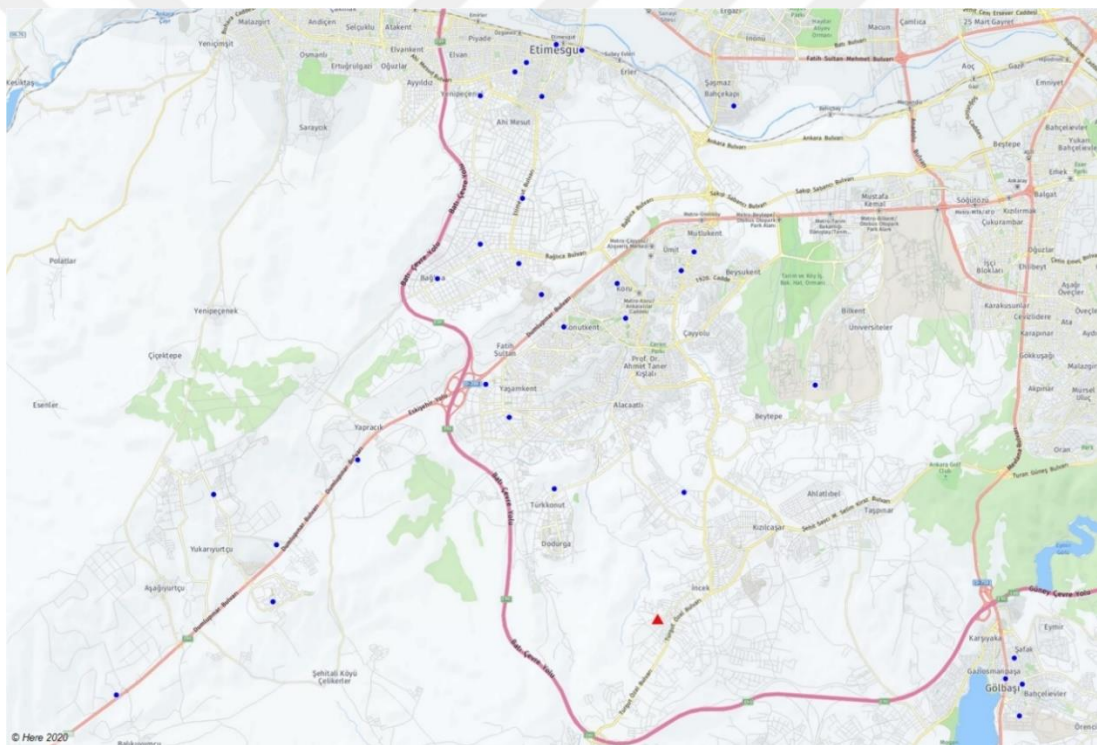
As can be seen in the Assigned drone ID column on the very right side of the table, it stops at 25 and all the demand point starting from 257 to 154 will not be served.

Table 5. 9 Coverage percentage by K drones for 4 open facilities.

| P | K | Coverage (%) |
|---|-----|--------------|
| 4 | 100 | 79.66 |
| 4 | 125 | 89.54 |
| 4 | 150 | 97.73 |
| 4 | 160 | 100 |

5.3. Evaluation of Efficiency and Comparison

According to the current delivery system of PTT, all parcels are delivered by trucks. Truck deliveries are done according to TSP Traveling Salesman Problem. In order to be able to test the efficiency of the solution, total delivery times and delivery times per parcel of the presented system must be compared with a truck delivery system.

**Figure 5. 3** Drone depot 142 and its assigned distribution nodes (demand points)

To test our solution, we compare the results of our allocated depot of the ID 142 with truck-based system. For the sake of comparison, we assume the deliveries of the depot are done by a truck, we solve the TSP and we find the shortest route for the truck, from that we find the total delivery times and delivery times per parcel and then compare it

with our presented solution. Figure 5. 3 illustrates depot 142 with its assigned demand nodes on the map.

5.3.1. TSP Application

Firstly, the shortest driving routes were obtained using Google Maps, a distance matrix is formed with the routes between 33 point (depot 142 and 32 distribution nodes). The route starts and ends at the depot passing from all the points and making the deliveries. After solving the TSP using excel solver, we discovered the shortest path is of a distance of = 152.852 km, with the route and distances between distribution points as in Table 5. 10.

Figure 5. 4 shows the plotted places and the route on the map, and we can see in Figure 5. 5 the route that the truck would use.

Table 5. 10 distances and delivery times for the truck route

| | | | | | | | | | | | | |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Route | 142 | 7 | 92 | 100 | 28 | 10 | 35 | 63 | 39 | 70 | 41 | 116 |
| distance | | 5 | 5.1 | 5.2 | 1.9 | 3.9 | 0.002 | 2.6 | 1.9 | 13.2 | 2.7 | 4.2 |
| time (min) | | 6.67 | 6.8 | 6.93 | 2.53 | 5.20 | 0.002 | 3.47 | 2.53 | 17.6 | 3.60 | 5.6 |
| Route | 72 | 140 | 141 | 95 | 143 | 139 | 114 | 137 | 136 | 113 | 112 | 124 |
| distance | 6.5 | 11.5 | 7.5 | 1.5 | 2.9 | 2.7 | 2.5 | 3.3 | 2.5 | 1.6 | 0.55 | 1.1 |
| time (min) | 8.67 | 15.33 | 10 | 2.00 | 3.87 | 3.60 | 3.33 | 4.40 | 3.33 | 2.13 | 0.73 | 1.47 |
| Route | 111 | 133 | 129 | 37 | 108 | 109 | 132 | 125 | 105 | 142 | | |
| distance | 1.1 | 8.3 | 5 | 0.8 | 8.9 | 20.4 | 0.9 | 1.2 | 1.9 | 14.5 | | |
| time (min) | 1.4 | 11.07 | 6.6 | 1.07 | 11.8 | 27.2 | 1.20 | 1.6 | 2.5 | 19.3 | | |

The average truck speed is set equal to 45 km/h, based on the regulations of the General Directory of Highways of Turkey. This means it will take approximately 3.396 hours (203.8 mins) to complete all deliveries by a truck. The first delivery to node 7 will be completed within 6.67 minutes, and the last delivery is completed within 184.43 minutes, without considering traffic jam and congested roads. By assuming the unloading time of the parcel to be 3 mins for each delivery of the 32, the total delivery time increases, making it 280.43 minutes, which is approximately 4 hours and 41 minutes.

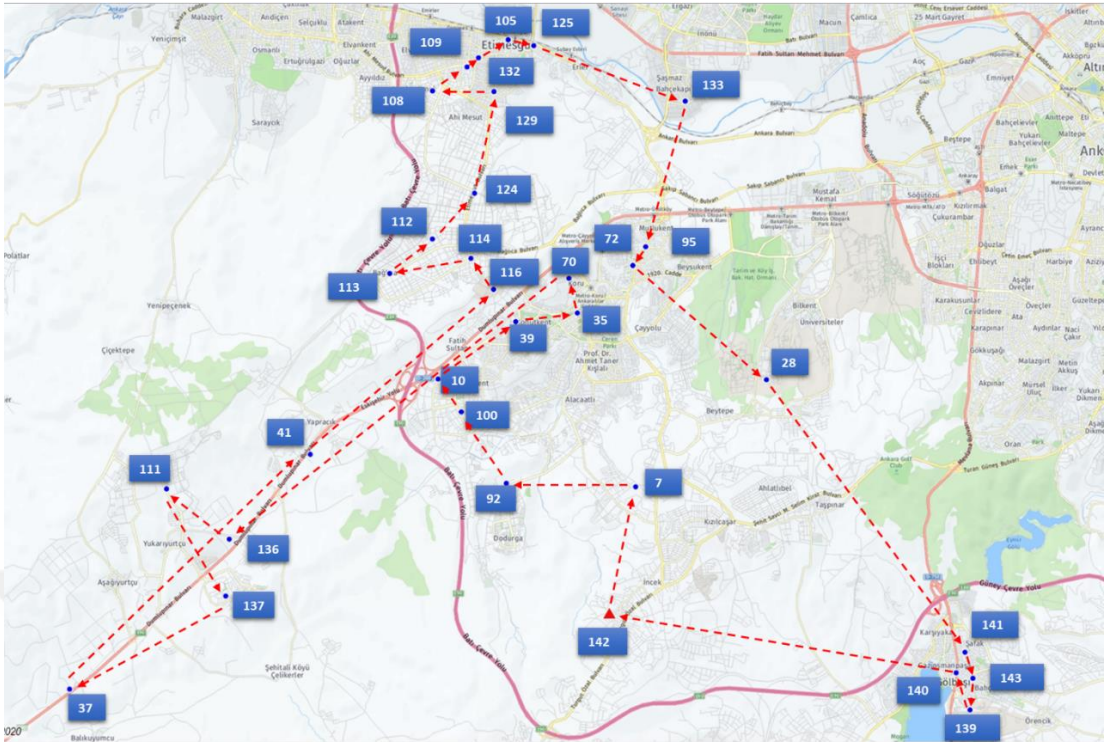


Figure 5. 4 TSP for truck delivery and shortest route

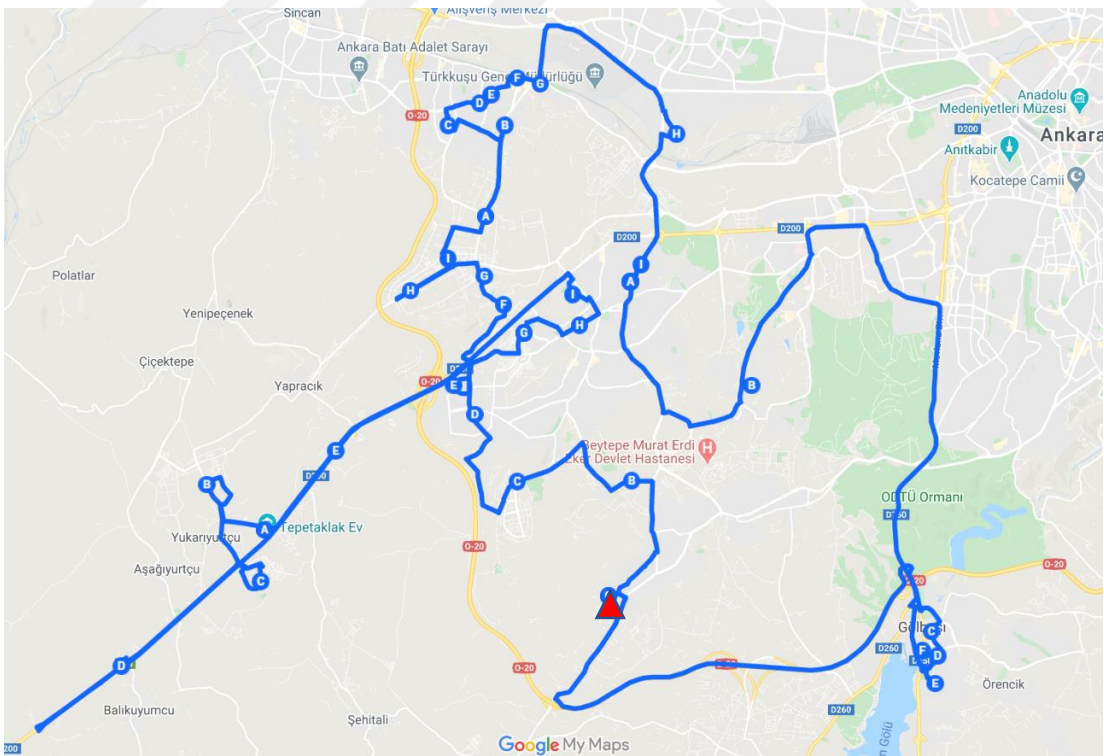


Figure 5. 5 Driving route for TSP (truck delivery) (source: maps.google.com)

Whereas drones fly directly to the delivery point (see Figure 5. 6), and they can fly at a speed of 50 mph, 10 miles per 12 mins (16.09 km per 12 mins). This means the drone completes the round trip within 24 mins plus 6 mins time of loading and unloading the package, taking in consideration the acceleration and deceleration. As for the same case, a drone performs a total distance of 345.67 km to complete all the 32 deliveries, but these deliveries can all be with short time interval. If we assume the loading and departing time of a drone to be 3 minutes and only one employee is setting the drones up for deliveries, drones will depart from the depot with a time interval of 3 mins, when the first drone departs, the second drone will get ready for the second trip. This adds up to 96 mins time until the last drone departures, by adding this value to the time of the last delivery, we get the total delivery time of all parcels. According to the assigned drones in Table 5. 11, delivery to node 105 is the last to be completed with a delivery time of 11.96 minutes, making the total delivery time of the system equal to 107.96 minutes, which is approximately 1 hour and 48 minutes.

Table 5. 11 Distances and delivery times for the drone delivery from depot 142

| | | | | | | | | | | | |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| node | 7 | 92 | 100 | 28 | 10 | 35 | 63 | 39 | 70 | 41 | 116 |
| Distance | 3.56 | 4.57 | 6.89 | 7.7 | 8.009 | 8.31 | 8.44 | 8.44 | 9.29 | 9.36 | 9.48 |
| time (min) | 2.65 | 3.41 | 5.14 | 5.7 | 5.973 | 6.20 | 6.29 | 6.29 | 6.93 | 6.98 | 7.07 |
| node | 72 | 140 | 141 | 95 | 143 | 139 | 114 | 137 | 136 | 113 | 112 |
| distance | 9.60 | 9.73 | 9.89 | 10.1 | 10.21 | 10.32 | 10.50 | 10.6 | 10.7 | 11.16 | 11.4 |
| time (min) | 7.16 | 7.25 | 7.37 | 7.5 | 7.615 | 7.70 | 7.83 | 7.92 | 7.98 | 8.32 | 8.51 |
| node | 124 | 111 | 133 | 129 | 37 | 108 | 109 | 132 | 125 | 105 | |
| distance | 12.1 | 12.7 | 14.2 | 14.7 | 15.08 | 15.19 | 15.552 | 15.72 | 15.77 | 16.04 | |
| time (min) | 9.06 | 9.48 | 10.6 | 10.97 | 11.24 | 11.33 | 11.59 | 11.72 | 11.7 | 11.9 | |

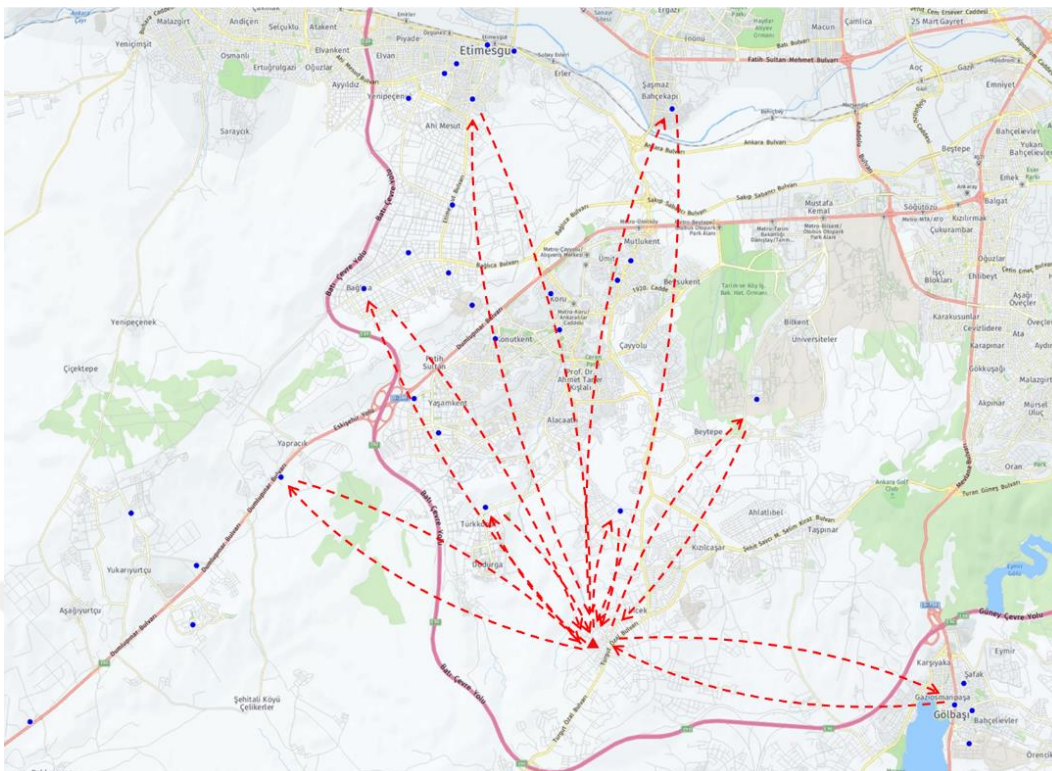


Figure 5. 6 Flying route (drone delivery)

In the Table 5. 12 we can find the comparison between the distance travelled and total time of delivery for both systems. Figure 5. 7 illustrates the results of the table in a chart.

Table 5. 12 Drone delivery and truck delivery systems' comparison

| | TSP | MCFLPD |
|------------------------|------------|---------------|
| Time (mins) | 280.43 | 107.96 |
| Distance Traveled (km) | 152.852 | 345.67 |

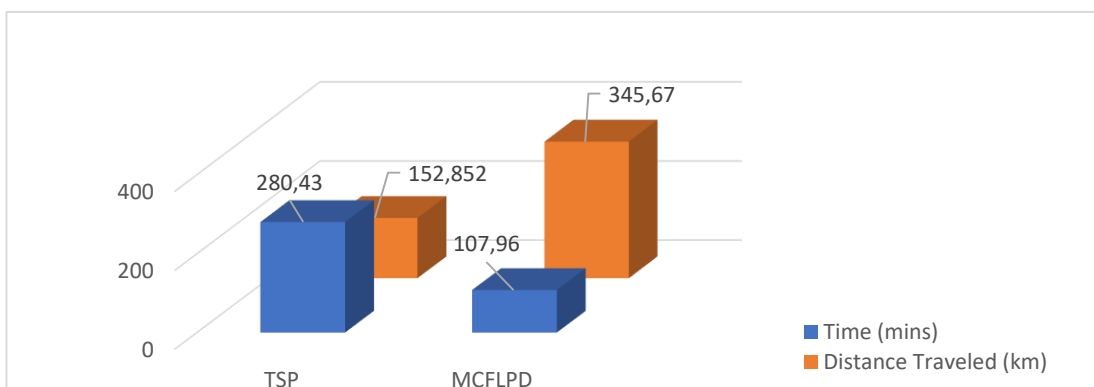


Figure 5. 7 Drone delivery and truck delivery systems' comparison chart

CHAPTER 6

CONCLUSION

This thesis aimed to present a real-world example of drone integration in the last mile delivery by integrating Amazon's Prime Air drones into the Turkish National Postal Service (PTT) delivery system in Ankara Province to obtain Light Cargo Delivering System. By analyzing drone deliveries in the past ten years this thesis has shown how drone delivery systems can be advantageous when compared to truck delivery systems and this study is a proof of it. We focused on finding the optimal locations for drone depots to reach maximum coverage of demand with drones. To do this, we applied the linear programming formulation of MCFLPD with modifications in the parameters, constraints and greedy heuristic method to make the model suitable for solving the problem with traveling distance measurements rather than battery consumption and ensure better coverage. After running the model on the Turkish National Postal Service (PTT) in Ankara province in Turkey, it gave an output of optimized depot locations, allocated demand points to the closest depot, estimated number of drones needed and drones assigned to each demand point to be served.

As the results of testing the efficiency of the proposed system with traditional truck delivery system using TSP, the shortest truck route was calculated and by that we confirmed that our proposed system is a more effective system that further reduces the delivery time per shipment and total delivery time.

When compared to trucks, delivering with a drone have many advantages, such as having an automated navigation system, and the ability to fly over congested roads directly to the customer through the fastest and shortest path possible with flying a speed of 50 mph, being unmanned and having no need for a human pilot, which is quite costly. Drones are known for being eco-friendly vehicles as they can reduce the CO₂ emissions when there is smaller number of delivery points or if the delivery points are closer to the depot. Some disadvantages the drones might have; the payload carrying capacity of the drone and range when compared to trucks, for instance, Amazon Prime Air can carry a package with a maximum weight of 5 pounds (2.25 kg)

with a flying range of 10 miles. Trucks would also have CO₂ advantage over drones if the delivery points were both many and they were of a big distance from the depot [7].

Another handicap that might face the system is the region of application, the population should be prepared for such integration in the industry, for example; no company would like their drones to be taken down with stones by kids playing or any other similar incident. And the regulations of the government regarding drones flying must change to allow such delivery system to operate. Such system can be revolutionary in the shipment industry in Turkey and should be taken seriously for future applications.

For future studies, different heuristic methods can be used to solve the problem or developing a new algorithm for the problem can be considered. Also more literature and application studies on drone deliveries in Turkey are needed.

A possible extension for the study can be constructed by having a truck operating alongside the drones at each depot and delivering parcels that cannot be delivered by drones based on their weight carrying capacity according to TSP, while no synchronization exists between trucks and drones while delivering.

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APPENDICES

Appendix A – Locations and Demands.

Appendix B – Drone assignment to distribution points at allocated depots with $K = 100$.

Appendix C – Drone assignment to distribution points at allocated depots with $K = 125$.

Appendix D – Drone assignment to distribution points at allocated depots with $K = 150$.

Appendix E – Districts and population information of Ankara Province.



Appendix A – Locations and Demands

Table A. 1 List of demand points and potential facility locations with assumed demand.

| ID | Latitude | Longitude | Demand (kg) | ID | Latitude | Longitude | Demand (kg) |
|----|-----------|-----------|-------------|-----|-----------|-----------|-------------|
| 1 | 39.898552 | 32.799631 | 1.073 | 153 | 40.011078 | 32.875869 | 2.087 |
| 2 | 39.918688 | 32.851275 | 0.954 | 154 | 39.981590 | 32.835077 | 2.024 |
| 3 | 39.924238 | 32.854201 | 1.503 | 155 | 39.992045 | 32.877791 | 1.412 |
| 4 | 39.850088 | 32.785908 | 1.124 | 156 | 40.050343 | 32.841913 | 1.606 |
| 5 | 39.921851 | 32.863005 | 0.474 | 157 | 39.991250 | 32.843718 | 1.943 |
| 6 | 39.916531 | 32.796195 | 0.678 | 158 | 39.971279 | 32.851821 | 0.513 |
| 7 | 39.837932 | 32.702254 | 1.897 | 159 | 39.998236 | 32.837529 | 0.137 |
| 8 | 39.848281 | 32.855411 | 1.888 | 160 | 39.984713 | 32.857696 | 1.866 |
| 9 | 39.844873 | 32.790004 | 1.157 | 161 | 39.991782 | 32.866724 | 1.738 |
| 10 | 39.864638 | 32.638236 | 1.929 | 162 | 40.006816 | 32.866760 | 1.824 |
| 11 | 39.895354 | 32.810957 | 0.991 | 163 | 40.002477 | 32.870668 | 1.897 |
| 12 | 39.91413 | 32.781302 | 0.808 | 164 | 39.991665 | 32.831582 | 1.309 |
| 13 | 39.911365 | 32.796791 | 1.578 | 165 | 39.974264 | 32.840215 | 1.219 |
| 14 | 39.911944 | 32.780549 | 0.198 | 166 | 39.978294 | 32.868072 | 1.966 |
| 15 | 39.899846 | 32.853235 | 2.134 | 167 | 39.967809 | 32.838912 | 1.737 |
| 16 | 39.878759 | 32.823434 | 2.235 | 168 | 40.044716 | 32.841886 | 2.169 |
| 17 | 39.910762 | 32.800802 | 0.275 | 169 | 39.982350 | 32.847006 | 0.404 |
| 18 | 39.92853 | 32.826043 | 0.544 | 170 | 40.035575 | 32.852082 | 1.126 |
| 19 | 39.919805 | 32.846066 | 2.097 | 171 | 39.975501 | 32.860463 | 1.599 |
| 20 | 39.893027 | 32.81631 | 0.460 | 172 | 40.021480 | 32.858990 | 0.784 |
| 21 | 39.903515 | 32.81798 | 1.475 | 173 | 39.975923 | 32.815592 | 0.572 |
| 22 | 39.930301 | 32.830163 | 2.134 | 174 | 39.998187 | 32.863751 | 2.043 |
| 23 | 39.908125 | 32.752234 | 1.159 | 175 | 39.999237 | 32.872941 | 0.426 |
| 24 | 39.909703 | 32.780881 | 0.211 | 176 | 39.998975 | 32.852055 | 1.432 |
| 25 | 39.904666 | 32.755333 | 1.146 | 177 | 39.980249 | 32.829471 | 1.694 |
| 26 | 39.885562 | 32.761433 | 0.577 | 178 | 39.982779 | 32.876525 | 1.847 |
| 27 | 39.884883 | 32.734977 | 0.687 | 179 | 40.015395 | 32.858046 | 1.697 |
| 28 | 39.864449 | 32.744604 | 1.642 | 180 | 39.975571 | 32.827612 | 1.512 |
| 29 | 39.879139 | 32.874414 | 2.211 | 181 | 39.992418 | 32.801102 | 2.024 |
| 30 | 39.917976 | 32.856564 | 1.668 | 182 | 40.000101 | 32.806420 | 1.099 |
| 31 | 39.900992 | 32.872976 | 0.868 | 183 | 39.970373 | 32.870937 | 1.658 |
| 32 | 39.915555 | 32.820182 | 1.998 | 184 | 39.998422 | 32.845919 | 0.258 |
| 33 | 39.882593 | 32.855675 | 1.221 | 185 | 39.985764 | 32.863320 | 0.176 |
| 34 | 39.905966 | 32.858899 | 0.378 | 186 | 40.009779 | 32.856915 | 1.039 |
| 35 | 39.880973 | 32.683378 | 1.654 | 187 | 40.013751 | 32.866760 | 2.108 |
| 36 | 39.885534 | 32.818161 | 0.597 | 188 | 39.993973 | 32.826848 | 0.417 |
| 37 | 39.787755 | 32.518968 | 1.625 | 189 | 39.985791 | 32.895767 | 1.101 |

Table A. 2 (continued): List of demand points and potential facility locations with assumed demand.

| | | | | | | | |
|----|-----------|-----------|-------|-----|-----------|-----------|-------|
| 38 | 39.883866 | 32.799342 | 0.418 | 190 | 39.994055 | 32.893251 | 2.053 |
| 39 | 39.878855 | 32.663426 | 0.244 | 191 | 40.002388 | 32.808361 | 0.246 |
| 40 | 39.903435 | 32.810193 | 1.277 | 192 | 39.925135 | 32.895875 | 1.353 |
| 41 | 39.845966 | 32.596888 | 0.251 | 193 | 39.918751 | 32.890215 | 0.505 |
| 42 | 39.915811 | 32.826363 | 0.265 | 194 | 39.965238 | 32.958712 | 0.166 |
| 43 | 39.881928 | 32.836101 | 1.026 | 195 | 39.913694 | 32.930558 | 1.603 |
| 44 | 39.925978 | 32.818197 | 1.094 | 196 | 39.926075 | 32.909771 | 0.295 |
| 45 | 39.90019 | 32.844509 | 2.129 | 197 | 39.933856 | 32.879822 | 0.712 |
| 46 | 39.910581 | 32.742766 | 1.607 | 198 | 39.911294 | 32.898039 | 0.991 |
| 47 | 39.917492 | 32.847752 | 1.251 | 199 | 39.902667 | 32.935921 | 2.101 |
| 48 | 39.885271 | 32.839559 | 0.265 | 200 | 39.962846 | 32.944150 | 0.197 |
| 49 | 39.912394 | 32.852055 | 1.672 | 201 | 39.903580 | 32.926121 | 0.262 |
| 50 | 39.914925 | 32.818601 | 0.522 | 202 | 39.914918 | 32.892506 | 0.683 |
| 51 | 39.884918 | 32.851282 | 0.580 | 203 | 39.943267 | 32.922492 | 0.327 |
| 52 | 39.894474 | 32.836442 | 0.658 | 204 | 39.914929 | 32.964609 | 2.228 |
| 53 | 39.864188 | 32.83619 | 0.399 | 205 | 39.914732 | 32.964811 | 1.653 |
| 54 | 39.911889 | 32.771817 | 0.128 | 206 | 39.890717 | 32.985320 | 0.606 |
| 55 | 39.843369 | 32.799279 | 2.084 | 207 | 39.888752 | 32.986317 | 1.095 |
| 56 | 39.894438 | 32.756263 | 1.997 | 208 | 39.906160 | 32.913338 | 0.704 |
| 57 | 39.918253 | 32.845165 | 1.358 | 209 | 39.907018 | 32.973480 | 1.014 |
| 58 | 39.910124 | 32.846476 | 0.732 | 210 | 39.914144 | 32.905918 | 0.952 |
| 59 | 39.895803 | 32.857058 | 1.240 | 211 | 39.900144 | 33.033654 | 0.450 |
| 60 | 39.866604 | 32.820560 | 1.805 | 212 | 39.971980 | 33.114673 | 1.492 |
| 61 | 39.889603 | 32.884879 | 0.993 | 213 | 39.931338 | 32.912987 | 1.974 |
| 62 | 39.920936 | 32.850815 | 1.904 | 214 | 39.923246 | 32.917344 | 1.345 |
| 63 | 39.878824 | 32.663343 | 1.449 | 215 | 39.916606 | 32.900743 | 1.340 |
| 64 | 39.908630 | 32.813867 | 1.801 | 216 | 39.896571 | 32.922896 | 2.131 |
| 65 | 39.913369 | 32.862520 | 0.299 | 217 | 39.919000 | 32.911254 | 0.297 |
| 66 | 39.900217 | 32.858909 | 0.459 | 218 | 39.935723 | 32.893377 | 0.952 |
| 67 | 39.908056 | 32.792416 | 1.030 | 219 | 39.913742 | 32.919985 | 0.633 |
| 68 | 39.903704 | 32.845883 | 0.960 | 220 | 39.924533 | 32.907265 | 2.015 |
| 69 | 39.933040 | 32.840969 | 0.131 | 221 | 39.922161 | 32.939057 | 0.921 |
| 70 | 39.889582 | 32.680656 | 1.585 | 222 | 39.907482 | 32.959466 | 0.337 |
| 71 | 39.911467 | 32.773254 | 0.950 | 223 | 39.904189 | 32.964120 | 1.043 |
| 72 | 39.892758 | 32.701335 | 1.620 | 224 | 40.031245 | 32.885679 | 0.228 |
| 73 | 39.910927 | 32.777045 | 0.337 | 225 | 40.074522 | 32.923641 | 1.061 |
| 74 | 39.846596 | 32.847222 | 1.271 | 226 | 40.043487 | 32.902558 | 1.885 |
| 75 | 39.848493 | 32.825680 | 1.907 | 227 | 40.068035 | 32.925672 | 1.511 |
| 76 | 39.891471 | 32.829031 | 0.226 | 228 | 40.142785 | 32.845671 | 2.071 |
| 77 | 39.887825 | 32.890287 | 1.996 | 229 | 40.068911 | 32.926013 | 0.995 |

Table A. 1 (continued): List of demand points and potential facility locations with assumed demand.

| | | | | | | | |
|-----|-----------|-----------|-------|-----|-----------|-----------|-------|
| 78 | 39.900494 | 32.748856 | 0.301 | 230 | 40.037598 | 32.896872 | 0.273 |
| 79 | 39.913736 | 32.821054 | 1.311 | 231 | 40.016376 | 32.530682 | 0.270 |
| 80 | 39.910339 | 32.870910 | 2.020 | 232 | 39.959383 | 32.588193 | 0.481 |
| 81 | 39.928081 | 32.851776 | 0.180 | 233 | 39.788413 | 32.386418 | 2.037 |
| 82 | 39.877291 | 32.842865 | 1.508 | 234 | 39.951460 | 32.580332 | 0.675 |
| 83 | 39.912594 | 32.821000 | 1.804 | 235 | 40.026626 | 32.560468 | 0.693 |
| 84 | 39.905489 | 32.846997 | 1.140 | 236 | 40.008764 | 32.526496 | 0.672 |
| 85 | 39.914337 | 32.827405 | 0.908 | 237 | 40.009379 | 32.521115 | 1.673 |
| 86 | 39.912421 | 32.796790 | 1.097 | 238 | 39.953576 | 32.590537 | 0.274 |
| 87 | 39.921434 | 32.872258 | 0.995 | 239 | 39.966717 | 32.592639 | 0.385 |
| 88 | 39.842642 | 32.808190 | 2.002 | 240 | 39.997006 | 32.578643 | 0.453 |
| 89 | 39.910816 | 32.860795 | 0.282 | 241 | 39.988010 | 32.584941 | 1.277 |
| 90 | 39.906119 | 32.858927 | 0.993 | 242 | 40.002436 | 32.533521 | 0.863 |
| 91 | 39.874287 | 32.862996 | 1.997 | 243 | 39.980786 | 32.555789 | 0.940 |
| 92 | 39.838792 | 32.660381 | 1.931 | 244 | 39.966553 | 32.571363 | 1.004 |
| 93 | 39.910332 | 32.880423 | 0.308 | 245 | 39.953842 | 32.571120 | 2.006 |
| 94 | 39.916918 | 32.824333 | 1.417 | 246 | 39.962258 | 32.595783 | 1.012 |
| 95 | 39.897394 | 32.705504 | 1.563 | 247 | 39.946889 | 32.575611 | 1.607 |
| 96 | 39.903580 | 32.879256 | 0.151 | 248 | 39.964767 | 32.581069 | 1.412 |
| 97 | 39.876945 | 32.760768 | 1.540 | 249 | 39.964589 | 32.581064 | 2.103 |
| 98 | 39.907790 | 32.837910 | 0.640 | 250 | 39.942783 | 32.598550 | 1.190 |
| 99 | 39.887485 | 32.815001 | 1.840 | 251 | 39.725444 | 32.353660 | 1.400 |
| 100 | 39.856483 | 32.645802 | 0.416 | 252 | 39.983912 | 32.569606 | 0.153 |
| 101 | 39.922659 | 32.857337 | 1.917 | 253 | 39.990089 | 32.595370 | 1.334 |
| 102 | 39.925474 | 32.855890 | 1.982 | 254 | 39.990718 | 32.557497 | 0.408 |
| 103 | 39.924588 | 32.855028 | 0.392 | 255 | 40.003403 | 32.519983 | 0.832 |
| 104 | 39.983539 | 32.654030 | 1.428 | 256 | 39.952490 | 32.877800 | 1.962 |
| 105 | 39.948639 | 32.660965 | 2.111 | 257 | 39.951958 | 32.773569 | 2.133 |
| 106 | 39.988936 | 32.624538 | 1.248 | 258 | 39.957445 | 32.822540 | 0.578 |
| 107 | 39.951992 | 32.603805 | 0.217 | 259 | 39.939648 | 32.796305 | 2.019 |
| 108 | 39.935979 | 32.636468 | 0.389 | 260 | 39.957684 | 32.726255 | 1.683 |
| 109 | 39.941891 | 32.647643 | 1.615 | 261 | 39.984174 | 32.693188 | 0.268 |
| 110 | 39.977879 | 32.646349 | 1.962 | 262 | 39.928952 | 32.813948 | 1.446 |
| 111 | 39.837400 | 32.550364 | 0.855 | 263 | 39.982419 | 32.803375 | 0.478 |
| 112 | 39.899311 | 32.636441 | 1.662 | 264 | 39.988277 | 32.694706 | 1.604 |
| 113 | 39.890786 | 32.622616 | 0.948 | 265 | 39.905919 | 32.858804 | 1.923 |
| 114 | 39.894509 | 32.648910 | 1.500 | 266 | 39.933786 | 32.798255 | 0.158 |
| 115 | 39.953016 | 32.607982 | 1.561 | 267 | 39.933807 | 32.798237 | 1.769 |
| 116 | 39.886835 | 32.656222 | 2.159 | 268 | 39.968866 | 32.787268 | 1.595 |
| 117 | 40.000191 | 32.628437 | 0.633 | 269 | 39.965023 | 32.796341 | 1.940 |
| 118 | 39.975840 | 32.604443 | 1.937 | 270 | 39.962438 | 32.805953 | 1.959 |

Table A. 1 (continued): List of demand points and potential facility locations with assumed demand.

| | | | | | | | |
|-----|-----------|-----------|-------|-----|-----------|-----------|-------|
| 119 | 39.948701 | 32.629371 | 1.286 | 271 | 39.952096 | 32.831986 | 0.400 |
| 120 | 39.954212 | 32.618690 | 1.327 | 272 | 39.956979 | 32.821630 | 1.360 |
| 121 | 40.001642 | 32.616274 | 1.604 | 273 | 39.935384 | 32.822672 | 0.977 |
| 122 | 39.974071 | 32.622382 | 1.593 | 274 | 39.942658 | 32.813337 | 0.181 |
| 123 | 39.972744 | 32.616193 | 0.651 | 275 | 39.935142 | 32.824045 | 1.447 |
| 124 | 39.910643 | 32.650077 | 0.879 | 276 | 39.957482 | 32.766885 | 1.442 |
| 125 | 39.947180 | 32.669257 | 1.969 | 277 | 39.956244 | 32.767487 | 0.624 |
| 126 | 39.952748 | 32.640732 | 1.758 | 278 | 39.976428 | 32.800653 | 0.825 |
| 127 | 39.988694 | 32.609213 | 1.400 | 279 | 39.975799 | 32.800429 | 0.817 |
| 128 | 39.970746 | 32.660013 | 1.323 | 280 | 39.935885 | 32.823090 | 1.419 |
| 129 | 39.935792 | 32.656348 | 1.256 | 281 | 39.992909 | 32.734977 | 0.478 |
| 130 | 39.952594 | 32.640088 | 1.774 | 282 | 39.961311 | 32.782094 | 0.437 |
| 131 | 39.945673 | 32.640205 | 2.064 | 283 | 40.018158 | 32.765358 | 0.286 |
| 132 | 39.944186 | 32.651371 | 1.265 | 284 | 39.975501 | 32.787556 | 1.282 |
| 133 | 39.933454 | 32.718305 | 0.618 | 285 | 39.992038 | 32.748829 | 0.725 |
| 134 | 39.965493 | 32.660157 | 1.901 | 286 | 39.982765 | 32.792838 | 1.196 |
| 135 | 39.948287 | 32.648236 | 0.384 | 287 | 39.974437 | 32.792398 | 1.212 |
| 136 | 39.824954 | 32.570666 | 2.241 | 288 | 39.957164 | 32.822734 | 0.145 |
| 137 | 39.810857 | 32.569508 | 1.499 | 289 | 39.958698 | 32.788256 | 1.983 |
| 138 | 39.949109 | 32.612178 | 2.209 | 290 | 39.978307 | 32.802396 | 2.003 |
| 139 | 39.782585 | 32.810526 | 1.208 | 291 | 39.967968 | 32.778481 | 1.441 |
| 140 | 39.791809 | 32.806034 | 1.415 | 292 | 39.913805 | 32.803357 | 0.423 |
| 141 | 39.796902 | 32.808882 | 2.026 | 293 | 39.971424 | 32.745371 | 1.637 |
| 142 | 39.806582 | 32.693772 | 1.858 | 294 | 39.981777 | 32.805809 | 2.181 |
| 143 | 39.790444 | 32.811442 | 1.718 | 295 | 39.990684 | 32.796144 | 1.655 |
| 144 | 39.537801 | 32.610111 | 0.679 | 296 | 39.983096 | 32.748793 | 0.870 |
| 145 | 39.987263 | 32.855666 | 2.200 | 297 | 39.946937 | 32.829299 | 2.093 |
| 146 | 39.995444 | 32.859780 | 2.057 | 298 | 39.947325 | 32.828231 | 1.747 |
| 147 | 39.998906 | 32.888760 | 2.166 | 299 | 39.956597 | 32.833100 | 0.543 |
| 148 | 40.000073 | 32.884942 | 1.617 | 300 | 39.976600 | 32.780333 | 1.669 |
| 149 | 39.976421 | 32.878681 | 2.109 | 301 | 40.041893 | 32.765304 | 2.219 |
| 150 | 39.970193 | 32.823183 | 2.031 | 302 | 39.957772 | 32.725877 | 0.458 |
| 151 | 40.007320 | 32.845003 | 1.048 | 303 | 39.966247 | 32.810445 | 2.234 |
| 152 | 39.983387 | 32.817883 | 1.947 | 304 | 39.951979 | 32.774420 | 0.678 |

Appendix B – Drone assignment to distribution points at allocated depots with $K = 100$.

Table B. 1 Drone assignment to distribution points at depot 110 with $K=100$.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 104 | 0.90797 | | | 285 | 8.872008 | 8.8720078 | 17 |
| 128 | 1.408823 | | | 235 | 9.104503 | 9.1045027 | 18 |
| 134 | 1.811454 | | | 242 | 9.992435 | 9.9924351 | 19 |
| 122 | 2.085668 | | | 276 | 10.51955 | 10.519551 | 20 |
| 106 | 2.228222 | | | 277 | 10.60014 | 10.600136 | 21 |
| 123 | 2.632298 | | | 231 | 10.74267 | 10.742668 | 22 |
| 126 | 2.835145 | 13.909579 | 1 | 236 | 10.7722 | 10.772204 | 23 |
| 130 | 2.861748 | | | 283 | 11.08282 | 11.082821 | 24 |
| 117 | 2.912718 | | | 255 | 11.1332 | 11.133196 | 25 |
| 135 | 3.294408 | | | 257 | 11.21877 | 11.218769 | |
| 127 | 3.384857 | | | 237 | 11.22873 | 11.228734 | |
| 120 | 3.532965 | 15.986695 | 2 | 304 | 11.28828 | 11.288278 | |
| 119 | 3.552484 | | | 291 | 11.3133 | 11.313302 | |
| 118 | 3.577964 | | | 300 | 11.41748 | 11.417479 | |
| 131 | 3.619225 | | | 282 | 11.71372 | 11.713719 | |
| 121 | 3.680577 | 14.430250 | 3 | 284 | 12.03506 | 12.035057 | |
| 261 | 4.051787 | | | 268 | 12.04994 | 12.049943 | |
| 264 | 4.279239 | | | 289 | 12.27992 | 12.279922 | |
| 115 | 4.281891 | 12.612916 | 4 | 301 | 12.3817 | 12.381701 | |
| 138 | 4.326118 | | | 287 | 12.45072 | 12.450716 | |
| 253 | 4.550675 | | | 286 | 12.49338 | 12.493383 | |
| 107 | 4.629469 | 13.506261 | 5 | 295 | 12.84169 | 12.841691 | |
| 246 | 4.646023 | | | 269 | 12.86139 | 12.861386 | |
| 239 | 4.74219 | | | 279 | 13.13106 | 13.131059 | |
| 241 | 5.351957 | 14.740170 | 6 | 278 | 13.14904 | 13.149039 | |
| 232 | 5.365815 | | | 181 | 13.28351 | 13.283509 | |
| 238 | 5.470537 | 10.836351 | 7 | 290 | 13.29647 | 13.296470 | |
| 250 | 5.641463 | | | 263 | 13.38892 | 13.388921 | |
| 248 | 5.750791 | 11.392254 | 8 | 294 | 13.59377 | 13.593765 | |
| 249 | 5.75626 | | | 270 | 13.70899 | 13.708991 | |
| 240 | 6.147876 | 11.904136 | 9 | 182 | 13.85914 | 13.859141 | |
| 234 | 6.347012 | | | 303 | 14.04315 | 14.043145 | |
| 244 | 6.51285 | 12.859861 | 10 | 191 | 14.0687 | 14.068698 | |
| 252 | 6.573138 | | | 173 | 14.42268 | 14.422675 | |
| 247 | 6.944124 | 13.517262 | 11 | 152 | 14.62828 | 14.628278 | |
| 245 | 6.946054 | | | 150 | 15.09271 | 15.092705 | |

Table B. 1 (continued): Drone assignment to distribution points at depot 110 with K=100.

| | | | | | | |
|--|----------|-----------|----|--|----------|-----------|
| 302 | 7.136667 | 14.082720 | 12 | 258 | 15.18604 | 15.186040 |
| 260 | 7.170328 | | | 180 | 15.44742 | 15.447419 |
| 254 | 7.703616 | 14.873944 | 13 | 188 | 15.48189 | 15.481893 |
| 243 | 7.723026 | | | 177 | 15.60538 | 15.605382 |
| 281 | 7.733709 | 15.456734 | 14 | 164 | 15.85598 | 15.855984 |
| 293 | 8.468322 | 8.4683223 | 15 | 154 | 16.08596 | 16.085959 |
| 296 | 8.747954 | 8.7479541 | 16 | | | |
| Total traveled distance = 741.05 km | | | | average distance of the grouped demands | | |
| ND₁₁₀ = 58 | | | | = 12.78 | | |

Table B. 2 Drone assignment to distribution points at depot 160, K=110.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 145 | 0.33213116 | | | 230 | 6.76112909 | | |
| 185 | 0.49320315 | | | 168 | 6.80652566 | 13.5676547 | 33 |
| 169 | 0.94793972 | | | 203 | 7.19265520 | | |
| 171 | 1.05110944 | | | 192 | 7.38090024 | 14.5735554 | 34 |
| 161 | 1.09974084 | | | 156 | 7.42046118 | | |
| 166 | 1.13623628 | | | 226 | 7.57019156 | 14.9906527 | 35 |
| 146 | 1.20636867 | | | 213 | 7.57846431 | | |
| 157 | 1.39517090 | | | 200 | 7.75789182 | 15.3363561 | 36 |
| 158 | 1.57544027 | | | 193 | 7.84095368 | | |
| 174 | 1.58455232 | | | 196 | 7.88766858 | 15.7286222 | 37 |
| 178 | 1.61859053 | | | 220 | 7.91394313 | 7.91394313 | 38 |
| 176 | 1.6570744 | | | 202 | 8.30877088 | 8.30877088 | 39 |
| 184 | 1.82491150 | 15.9224 | 26 | 215 | 8.41529293 | 8.41529293 | 40 |
| 165 | 1.88905152 | | | 214 | 8.51847291 | 8.51847291 | 41 |
| 155 | 1.89620359 | | | 217 | 8.61588641 | 8.61588641 | 42 |
| 183 | 1.95332384 | | | 210 | 8.85839264 | 8.85839264 | 43 |
| 149 | 2.01175009 | | | 198 | 8.85860993 | 8.85860993 | 44 |
| 175 | 2.07241341 | | | 194 | 8.87594155 | 8.87594155 | 45 |
| 163 | 2.26336922 | | | 219 | 9.51161785 | 9.51161785 | 46 |
| 159 | 2.28314652 | 14.36925 | 27 | 221 | 9.82210431 | 9.82210431 | 47 |
| 167 | 2.46878629 | | | 208 | 9.93954664 | 9.93954664 | 48 |
| 162 | 2.57617255 | | | 195 | 10.0468199 | 10.0468199 | 49 |
| 151 | 2.73646178 | | | 201 | 10.7431536 | 10.7431536 | 50 |
| 186 | 2.78800590 | | | 227 | 10.9243108 | 10.9243108 | |
| 148 | 2.88175611 | 13.45118 | 28 | 229 | 11.0223191 | 11.0223191 | |
| 147 | 3.08121512 | | | 77 | 11.1260269 | 11.1260269 | |

Table B. 2 (continued): Drone assignment to distribution points at depot 160, K=110.

| | | | | | | | |
|--|------------|----------|----|--|------------|------------|--|
| 190 | 3.20222468 | | | 216 | 11.2674865 | 11.2674865 | |
| 189 | 3.24581192 | | | 199 | 11.3005618 | 11.3005618 | |
| 153 | 3.31526600 | 12.84451 | 29 | 225 | 11.4565249 | 11.4565249 | |
| 187 | 3.31990456 | | | 204 | 11.9694963 | 11.9694963 | |
| 179 | 3.411813 | | | 205 | 11.9968191 | 11.9968191 | |
| 299 | 3.76394666 | | | 222 | 12.2071738 | 12.2071738 | |
| 256 | 3.97156926 | 14.46723 | 30 | 223 | 12.7469025 | 12.7469025 | |
| 172 | 4.08978930 | | | 209 | 13.1171868 | 13.1171868 | |
| 170 | 5.67577125 | | | 206 | 15.0876384 | 15.0876384 | |
| 224 | 5.69664441 | 15.46220 | 31 | 207 | 15.3007348 | 15.3007348 | |
| 197 | 5.96119152 | | | 206 | 15.0876384 | 15.0876384 | |
| 218 | 6.23881423 | 12.20000 | 32 | 207 | 15.3007348 | 15.3007348 | |
| Total traveled distance = 481.25 km | | | | average distance of the grouped demands | | | |
| ND₁₆₀ = 40 drones | | | | = 12.03 km | | | |

Table B. 3 Drone assignment to distribution points at depot 11, K=100.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 1 | 1.029566 | | | 22 | 4.21707 | | |
| 20 | 0.524885 | | | 265 | 4.247246 | | |
| 40 | 0.900927 | | | 34 | 4.256479 | 12.72079 | 61 |
| 99 | 0.940558 | | | 90 | 4.263515 | | |
| 21 | 1.087386 | | | 2 | 4.307967 | | |
| 36 | 1.253029 | | | 26 | 4.363264 | 12.93474 | 62 |
| 64 | 1.496949 | | | 266 | 4.408615 | | |
| 76 | 1.601259 | | | 267 | 4.411255 | | |
| 38 | 1.61672 | | | 62 | 4.432775 | 13.25264 | 63 |
| 17 | 1.919824 | | | 273 | 4.561889 | | |
| 83 | 2.099707 | 14.470809 | 51 | 275 | 4.562862 | | |
| 67 | 2.120453 | | | 89 | 4.585734 | 13.71048 | 64 |
| 16 | 2.130334 | | | 280 | 4.624107 | | |
| 292 | 2.151641 | | | 30 | 4.632552 | | |
| 13 | 2.151691 | | | 56 | 4.667124 | 13.92378 | 65 |
| 52 | 2.176357 | | | 97 | 4.746332 | | |
| 79 | 2.218029 | | | 65 | 4.832982 | | |
| 86 | 2.249855 | 15.198360 | 52 | 25 | 4.856661 | 14.43597 | 66 |
| 50 | 2.271775 | | | 3 | 4.89077 | | |
| 32 | 2.380085 | | | 69 | 4.910395 | | |

Table B. 3 (continued): Drone assignment to distribution points at depot 11, K=100.

| | | | | | | | |
|--|----------|-----------|----|---|----------|----------|----|
| 85 | 2.534547 | | | 103 | 4.969545 | 14.77071 | 67 |
| 43 | 2.6136 | | | 101 | 4.98675 | | |
| 42 | 2.627011 | | | 91 | 5.020215 | | |
| 94 | 2.655412 | 15.082429 | 53 | 81 | 5.036216 | 15.04318 | 68 |
| 6 | 2.670291 | | | 259 | 5.081307 | | |
| 98 | 2.682978 | | | 102 | 5.08965 | | |
| 48 | 2.685477 | | | 23 | 5.20663 | 15.37758 | 69 |
| 45 | 2.912317 | | | 274 | 5.263879 | | |
| 24 | 3.021209 | 13.972272 | 54 | 31 | 5.327678 | | |
| 68 | 3.1207 | | | 5 | 5.328138 | 15.91969 | 70 |
| 14 | 3.182903 | | | 78 | 5.32842 | | |
| 84 | 3.274413 | | | 75 | 5.36005 | | |
| 12 | 3.279858 | 12.857873 | 55 | 80 | 5.378673 | 16.06714 | 71 |
| 60 | 3.300198 | | | 4 | 5.46847 | | |
| 73 | 3.371415 | | | 29 | 5.706527 | 11.17499 | 72 |
| 82 | 3.383174 | | | 55 | 5.865756 | | |
| 58 | 3.446322 | 13.501109 | 56 | 88 | 5.866062 | 11.73181 | 73 |
| 44 | 3.460771 | | | 9 | 5.891173 | | |
| 51 | 3.630847 | | | 96 | 5.897646 | 11.78881 | 74 |
| 15 | 3.641069 | | | 297 | 5.945224 | | |
| 71 | 3.681489 | 14.414175 | 57 | 298 | 5.96371 | 11.90893 | 75 |
| 262 | 3.744627 | | | 87 | 5.978996 | | |
| 54 | 3.811444 | | | 46 | 6.058189 | 12.03718 | |
| 57 | 3.872605 | | | 93 | 6.15515 | | |
| 18 | 3.906955 | 15.335631 | 58 | 74 | 6.2428 | 12.39794 | |
| 59 | 3.933211 | | | 61 | 6.338937 | | |
| 49 | 3.984945 | | | 8 | 6.464507 | 12.80344 | |
| 47 | 3.98871 | | | 271 | 6.559312 | | |
| 19 | 4.044734 | 15.951599 | 59 | 27 | 6.586132 | 13.14544 | |
| 33 | 4.0706 | | | 272 | 6.912562 | | |
| 53 | 4.079912 | | | 288 | 6.94594 | 13.85850 | |
| 66 | 4.126257 | 12.276767 | 60 | | | | |
| Total traveled distance = 412.06 km | | | | average distance of the grouped demands = 13.74 km | | | |
| ND₁₄₂ = 30 drones | | | | | | | |

Table B. 4 Drone assignment to distribution points at depot 142, K=100.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|--|------------------|---------------------------|-------------------|--|------------------|---------------------------|-------------------|
| 7 | 3.560428 | | | 139 | 10.32572 | 10.32571876 | 89 |
| 92 | 4.57816 | | | 114 | 10.50034 | 10.50033766 | 90 |
| 100 | 6.896885 | 15.03547228 | 76 | 137 | 10.62507 | 10.62506976 | 91 |
| 28 | 7.761518 | | | 136 | 10.71106 | 10.71105679 | 92 |
| 10 | 8.009987 | 15.771505 | 77 | 113 | 11.16093 | 11.16092895 | 93 |
| 35 | 8.319364 | 8.319363712 | 78 | 112 | 11.41348 | 11.41348028 | 94 |
| 63 | 8.44259 | 8.442590053 | 79 | 124 | 12.15728 | 12.15728474 | 95 |
| 39 | 8.443693 | 8.44369273 | 80 | 111 | 12.71769 | 12.71769278 | 96 |
| 70 | 9.296853 | 9.296853452 | 81 | 133 | 14.26204 | 14.26203951 | 97 |
| 41 | 9.361095 | 9.361094869 | 82 | 129 | 14.71819 | 14.71819437 | 98 |
| 116 | 9.482053 | 9.482052625 | 83 | 37 | 15.08 | 15.08000212 | 99 |
| 72 | 9.60406 | 9.604059993 | 84 | 108 | 15.19666 | 15.19665955 | 100 |
| 140 | 9.730231 | 9.730230996 | 85 | 109 | 15.55212 | 15.55211835 | |
| 141 | 9.892243 | 9.892242516 | 86 | 132 | 15.72287 | 15.72287109 | |
| 95 | 10.14738 | 10.14737611 | 87 | 125 | 15.77313 | 15.77312517 | |
| 143 | 10.21158 | 10.21157947 | 88 | 105 | 16.04218 | 16.04217645 | |
| Total traveled distance = 345.69 km | | | | average distance of the grouped demands | | | |
| ND₁₄₂ = 29 drones | | | | = 11.92 km | | | |

Appendix C – Drone assignment to distribution points at allocated depots with K = 125.

Table C. 1 Drone assignment to distribution points at depot 110 with K=125.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 104 | 0.90797 | | | 285 | 8.872008 | 8.8720078 | 17 |
| 128 | 1.408823 | | | 235 | 9.104503 | 9.1045027 | 18 |
| 134 | 1.811454 | | | 242 | 9.992435 | 9.9924351 | 19 |
| 122 | 2.085668 | | | 276 | 10.51955 | 10.519551 | 20 |
| 106 | 2.228222 | | | 277 | 10.60014 | 10.600136 | 21 |
| 123 | 2.632298 | | | 231 | 10.74267 | 10.742668 | 22 |
| 126 | 2.835145 | 13.909579 | 1 | 236 | 10.7722 | 10.772204 | 23 |
| 130 | 2.861748 | | | 283 | 11.08282 | 11.082821 | 24 |
| 117 | 2.912718 | | | 255 | 11.1332 | 11.133196 | 25 |
| 135 | 3.294408 | | | 257 | 11.21877 | 11.218769 | 26 |
| 127 | 3.384857 | | | 237 | 11.22873 | 11.228734 | 27 |
| 120 | 3.532965 | 15.986695 | 2 | 304 | 11.28828 | 11.288278 | 28 |
| 119 | 3.552484 | | | 291 | 11.3133 | 11.313302 | 29 |
| 118 | 3.577964 | | | 300 | 11.41748 | 11.417479 | 30 |
| 131 | 3.619225 | | | 282 | 11.71372 | 11.713719 | 31 |
| 121 | 3.680577 | 14.430250 | 3 | 284 | 12.03506 | 12.035057 | 32 |
| 261 | 4.051787 | | | 268 | 12.04994 | 12.049943 | 33 |
| 264 | 4.279239 | | | 289 | 12.27992 | 12.279922 | |
| 115 | 4.281891 | 12.612916 | 4 | 301 | 12.3817 | 12.381701 | |
| 138 | 4.326118 | | | 287 | 12.45072 | 12.450716 | |
| 253 | 4.550675 | | | 286 | 12.49338 | 12.493383 | |
| 107 | 4.629469 | 13.506261 | 5 | 295 | 12.84169 | 12.841691 | |
| 246 | 4.646023 | | | 269 | 12.86139 | 12.861386 | |
| 239 | 4.74219 | | | 279 | 13.13106 | 13.131059 | |
| 241 | 5.351957 | 14.740170 | 6 | 278 | 13.14904 | 13.149039 | |
| 232 | 5.365815 | | | 181 | 13.28351 | 13.283509 | |
| 238 | 5.470537 | 10.836351 | 7 | 290 | 13.29647 | 13.296470 | |
| 250 | 5.641463 | | | 263 | 13.38892 | 13.388921 | |
| 248 | 5.750791 | 11.392254 | 8 | 294 | 13.59377 | 13.593765 | |
| 249 | 5.75626 | | | 270 | 13.70899 | 13.708991 | |
| 240 | 6.147876 | 11.904136 | 9 | 182 | 13.85914 | 13.859141 | |
| 234 | 6.347012 | | | 303 | 14.04315 | 14.043145 | |
| 244 | 6.51285 | 12.859861 | 10 | 191 | 14.0687 | 14.068698 | |
| 252 | 6.573138 | | | 173 | 14.42268 | 14.422675 | |
| 247 | 6.944124 | 13.517262 | 11 | 152 | 14.62828 | 14.628278 | |
| 245 | 6.946054 | | | 150 | 15.09271 | 15.092705 | |

Table C. 1 (continued): Drone assignment to distribution points at depot 110 with K=125.

| | | | | | | |
|--|----------|-----------|----|--|----------|-----------|
| 302 | 7.136667 | 14.082720 | 12 | 258 | 15.18604 | 15.186040 |
| 260 | 7.170328 | | | 180 | 15.44742 | 15.447419 |
| 254 | 7.703616 | 14.873944 | 13 | 188 | 15.48189 | 15.481893 |
| 243 | 7.723026 | | | 177 | 15.60538 | 15.605382 |
| 281 | 7.733709 | 15.456734 | 14 | 164 | 15.85598 | 15.855984 |
| 293 | 8.468322 | 8.4683223 | 15 | 154 | 16.08596 | 16.085959 |
| 296 | 8.747954 | 8.7479541 | 16 | | | |
| Total traveled distance = 741.05 km | | | | average distance of the grouped demands = 12.78 | | |
| ND₁₁₀ = 58 | | | | | | |

Table C. 2 Drone assignment to distribution points at depot 160, K=125.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 145 | 0.33213116 | | | 230 | 6.76112909 | | |
| 185 | 0.49320315 | | | 168 | 6.80652566 | 13.5676547 | 41 |
| 169 | 0.94793972 | | | 203 | 7.19265520 | | |
| 171 | 1.05110944 | | | 192 | 7.38090024 | 14.5735554 | 42 |
| 161 | 1.09974084 | | | 156 | 7.42046118 | | |
| 166 | 1.13623628 | | | 226 | 7.57019156 | 14.9906527 | 43 |
| 146 | 1.20636867 | | | 213 | 7.57846431 | | |
| 157 | 1.39517090 | | | 200 | 7.75789182 | 15.3363561 | 44 |
| 158 | 1.57544027 | | | 193 | 7.84095368 | | |
| 174 | 1.58455232 | | | 196 | 7.88766858 | 15.7286222 | 45 |
| 178 | 1.61859053 | | | 220 | 7.91394313 | 7.91394313 | 46 |
| 176 | 1.6570744 | | | 202 | 8.30877088 | 8.30877088 | 47 |
| 184 | 1.82491150 | 15.9224 | 34 | 215 | 8.41529293 | 8.41529293 | 48 |
| 165 | 1.88905152 | | | 214 | 8.51847291 | 8.51847291 | 49 |
| 155 | 1.89620359 | | | 217 | 8.61588641 | 8.61588641 | 50 |
| 183 | 1.95332384 | | | 210 | 8.85839264 | 8.85839264 | 51 |
| 149 | 2.01175009 | | | 198 | 8.85860993 | 8.85860993 | 52 |
| 175 | 2.07241341 | | | 194 | 8.87594155 | 8.87594155 | 53 |
| 163 | 2.26336922 | | | 219 | 9.51161785 | 9.51161785 | 54 |
| 159 | 2.28314652 | 14.36925 | 35 | 221 | 9.82210431 | 9.82210431 | 55 |
| 167 | 2.46878629 | | | 208 | 9.93954664 | 9.93954664 | 56 |
| 162 | 2.57617255 | | | 195 | 10.0468199 | 10.0468199 | 57 |
| 151 | 2.73646178 | | | 201 | 10.7431536 | 10.7431536 | 58 |
| 186 | 2.78800590 | | | 227 | 10.9243108 | 10.9243108 | 59 |
| 148 | 2.88175611 | 13.45118 | 36 | 229 | 11.0223191 | 11.0223191 | 60 |

Table C. 2 (continued): Drone assignment to distribution points at depot 160, K=125.

| | | | | | | | |
|--|------------|----------|----|--|------------|------------|----|
| 147 | 3.08121512 | | | 77 | 11.1260269 | 11.1260269 | 61 |
| 190 | 3.20222468 | | | 216 | 11.2674865 | 11.2674865 | 62 |
| 189 | 3.24581192 | | | 199 | 11.3005618 | 11.3005618 | 63 |
| 153 | 3.31526600 | 12.84451 | 37 | 225 | 11.4565249 | 11.4565249 | 64 |
| 187 | 3.31990456 | | | 204 | 11.9694963 | 11.9694963 | 65 |
| 179 | 3.411813 | | | 205 | 11.9968191 | 11.9968191 | 66 |
| 299 | 3.76394666 | | | 222 | 12.2071738 | 12.2071738 | |
| 256 | 3.97156926 | 14.46723 | 38 | 223 | 12.7469025 | 12.7469025 | |
| 172 | 4.08978930 | | | 209 | 13.1171868 | 13.1171868 | |
| 170 | 5.67577125 | | | 206 | 15.0876384 | 15.0876384 | |
| 224 | 5.69664441 | 15.46220 | 39 | 207 | 15.3007348 | 15.3007348 | |
| 197 | 5.96119152 | | | 206 | 15.0876384 | 15.0876384 | |
| 218 | 6.23881423 | 12.20000 | 40 | 207 | 15.3007348 | 15.3007348 | |
| Total traveled distance = 481.25 km | | | | average distance of the grouped demands | | | |
| ND₁₆₀ = 40 drones | | | | = 12.03 km | | | |

Table C. 3 Drone assignment to distribution points at depot 11, K=125.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 1 | 1.029566 | | | 22 | 4.21707 | | |
| 20 | 0.524885 | | | 265 | 4.247246 | | |
| 40 | 0.900927 | | | 34 | 4.256479 | 12.72079 | 77 |
| 99 | 0.940558 | | | 90 | 4.263515 | | |
| 21 | 1.087386 | | | 2 | 4.307967 | | |
| 36 | 1.253029 | | | 26 | 4.363264 | 12.93474 | 78 |
| 64 | 1.496949 | | | 266 | 4.408615 | | |
| 76 | 1.601259 | | | 267 | 4.411255 | | |
| 38 | 1.61672 | | | 62 | 4.432775 | 13.25264 | 79 |
| 17 | 1.919824 | | | 273 | 4.561889 | | |
| 83 | 2.099707 | 14.470809 | 67 | 275 | 4.562862 | | |
| 67 | 2.120453 | | | 89 | 4.585734 | 13.71048 | 80 |
| 16 | 2.130334 | | | 280 | 4.624107 | | |
| 292 | 2.151641 | | | 30 | 4.632552 | | |
| 13 | 2.151691 | | | 56 | 4.667124 | 13.92378 | 81 |
| 52 | 2.176357 | | | 97 | 4.746332 | | |
| 79 | 2.218029 | | | 65 | 4.832982 | | |
| 86 | 2.249855 | 15.198360 | 68 | 25 | 4.856661 | 14.43597 | 82 |
| 50 | 2.271775 | | | 3 | 4.89077 | | |

Table C. 3 (continued): Drone assignment to distribution points at depot 11, K=125.

| | | | | | | | |
|--|----------|-----------|----|--|----------|----------|----|
| 32 | 2.380085 | | | 69 | 4.910395 | | |
| 85 | 2.534547 | | | 103 | 4.969545 | 14.77071 | 83 |
| 43 | 2.6136 | | | 101 | 4.98675 | | |
| 42 | 2.627011 | | | 91 | 5.020215 | | |
| 94 | 2.655412 | 15.082429 | 69 | 81 | 5.036216 | 15.04318 | 84 |
| 6 | 2.670291 | | | 259 | 5.081307 | | |
| 98 | 2.682978 | | | 102 | 5.08965 | | |
| 48 | 2.685477 | | | 23 | 5.20663 | 15.37758 | 85 |
| 45 | 2.912317 | | | 274 | 5.263879 | | |
| 24 | 3.021209 | 13.972272 | 70 | 31 | 5.327678 | | |
| 68 | 3.1207 | | | 5 | 5.328138 | 15.91969 | 86 |
| 14 | 3.182903 | | | 78 | 5.32842 | | |
| 84 | 3.274413 | | | 75 | 5.36005 | | |
| 12 | 3.279858 | 12.857873 | 71 | 80 | 5.378673 | 16.06714 | 87 |
| 60 | 3.300198 | | | 4 | 5.46847 | | |
| 73 | 3.371415 | | | 29 | 5.706527 | 11.17499 | 88 |
| 82 | 3.383174 | | | 55 | 5.865756 | | |
| 58 | 3.446322 | 13.501109 | 72 | 88 | 5.866062 | 11.73181 | 89 |
| 44 | 3.460771 | | | 9 | 5.891173 | | |
| 51 | 3.630847 | | | 96 | 5.897646 | 11.78881 | 90 |
| 15 | 3.641069 | | | 297 | 5.945224 | | |
| 71 | 3.681489 | 14.414175 | 73 | 298 | 5.96371 | 11.90893 | 91 |
| 262 | 3.744627 | | | 87 | 5.978996 | | |
| 54 | 3.811444 | | | 46 | 6.058189 | 12.03718 | 92 |
| 57 | 3.872605 | | | 93 | 6.15515 | | |
| 18 | 3.906955 | 15.335631 | 74 | 74 | 6.2428 | 12.39794 | 93 |
| 59 | 3.933211 | | | 61 | 6.338937 | | |
| 49 | 3.984945 | | | 8 | 6.464507 | 12.80344 | 94 |
| 47 | 3.98871 | | | 271 | 6.559312 | | |
| 19 | 4.044734 | 15.951599 | 75 | 27 | 6.586132 | 13.14544 | 95 |
| 33 | 4.0706 | | | 272 | 6.912562 | | |
| 53 | 4.079912 | | | 288 | 6.94594 | 13.85850 | 96 |
| 66 | 4.126257 | 12.276767 | 76 | | | | |
| Total traveled distance = 412.06 km | | | | average distance of the grouped demands | | | |
| ND₁₄₂ = 30 drones | | | | = 13.74 km | | | |

Table C. 4 Drone assignment to distribution points at depot 142, K=125.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|--|------------------|---------------------------|-------------------|--|------------------|---------------------------|-------------------|
| 7 | 3.560428 | | | 139 | 10.32572 | 10.32571876 | 110 |
| 92 | 4.57816 | | | 114 | 10.50034 | 10.50033766 | 111 |
| 100 | 6.896885 | 15.03547228 | 97 | 137 | 10.62507 | 10.62506976 | 112 |
| 28 | 7.761518 | | | 136 | 10.71106 | 10.71105679 | 113 |
| 10 | 8.009987 | 15.771505 | 98 | 113 | 11.16093 | 11.16092895 | 114 |
| 35 | 8.319364 | 8.319363712 | 99 | 112 | 11.41348 | 11.41348028 | 115 |
| 63 | 8.44259 | 8.442590053 | 100 | 124 | 12.15728 | 12.15728474 | 116 |
| 39 | 8.443693 | 8.44369273 | 101 | 111 | 12.71769 | 12.71769278 | 117 |
| 70 | 9.296853 | 9.296853452 | 102 | 133 | 14.26204 | 14.26203951 | 118 |
| 41 | 9.361095 | 9.361094869 | 103 | 129 | 14.71819 | 14.71819437 | 119 |
| 116 | 9.482053 | 9.482052625 | 104 | 37 | 15.08 | 15.08000212 | 120 |
| 72 | 9.60406 | 9.604059993 | 105 | 108 | 15.19666 | 15.19665955 | 121 |
| 140 | 9.730231 | 9.730230996 | 106 | 109 | 15.55212 | 15.55211835 | 122 |
| 141 | 9.892243 | 9.892242516 | 107 | 132 | 15.72287 | 15.72287109 | 123 |
| 95 | 10.14738 | 10.14737611 | 108 | 125 | 15.77313 | 15.77312517 | 124 |
| 143 | 10.21158 | 10.21157947 | 109 | 105 | 16.04218 | 16.04217645 | 125 |
| Total traveled distance = 345.69 km | | | | average distance of the grouped demands | | | |
| ND₁₄₂ = 29 drones | | | | = 11.92 km | | | |

Appendix D – Drone assignment to distribution points at allocated depots with K = 150.

Table D. 1 Drone assignment to distribution points at depot 110 with K=150.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 104 | 0.90797 | | | 285 | 8.872008 | 8.8720078 | 17 |
| 128 | 1.408823 | | | 235 | 9.104503 | 9.1045027 | 18 |
| 134 | 1.811454 | | | 242 | 9.992435 | 9.9924351 | 19 |
| 122 | 2.085668 | | | 276 | 10.51955 | 10.519551 | 20 |
| 106 | 2.228222 | | | 277 | 10.60014 | 10.600136 | 21 |
| 123 | 2.632298 | | | 231 | 10.74267 | 10.742668 | 22 |
| 126 | 2.835145 | 13.909579 | 1 | 236 | 10.7722 | 10.772204 | 23 |
| 130 | 2.861748 | | | 283 | 11.08282 | 11.082821 | 24 |
| 117 | 2.912718 | | | 255 | 11.1332 | 11.133196 | 25 |
| 135 | 3.294408 | | | 257 | 11.21877 | 11.218769 | 26 |
| 127 | 3.384857 | | | 237 | 11.22873 | 11.228734 | 27 |
| 120 | 3.532965 | 15.986695 | 2 | 304 | 11.28828 | 11.288278 | 28 |
| 119 | 3.552484 | | | 291 | 11.3133 | 11.313302 | 29 |
| 118 | 3.577964 | | | 300 | 11.41748 | 11.417479 | 30 |
| 131 | 3.619225 | | | 282 | 11.71372 | 11.713719 | 31 |
| 121 | 3.680577 | 14.430250 | 3 | 284 | 12.03506 | 12.035057 | 32 |
| 261 | 4.051787 | | | 268 | 12.04994 | 12.049943 | 33 |
| 264 | 4.279239 | | | 289 | 12.27992 | 12.279922 | 34 |
| 115 | 4.281891 | 12.612916 | 4 | 301 | 12.3817 | 12.381701 | 35 |
| 138 | 4.326118 | | | 287 | 12.45072 | 12.450716 | 36 |
| 253 | 4.550675 | | | 286 | 12.49338 | 12.493383 | 37 |
| 107 | 4.629469 | 13.506261 | 5 | 295 | 12.84169 | 12.841691 | 38 |
| 246 | 4.646023 | | | 269 | 12.86139 | 12.861386 | 39 |
| 239 | 4.74219 | | | 279 | 13.13106 | 13.131059 | 40 |
| 241 | 5.351957 | 14.740170 | 6 | 278 | 13.14904 | 13.149039 | 41 |
| 232 | 5.365815 | | | 181 | 13.28351 | 13.283509 | 42 |
| 238 | 5.470537 | 10.836351 | 7 | 290 | 13.29647 | 13.296470 | 43 |
| 250 | 5.641463 | | | 263 | 13.38892 | 13.388921 | 44 |
| 248 | 5.750791 | 11.392254 | 8 | 294 | 13.59377 | 13.593765 | 45 |
| 249 | 5.75626 | | | 270 | 13.70899 | 13.708991 | 46 |
| 240 | 6.147876 | 11.904136 | 9 | 182 | 13.85914 | 13.859141 | 47 |
| 234 | 6.347012 | | | 303 | 14.04315 | 14.043145 | 48 |
| 244 | 6.51285 | 12.859861 | 10 | 191 | 14.0687 | 14.068698 | 49 |
| 252 | 6.573138 | | | 173 | 14.42268 | 14.422675 | 50 |
| 247 | 6.944124 | 13.517262 | 11 | 152 | 14.62828 | 14.628278 | 51 |
| 245 | 6.946054 | | | 150 | 15.09271 | 15.092705 | |

Table D. 1 (continued): Drone assignment to distribution points at depot 110 with K=150.

| | | | | | | |
|--|----------|-----------|----|--|----------|-----------|
| 302 | 7.136667 | 14.082720 | 12 | 258 | 15.18604 | 15.186040 |
| 260 | 7.170328 | | | 180 | 15.44742 | 15.447419 |
| 254 | 7.703616 | 14.873944 | 13 | 188 | 15.48189 | 15.481893 |
| 243 | 7.723026 | | | 177 | 15.60538 | 15.605382 |
| 281 | 7.733709 | 15.456734 | 14 | 164 | 15.85598 | 15.855984 |
| 293 | 8.468322 | 8.4683223 | 15 | 154 | 16.08596 | 16.085959 |
| 296 | 8.747954 | 8.7479541 | 16 | | | |
| Total traveled distance = 741.05 km | | | | average distance of the grouped demands | | |
| ND₁₁₀ = 58 | | | | = 12.78 | | |

Table D. 2 Drone assignment to distribution points at depot 160, K=150.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 145 | 0.33213116 | | | 230 | 6.76112909 | | |
| 185 | 0.49320315 | | | 168 | 6.80652566 | 13.5676547 | 59 |
| 169 | 0.94793972 | | | 203 | 7.19265520 | | |
| 171 | 1.05110944 | | | 192 | 7.38090024 | 14.5735554 | 60 |
| 161 | 1.09974084 | | | 156 | 7.42046118 | | |
| 166 | 1.13623628 | | | 226 | 7.57019156 | 14.9906527 | 61 |
| 146 | 1.20636867 | | | 213 | 7.57846431 | | |
| 157 | 1.39517090 | | | 200 | 7.75789182 | 15.3363561 | 62 |
| 158 | 1.57544027 | | | 193 | 7.84095368 | | |
| 174 | 1.58455232 | | | 196 | 7.88766858 | 15.7286222 | 63 |
| 178 | 1.61859053 | | | 220 | 7.91394313 | 7.91394313 | 64 |
| 176 | 1.6570744 | | | 202 | 8.30877088 | 8.30877088 | 65 |
| 184 | 1.82491150 | 15.9224 | 52 | 215 | 8.41529293 | 8.41529293 | 66 |
| 165 | 1.88905152 | | | 214 | 8.51847291 | 8.51847291 | 67 |
| 155 | 1.89620359 | | | 217 | 8.61588641 | 8.61588641 | 68 |
| 183 | 1.95332384 | | | 210 | 8.85839264 | 8.85839264 | 69 |
| 149 | 2.01175009 | | | 198 | 8.85860993 | 8.85860993 | 70 |
| 175 | 2.07241341 | | | 194 | 8.87594155 | 8.87594155 | 71 |
| 163 | 2.26336922 | | | 219 | 9.51161785 | 9.51161785 | 72 |
| 159 | 2.28314652 | 14.36925 | 53 | 221 | 9.82210431 | 9.82210431 | 73 |
| 167 | 2.46878629 | | | 208 | 9.93954664 | 9.93954664 | 74 |
| 162 | 2.57617255 | | | 195 | 10.0468199 | 10.0468199 | 75 |
| 151 | 2.73646178 | | | 201 | 10.7431536 | 10.7431536 | 76 |
| 186 | 2.78800590 | | | 227 | 10.9243108 | 10.9243108 | 77 |
| 148 | 2.88175611 | 13.45118 | 54 | 229 | 11.0223191 | 11.0223191 | 78 |

Table D. 2 (continued): Drone assignment to distribution points at depot 160, K=150

| | | | | | | | |
|--|------------|----------|----|--|------------|------------|----|
| 147 | 3.08121512 | | | 77 | 11.1260269 | 11.1260269 | 79 |
| 190 | 3.20222468 | | | 216 | 11.2674865 | 11.2674865 | 80 |
| 189 | 3.24581192 | | | 199 | 11.3005618 | 11.3005618 | 81 |
| 153 | 3.31526600 | 12.84451 | 55 | 225 | 11.4565249 | 11.4565249 | 82 |
| 187 | 3.31990456 | | | 204 | 11.9694963 | 11.9694963 | 83 |
| 179 | 3.411813 | | | 205 | 11.9968191 | 11.9968191 | 84 |
| 299 | 3.76394666 | | | 222 | 12.2071738 | 12.2071738 | 85 |
| 256 | 3.97156926 | 14.46723 | 56 | 223 | 12.7469025 | 12.7469025 | 86 |
| 172 | 4.08978930 | | | 209 | 13.1171868 | 13.1171868 | 87 |
| 170 | 5.67577125 | | | 206 | 15.0876384 | 15.0876384 | 88 |
| 224 | 5.69664441 | 15.46220 | 57 | 207 | 15.3007348 | 15.3007348 | 89 |
| 197 | 5.96119152 | | | 206 | 15.0876384 | 15.0876384 | 90 |
| 218 | 6.23881423 | 12.20000 | 58 | 207 | 15.3007348 | 15.3007348 | 91 |
| Total traveled distance = 481.25 km | | | | average distance of the grouped demands | | | |
| ND₁₆₀ = 40 drones | | | | = 12.03 km | | | |

Table D. 3 Drone assignment to distribution points at depot 11, K=150.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|-----------|------------------|---------------------------|-------------------|-----------|------------------|---------------------------|-------------------|
| 1 | 1.029566 | | | 22 | 4.21707 | | |
| 20 | 0.524885 | | | 265 | 4.247246 | | |
| 40 | 0.900927 | | | 34 | 4.256479 | 12.72079 | 102 |
| 99 | 0.940558 | | | 90 | 4.263515 | | |
| 21 | 1.087386 | | | 2 | 4.307967 | | |
| 36 | 1.253029 | | | 26 | 4.363264 | 12.93474 | 103 |
| 64 | 1.496949 | | | 266 | 4.408615 | | |
| 76 | 1.601259 | | | 267 | 4.411255 | | |
| 38 | 1.61672 | | | 62 | 4.432775 | 13.25264 | 104 |
| 17 | 1.919824 | | | 273 | 4.561889 | | |
| 83 | 2.099707 | 14.470809 | 92 | 275 | 4.562862 | | |
| 67 | 2.120453 | | | 89 | 4.585734 | 13.71048 | 105 |
| 16 | 2.130334 | | | 280 | 4.624107 | | |
| 292 | 2.151641 | | | 30 | 4.632552 | | |
| 13 | 2.151691 | | | 56 | 4.667124 | 13.92378 | 106 |
| 52 | 2.176357 | | | 97 | 4.746332 | | |
| 79 | 2.218029 | | | 65 | 4.832982 | | |
| 86 | 2.249855 | 15.198360 | 93 | 25 | 4.856661 | 14.43597 | 107 |
| 50 | 2.271775 | | | 3 | 4.89077 | | |

Table D. 3 (continued): Drone assignment to distribution points at depot 11, K=150.

| | | | | | | | |
|--|----------|-----------|-----|--|----------|----------|-----|
| 32 | 2.380085 | | | 69 | 4.910395 | | |
| 85 | 2.534547 | | | 103 | 4.969545 | 14.77071 | 108 |
| 43 | 2.6136 | | | 101 | 4.98675 | | |
| 42 | 2.627011 | | | 91 | 5.020215 | | |
| 94 | 2.655412 | 15.082429 | 94 | 81 | 5.036216 | 15.04318 | 109 |
| 6 | 2.670291 | | | 259 | 5.081307 | | |
| 98 | 2.682978 | | | 102 | 5.08965 | | |
| 48 | 2.685477 | | | 23 | 5.20663 | 15.37758 | 110 |
| 45 | 2.912317 | | | 274 | 5.263879 | | |
| 24 | 3.021209 | 13.972272 | 95 | 31 | 5.327678 | | |
| 68 | 3.1207 | | | 5 | 5.328138 | 15.91969 | 111 |
| 14 | 3.182903 | | | 78 | 5.32842 | | |
| 84 | 3.274413 | | | 75 | 5.36005 | | |
| 12 | 3.279858 | 12.857873 | 96 | 80 | 5.378673 | 16.06714 | 112 |
| 60 | 3.300198 | | | 4 | 5.46847 | | |
| 73 | 3.371415 | | | 29 | 5.706527 | 11.17499 | 113 |
| 82 | 3.383174 | | | 55 | 5.865756 | | |
| 58 | 3.446322 | 13.501109 | 97 | 88 | 5.866062 | 11.73181 | 114 |
| 44 | 3.460771 | | | 9 | 5.891173 | | |
| 51 | 3.630847 | | | 96 | 5.897646 | 11.78881 | 115 |
| 15 | 3.641069 | | | 297 | 5.945224 | | |
| 71 | 3.681489 | 14.414175 | 98 | 298 | 5.96371 | 11.90893 | 116 |
| 262 | 3.744627 | | | 87 | 5.978996 | | |
| 54 | 3.811444 | | | 46 | 6.058189 | 12.03718 | 117 |
| 57 | 3.872605 | | | 93 | 6.15515 | | |
| 18 | 3.906955 | 15.335631 | 99 | 74 | 6.2428 | 12.39794 | 118 |
| 59 | 3.933211 | | | 61 | 6.338937 | | |
| 49 | 3.984945 | | | 8 | 6.464507 | 12.80344 | 119 |
| 47 | 3.98871 | | | 271 | 6.559312 | | |
| 19 | 4.044734 | 15.951599 | 100 | 27 | 6.586132 | 13.14544 | 120 |
| 33 | 4.0706 | | | 272 | 6.912562 | | |
| 53 | 4.079912 | | | 288 | 6.94594 | 13.85850 | 121 |
| 66 | 4.126257 | 12.276767 | 101 | | | | |
| Total traveled distance = 412.06 km | | | | average distance of the grouped demands | | | |
| ND₁₄₂ = 30 drones | | | | = 13.74 km | | | |

Table D. 4 Drone assignment to distribution points at depot 142, K=150.

| Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID | Demand ID | Sorted Distances | Grouped Distances < 16.09 | Assigned Drone ID |
|--|------------------|---------------------------|-------------------|---|------------------|---------------------------|-------------------|
| 7 | 3.560428 | | | 139 | 10.32572 | 10.32571876 | 135 |
| 92 | 4.57816 | | | 114 | 10.50034 | 10.50033766 | 136 |
| 100 | 6.896885 | 15.03547228 | 122 | 137 | 10.62507 | 10.62506976 | 137 |
| 28 | 7.761518 | | | 136 | 10.71106 | 10.71105679 | 138 |
| 10 | 8.009987 | 15.771505 | 123 | 113 | 11.16093 | 11.16092895 | 139 |
| 35 | 8.319364 | 8.319363712 | 124 | 112 | 11.41348 | 11.41348028 | 140 |
| 63 | 8.44259 | 8.442590053 | 125 | 124 | 12.15728 | 12.15728474 | 141 |
| 39 | 8.443693 | 8.44369273 | 126 | 111 | 12.71769 | 12.71769278 | 142 |
| 70 | 9.296853 | 9.296853452 | 127 | 133 | 14.26204 | 14.26203951 | 143 |
| 41 | 9.361095 | 9.361094869 | 128 | 129 | 14.71819 | 14.71819437 | 144 |
| 116 | 9.482053 | 9.482052625 | 129 | 37 | 15.08 | 15.08000212 | 145 |
| 72 | 9.60406 | 9.604059993 | 130 | 108 | 15.19666 | 15.19665955 | 146 |
| 140 | 9.730231 | 9.730230996 | 131 | 109 | 15.55212 | 15.55211835 | 147 |
| 141 | 9.892243 | 9.892242516 | 132 | 132 | 15.72287 | 15.72287109 | 148 |
| 95 | 10.14738 | 10.14737611 | 133 | 125 | 15.77313 | 15.77312517 | 149 |
| 143 | 10.21158 | 10.21157947 | 134 | 105 | 16.04218 | 16.04217645 | 150 |
| Total traveled distance = 345.69 km | | | | average distance of the grouped demands = 11.92 km | | | |
| ND₁₄₂ = 29 drones | | | | | | | |

Appendix E – Districts and population information of Ankara Province.

Table E. 1 Numerical information about the settlement and population of Ankara province and its districts at the end of 2019.





| | | Population 2019 | Area (km ²) |
|---|------------------|------------------|-------------------------|
| ANKARA | | 5,639,076 | 25,632 |
| Place of the Map | Districts | | |
|  | Akyurt | 36,123 | 369 |
|  | Altındağ | 389,510 | 123 |
|  | Ayaş | 13,900 | 1,041 |
|  | Balâ | 30,280 | 1,851 |

Table E. 2 (continued): Numerical information about the settlement and population of Ankara province and its districts at the end of 2019.

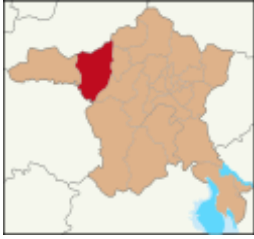




| | | | |
|---|-----------|---------|-------|
|  | Beypazari | 48,371 | 1,697 |
|  | Çamlıdere | 9,825 | 782 |
|  | Çankaya | 944,609 | 483 |
|  | Çubuk | 90,764 | 1,198 |
|  | Elmadağ | 45,557 | 647 |

Table E. 3 (continued): Numerical information about the settlement and population of Ankara province and its districts at the end of 2019.





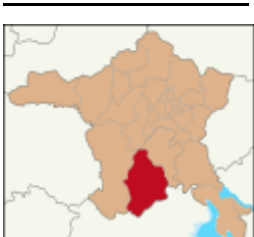
| | | | |
|---|------------------|----------------|-------|
|  | Etimesgut | 587,052 | 273 |
|  | Evren | 3,097 | 222 |
|  | Gölbaşı | 138,944 | 1,364 |
|  | Güdül | 8,892 | 540 |
|  | Haymana | 30,930 | 2,164 |

Table E. 4 (continued): Numerical information about the settlement and population of Ankara province and its districts at the end of 2019.






| | | | |
|---|-----------------|----------------|-------|
|  | Kahramankazan | 54,806 | 547 |
|  | Kalecik | 13,234 | 1,110 |
|  | Keçiören | 939,161 | 159 |
|  | Kızılcahamam | 28,350 | 1,623 |
|  | Mamak | 665,978 | 321 |

Table E. 5 (continued): Numerical information about the settlement and population of Ankara province and its districts at the end of 2019.




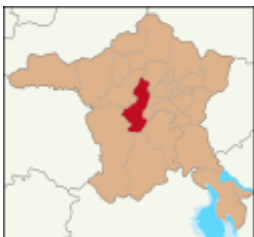
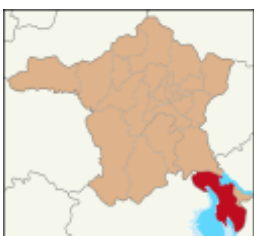

| | | | |
|---|-----------------|---------|-------|
|  | Nallıhan | 27,579 | 2,079 |
|  | Polatlı | 125,075 | 3,618 |
|  | Pursaklar | 150,488 | 169 |
|  | Sincan | 535,637 | 880 |
|  | Şereflikoçhisar | 33,821 | 2,155 |

Table E. 6 (continued): Numerical information about the settlement and population of Ankara province and its districts at the end of 2019.

| | | | |
|---|--------------------|----------------|-----|
|  | Yenimahalle | 687,093 | 219 |
|---|--------------------|----------------|-----|

TurkStat, The Results of Address Based Population Registration System, 2019 [33, 34].



CURRICULUM VITAE

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- Sales and Marketing
- Supply Chain
- Humanitarian Aid