Open-Loop Reverse Logistics Network Design of Waste of Electric and Electronic Equipment by Consideration of Hazardous Materials

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ABSTRACT

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In developed countries, technology has become an inseparable part of people's lives. While it is changing in a rapid pace, people are intensely eager to own its latest versions. This insatiable demand for technological equipment results in creating the world's fastest-growing waste stream called "Waste of Electrical and electronic equipment(WEEE)". Due to limited resources of the materials used in the components of WEEE and the risk that is exposed to the environment caused by some hazardous material included in, it is intensively needed to design a WEEE recovery system. In this thesis, we aim to make use of reverse logistics to design a network, which enables us to benefit from the recycling of valuable materials and diminish the environmental risk of hazardous material by treating and recycling. We are planning to decide on the location of facilities and the flows between the related points under different scenarios.

Keywords: Open-loop, Reverse Logistics, Network Design, WEEE, Scenarios, MILP Facility Location Model

ÖZ

AÇIK-DÖNGÜ TERS LOJİSTİK TEHLİKELİ MALZEMELER DİKKATA ALINARAK ELEKTRİK VE ELEKTRONİK EKİPMANLARIN ATIK AĞI TASARIMI

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Teknoloji gelişmiş ülkelerde insanların yaşamlarının ayrılmaz bir parçası haline gelmiştir. Ayrıca, bu durum hızlı bir şekilde değişirken, insanlar da buna yetişmeye çalışıyor. Bu teknolojik aletlere duyulan doyumsuz talep, "Elektrikli ve elektronik ekipman atıkları (EEEA)" olarak adlandırılan, dünyanın en hızlı büyüyen atık akışını oluşturuyor. EEEA bileşenlerinde kullanılan malzemelerin sınırlı kaynakları ve içerdiği bazı tehlikeli maddelerden dolayı çevreyi maruz bıraktığı risk nedeniyle, bir EEEA geri kazanım sistemi tasarlanması için ihtiyaç duyulmaktadır. Bu tezde, değerli malzemelerin geri dönüşümünden faydalanmamızı ve tehlikeli malzemelerin çevresel riskini arıtıp geri dönüştürerek azaltmamızı sağlayan bir ağ oluşturmak için tersine lojistikten yararlanmayı hedefliyoruz. Tesislerin kurulacağı yere ve farklı senaryolar geliştirerek ilgili noktalar arasındaki akışlara karar vermeyi planlıyoruz.

Anahtar Kelimeler: Açık döngü, Tersine Lojistik, Ağ Tasarımı, EEEA, Senaryolar, KİLP Tesisi Yerleşim Modeli

To the soul of my one and only hero, Daddy…

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TABLE OF CONTENTS

ABSTRACT v

ÖZ vii

ACKNOWLEDGEMENTS ix

TABLE OF CONTENTS x

LIST OF TABLES xiii

LIST OF FIGURES xv

LIST OF ABBREVIATIONS xvii

1. INTRODUCTION 1

2. Literature review 3

2.1. Basic information about reverse logistics and WEEE 3

2.1.1. Reverse Logistics (RL) 3

2.1.2. Waste of Electronic and Electrical Equipment 3

2.2. Structure of Literature on Reverse Logistics Network Design for WEEE 5

2.3. Literature review of "Open-Loop Reverse Logistics Network Design" 7

2.3.1. Location-Allocation 8

2.3.2. Product Recovery 13

2.3.3. Cost 15

2.3.4. Secondary market 18

3. PROBLEM STATEMENT and MODELING 21

3.1. Network Representation 21

3.2. Model Explanation and Mathematical Formulation 27

3.2.1. Objectives and Decision Variables 27

3.2.2. The Model and Parameters 27
4. COMPUTATIONAL STUDIES 39
4.1. Data Description..39
4.1.1. Data related with collection points 39
4.1.2. Data related with storage sites 41
4.1.3. Data related with WEEE-recycling facilities..43
4.1.4. Data related with secondary markets 45
4.1.5. Data related with treatment facilities and hazardous material recycling facilities..46
4.1.5.1. Properties of treatment facilities 46
4.1.5.2. Properties of hazardous material recycling facilities 47
4.2. Computational results and discussion 48
4.2.1. Definition of scenarios..48
4.2.2. The results for scenarios with 20% collection rate 49
4.2.3. The results for scenarios with 50% collection rate 52
4.2.4. The results for scenarios with 70% collection rate 55
4.2.5. The results for scenarios with 100% collection rate 60
4.3. Evaluating the environmental aspect of the proposed network..64
4.3.1. The results for scenarios with 20% collection rate 65
4.3.2. The results for scenarios with 50% collection rate 67
4.3.3. The results for scenarios with 70% collection rate 69
4.3.4. The results for scenarios with 100% collection rate 71
4.4. Summary of the chapter 73
5. Conclusion and future work..77

REFERENCES 79
A. Population information of Turkey 87
B. The results of optimum solution 88
C. CPLEX code 91
CURRICULUM VITAE 97

LIST OF TABLES

TABLES

Table 3.1 Types of facilities used in the suggested network.....................................22

Table 3.2 “Global Warming Potential, GWP” and “Ozone Depleting Potential, ODP” of some of refrigerants. (Devotta, S., Asthana, S., & Joshi, R., 2004) 24

Table 4.1 Types and Capacities information of storage sites....................................42

Table 4.2 Minimum recycling rates, volume, and transportation cost of product categories 42

Table 4.3 Fixed and variable costs of storage sites...42

Table 4.4 Candidate locations, types, and Minimum/Maximum capacity of WEEE-recycling facilities 44

Table 4.5 Annual fixed costs and processing costs of different types of WEEE-recycling facilities 44

Table 4.6 Market location for each type of useful material 45

Table 4.7 Compatibility of useful materials with secondary markets........................45

Table 4.8 Revenue and transportation cost of useful materials 45

Table 4.9 Properties of treatment facilities and hazardous materials.........................46

Table 4.10 Capacity and cost information of Haz-Mat recycling facilities 47

Table 4.11 Parameters of scenarios...48

Table 4.12 Results of scenarios with collection rate of 20% 51

Table 4.13 Results of scenarios with collection rate of 50% 54

Table 4.14 Results of scenarios with collection rate of 70% 57

Table 4.15 Results of scenarios with collection rate of 70% (continued)..................58

Table 4.16 comparison of costs for two different locations when collection rate is 70% 59

Table 4.17 Results of scenarios with collection rate of 100% 62

Table 4.18 Results of scenarios with collection rate of 100% (continued)................63

Table 4.19 The fixed cost of opening HRs at recently added candidate locations in new dataset....65
Table 4.20 Comparisons of selected facilities in old and new datasets for collection rate 20%....66
Table 4.21 Comparisons of results in old and new datasets for collection rate 20%.66
Table 4.22 Comparisons of selected facilities in old and new datasets for collection rate 50%....68
Table 4.23 Comparisons of results in old and new datasets for collection rate 50%.68
Table 4.24 Comparisons of selected facilities in old and new datasets for collection rate 70%....70
Table 4.25 Comparisons of results in old and new datasets for collection rate 70%.70
Table 4.26 Comparisons of selected facilities in old and new datasets for collection rate 100%....72
Table 4.27 Comparisons of results in old and new datasets for collection rate 100%. 72
Table 4.28 Summery of effect of HR performance on the facilities of network for different collection rates. 75

LIST OF FIGURES

FIGURES

Figure 2.1 Distribution of articles in the literature..5
Figure 2.2 Categories of RL and CLSC studies in the literature 6
Figure 2.3 Sub-categories of Open-Loop Network design 7
Figure 3.1 The reverse logistics network of WEEE in Turkey designed by (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015) 24
Figure 3.2 The extension of suggested network..25
Figure 3.3 Flows of different types of materials in the suggested network 26
Figure 4.1 WEEE generation estimation in Turkey. 41
Figure 4.2 Map of candidate locations for storage sites..43
Figure 4.3 Map of candidate locations for WEEE-recycling facilities 44
Figure 4.4 Candidate locations of Haz-Mat recycling, and treatment facilities.........47
Figure 4.5 The map of the results for collection rate 20%, HR 20%, TR (10%, 30%, 90%) 50
Figure 4.6 The map of the results for collection rate 20%, HR (50%, 90%), TR (10%, 30% ,90%)...50
Figure 4.7 The map of the results for collection rate 50%, HR (20%, 50%), TR (10%, 30%, 90%)...53
Figure 4.8 The map of the results for collection rate 50%, HR 90%, TR (10%, 30%, 90%) 53
Figure 4.9 The map of the results for collection rate 70% HR 20%, TR (10%, 30%, 90%) 56
Figure 4.10 The map of the results for collection rate 70% HR 50%, TR (10%, 30%, 90%) 56
Figure 4.11 The map of the results for collection rate 70% HR 90%, TR (10%, 30%, 90%) 56

Figure 4.12 The map of results for collection rate 100%, HR 20%, TR (10%, 30%, 90%)..61
Figure 4.13 The map of results for collection rate 100%, HR (50%, 90%), TR (10%, 30%, 90%)..61

LIST OF ABBREVIATIONS

ABBREVIATIONS

RL: Reverse Logistics

WEEE: Waste of Electric, and Electronic Equipment

RLND: Reverse Logistic Network Design

Haz-Mat: Hazardous Materials

WR: WEEE-Recycling Facility

HR: Hazardous Material Recycling facility

TR: Treatment Facility

CHAPTER 1

INTRODUCTION

This thesis provides a reverse logistics network design for WEEE in Turkey. It considers the effect of hazardous material by considering the processes which are used to treat or recycle it. To the best of our knowledge there is no study working on this aspect of the network, hazardous material treatment facilities are considered in some of the studies but none of them focuses on the processes and the performance of them. In this thesis we consider 9 types of facilities:

1. Generation points
2. Collection points
3. Storage sites
4. WEEE-recycling facilities
5. Fictitious separation point
6. Secondary markets
7. Treatment facilities
8. Hazardous material recycling facilities
9. Disposals.

In order to see the effect of hazardous materials on the network, we consider 36 scenarios by changing 3 parameters related to hazardous material part including the rates used in treatment and hazardous material recycling facility. Based on these scenarios, we get able to check how hazardous material related part can affect the location of other facilities and the objective function. A single-objective Mixed Integer Linear Programming model (MILP) is used to design the network and coded in OPL. We use CPLEX to solve this optimization problem.

This thesis is organized as follows: the second chapter categorizes the studies concerning WEEE-reverse logistics and reviews the literature about Open-Loop

Reverse Logistics Network Design of WEEE. The third chapter defines the problem. It includes the definition of parameters and the model. It also provides detailed definition of objective and constraints. The fourth chapter describes the parameters and gives their values. It provides a detailed explanation of scenarios which are considered to evaluate the effect of hazardous materials on the network. Additionally, it gives result of different scenarios and analyses them and briefly. The last part of this chapter briefly describes the study and provides a summary of obtained results. The fifth chapter also gives some advices about the extensions that can be implemented in this study as a future work.

CHAPTER 2

LITERATURE REVIEW

2.1. Basic information about reverse logistics and WEEE

Nowadays, by population growth and intensification of consumerism, the number of used products increases. It results in declination of natural resources which are utilized in production of them (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015). These are some challenging problems in our current modern world, and finding a solution to them is getting crucial. Reverse logistic is a concept which helps us to recover and restore the used products, and to overcome the above-mentioned problems.

2.1.1. Reverse Logistics (RL)

Traditionally reverse logistics is defined as recycling process (Krumwiede, D. W., & Sheu, C., 2002). The definition of RL according to (Stock, J. R., 1992) refers to "the term often used for the role of logistics in recycling, waste disposal, and management of hazardous materials, a broader perspective includes all issues relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials, and disposal". Its more professional definition is provided by the Council of Logistics Management. It defines "Reverse Logistics" as "the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal".

2.1.2. Waste of Electronic and Electrical Equipment

"Electrical and Electronic Equipment" or "EEE" means "equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer, and measurement of such currents and fields falling under the categories set out in 10 categories, and designed for use with a voltage rating not exceeding 1000 Volt for alternating current, and 1500 Volt for direct current" (EC Directive 2002). The mentioned categories are as follows:

- Large household appliances
- Small household appliances
- IT and telecommunications equipment
- Consumer equipment
- Lighting equipment
- Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
- Toys, leisure, and sports equipment
- Medical devices (with the exception of all implanted and infected products)
- Monitoring and control instruments
- Automatic dispensers

EEE is one of the fastest growing product types (R. Hischier, 2005). Consequently, waste of electrical and electronic equipment or WEEE is expected to grow extremely fast in the future. Its current rate of growth is 3-5% per year (Afroz, R., Masud, M. M., Akhtar, R., & Duasa, J. B., 2013). Intending to be capable of confronting that kind of waste stream, several countries have issued some environmental regulations (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015). For instance, in Taiwan, a "Scrap Home Appliances and Computers Recycling Regulation" is announced by the Environmental Protection Administration (EPA) in March in 1998. According to that, manufacturers and importers should take back their products (Shih, L. H., 2001). Besides, China also has started to legislate and issue some regulations related to e-waste management from a couple of years ago. The first regulation that is set by Ministry of Environmental Protection is "Notification on Importation of the Seventh Category Waste", which is effective from February 1, 2000. There is another environmental regulation, which is implemented in Europe by WEEE (EC Directive 2002). This directive provides many information in order to achieve some major objectives which are indicated as: “The purpose of this Directive is, as a priority, the prevention of waste electrical and electronic equipment (WEEE), and in addition, the reuse, recycling, and other forms of recovery of such wastes so as to reduce the disposal of waste. It also seeks to improve the environmental performance of all operators involved in the life cycle of electrical and electronic equipment, e.g. producers, distributors, and consumers; and in particular those operators directly involved in the treatment of waste electrical and electronic equipment.” (EC Directive 2002)

2.2. Structure of Literature on Reverse Logistics Network Design for WEEE

Based on the classification proposed by (Islam, M. T., & Huda, N., 2018) the literature of the reverse logistic and closed-loop supply chain of WEEE is studied under four major categories as given in Figure 2.1. The categories are designing and planning of reverse distribution, decision making and performance evaluation, qualitative studies, and conceptual frameworks. Designing and Planning of Reverse Distribution (DPRP) with 55% contribution in the literature is the category which is studied the most. Each category is also divided into some sub-categories which are shown on Figure 2.2.

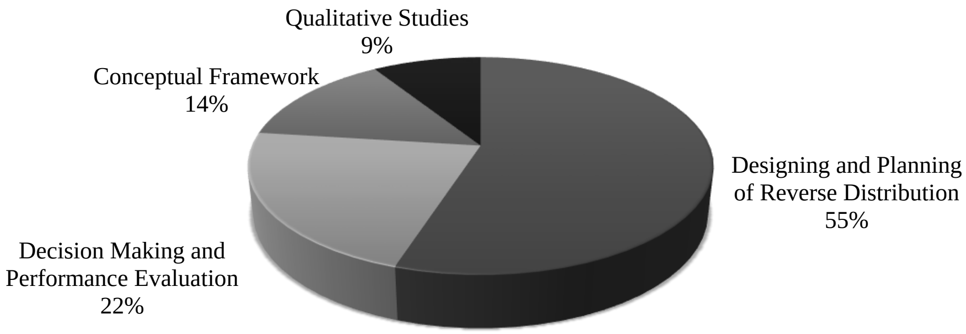

Figure 2.1 Distribution of articles in the literature

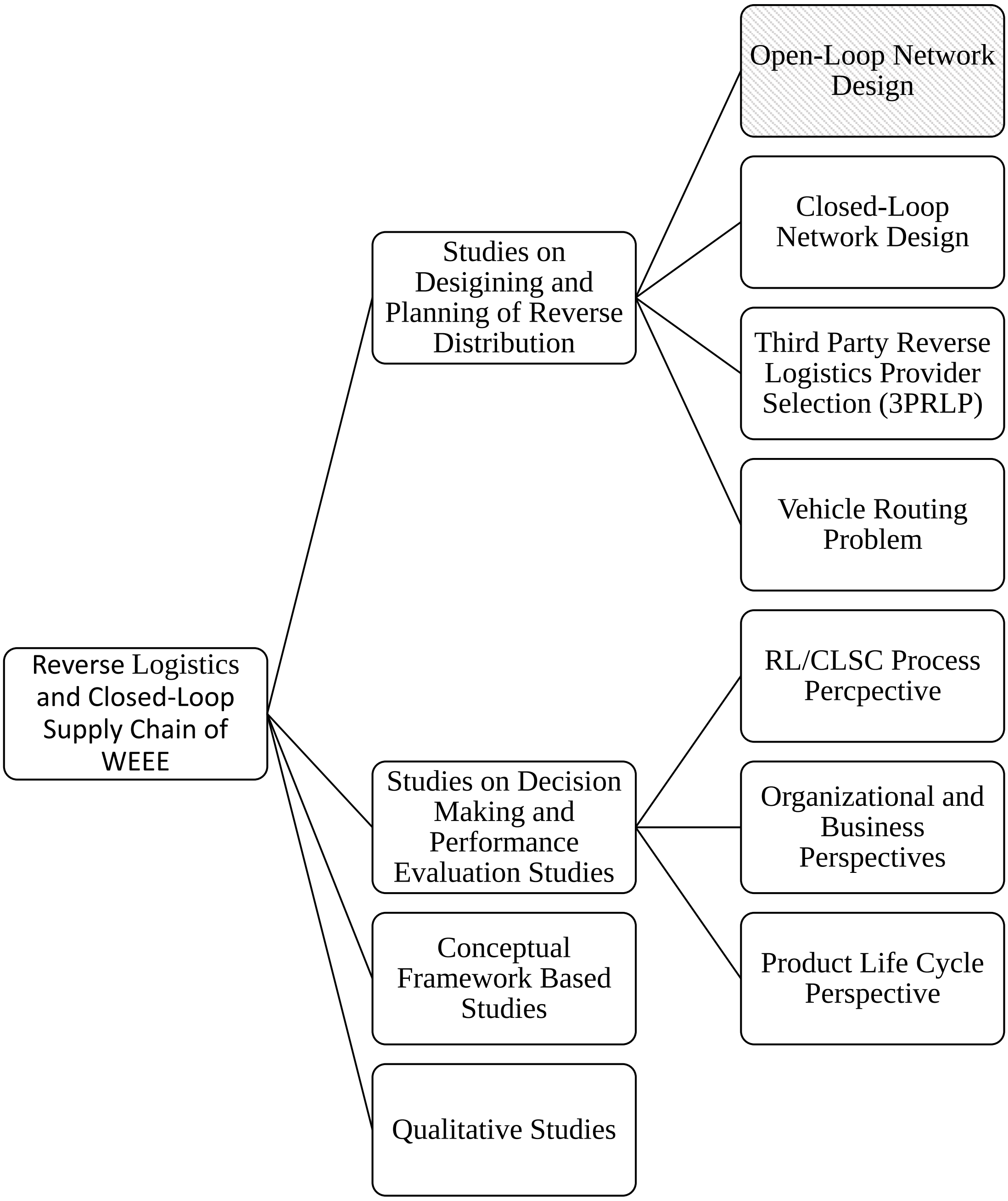

Figure 2.2 Categories of RL and CLSC studies in the literature

The categories and their corresponding sub-categories are shown on Figure 2.2. The part of the literature to be reviewed is the hachured part named as open-loop network design.

2.3. Literature review of "Open-Loop Reverse Logistics Network Design"

Based on the definition by (Salema, M.I.G., Barbosa-Povoa, A.P., & Novais, A.Q., 2007), "An RL network establishes a relationship between the market that releases used products and the market for new products. When these two markets coincide, we talk about a closed-loop network, otherwise an open loop". As it is stated at (Islam, M. T., & Huda, N., 2018) and (Akçalı, E., Çetinkaya, S., & Üster, H., 2009) "OLND (open-loop network design) focuses on the activities and flows of the reverse channel. Collection, inspection, sorting, disassembly, reprocessing/recycling, and disposal operations are the major RL activities, with the flow of returned products from one place/process to another". Open-loop network design studies are grouped in 5 different sub-categories as shown on Figure 2.3.

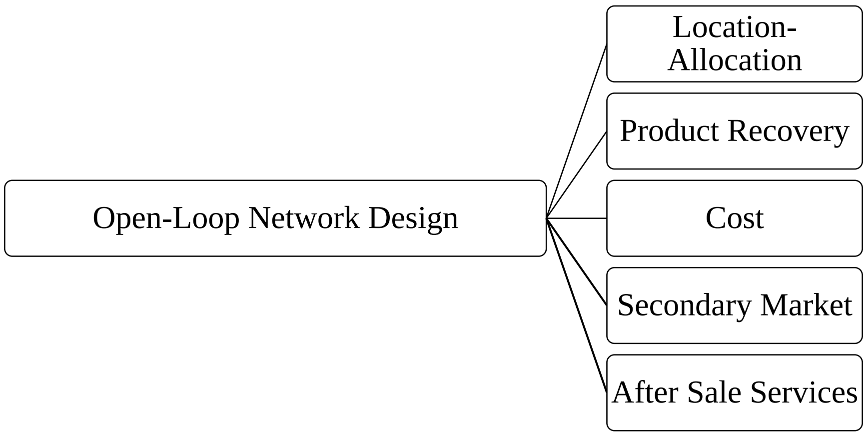

Figure 2.3 Sub-categories of Open-Loop Network design

The sub-categories are named as location-allocation, product recovery, cost, secondary market, and after sale services. Major part of the literature focuses on the location-allocation part of RLND, the main concern in these studies is to find the optimum location of facilities and the flow between them. The next part concerns the product recovery (PR) network of different e-wastes and aims to design RL based on

PR. The other part focuses on cost and tries to minimize it. In the following part we will review the literature under each sub-category.

2.3.1. Location-Allocation

Being intended for filling the gap of the uncertain aspect of WEEE RL literature, (Ayvaz, B., Bolat, B., & Aydın, N., 2015) constructs a two-stage stochastic programming model. Their network consists of 7 different types of facilities including regions (WEEE generation points), collection centers, sorting centers, recycling centers, refinery centers, raw material markets, and disposal centers. The location of the last three facilities are known in advance. The aim is to find the optimum locations for collection, sorting, and recycling centers, and the optimum weighted flow of the materials between all facilities while maximizing the revenue of the network obtained by (selling valuable material) - (transportation costs+ fixed costs of locating facilities+ processing cost). The SAA method is utilized to solve this problem. It enables the problem to handle the uncertainty caused by the amount of collected WEEE, its quality, and the transportation cost.

(Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015) is another related work in open-loop network design (OLND). This paper proposes a reverse logistics network for Turkey. The recommended network is made up of generation points, collection points, storage sites, recycling facilities, disposal facilities, and secondary markets. Generation points are not considered during the modeling; it is used to properly present the whole network. The modeling effort starts from collection points and covers all 81 cities belonging to Turkey. In other words, the WEEE is collected at all different 81 cities. They are transported to the candidate storage sites in 21 different cities with 6 different capacities. Once a month, all stored products are transmitted to recycling facilities. After being recycled by one of four types of the recycling process, the useful material can be sold at secondary markets while the hazardous materials are disposed at disposal facilities. This article focuses on the financial aspect of the network by taking into account the transportation, handling, and recycling costs, and the revenue obtained by selling useful material at secondary markets. There are some important assumptions in the model. First, the model forces the network to satisfy the minimum recycling rate stated in (EC Directive 2002) for each category of WEEE. Second, the maximum collection amount per capita is 4kg. (EC Directive 2002). Third, just four of the 10 categories are going to be collected and recycled in this network, which are small household appliances, large household appliances, TVs and monitors, and cooling appliances. Forth, secondary markets and disposal facilities are known in advance in terms of location. Except disposal facilities, all the remaining facilities are capacitated. Fifth, it ignores the uncertainty aspects of the problem and solves it as a deterministic model. The model attempts to find the best location of storage sites and recycling facilities, and the flow between all nodes of the network.

Another network design model is suggested by (Chong, S.H., Pauline, O., & Sulaiman, H., 2014) to be applied in Malaysia. This network consists of different facilities including collection centers, processing centers, secondary markets, recycling centers, and disposal facilities. It considers only end-of-life computers. The model is applied separately for each state to be considered as a candidate place to establish this network. All states whose network's potential income is greater than or equal to the cost of establishing it, are selected. The income is obtained by two ways: first, selling computers for reuse, second, selling recyclable materials in them. The cost types include collection, transportation, purchasing EOL computers, and processing costs. The model is applied to a real case and it is to be solved by MATLAB, besides the suitable locations are found for establishing the network.

In the study of (Ayvaz, B., & Bolat, B., 2014), a generic bi-level stochastic programming model is developed to design a recycling network for third party companies in Turkey which intend to recycle WEEEs. The network contains collection, inspection, recycling, refinery centers, raw material markets, and disposal facilities. Their corresponding numbers are to be calculated by the model with minimizing the total cost. The input of the model is diverse types of WEEE and that is why the model is called multi-product. It copes with the uncertainty related to the quantity of WEEEs and their quality by using different scenarios.

(Shokohyar, S., & Mansour, S., 2013) proposes a multi-objective model to establish a reverse logistics network in Iran. The model maximizes the total profit and social benefits of the network, while trying to minimize the environmental impacts. It designs the network by considering all types of WEEE and diverse facilities including EOL (end of life) products, generation nodes, collection centers, and recovery plants. These plants change from country to country. In Iran, it is assumed to be consisting of fluorescent plants, general plants, hi-tech plants, and coolant plants. It makes use of Arena simulation software to apply its simulation-based optimization method. It aims to find the best locations for collection centers and recycling facilities by using multi-objective genetic algorithms.

The considered problem in (Zhi, Guo-jian, Dong, X.-b., Zhang, & R.-x., 2010) is defined as a two-level resource constrained project scheduling (RCPSP). It is solved by using priority based genetic algorithm approach. The aim is to design a network that results in the minimum cost including transportation costs and fixed operational costs. The network consists of three different facilities; namely, collection points, disassembly facilities, and recycling facilities. It tries to find the optimum amounts of WEEE transported between them in each time period. By this study, it is concluded that the proposed solution approach is not only very efficient but also applicable to larger problems. It can also be applied to the problems with uncertain collection and disassembly facility locations.

(Xianfeng, L., Jianwei, Q., & Meilian, L., 2010) develops a linear programming model to design a reverse logistics network in Guangxi, China, under a p-hub location problem. The intended network is for recycling WEEEs and it consists of different facilities such as warehouses, processing centers, and disposals. Simulation methods are used to deal with the uncertainties related with time, quality, and quantity of WEEEs. The results play the role of DSS for RL network design in the region.

With the intention of assisting policy makers, a DSS is developed in (Achillas, C., Vlachokostas, C., Moussiopoulos, N., & Banias, G., 2010). This DSS is used to optimize the current infrastructure of collection centers and recycling plants in reverse logistic network of Greece. A mixed integer linear programming is developed and the problem is solved by Cplex.

The MILP model developed in a study conducted by (Grunow, M., & Gobbi, C., 2009), is used to evaluate the current situation of WEEE collection centers and their locations in Denmark. The study aims to assist the WEEE-System (a Danish institutional company in charge of WEEE collection) in its assignments and ease its task of assigning by offering several alternatives.

(Guerra, L., Murino, T., & Romano, E., 2009) proposes a modular simulation model. They find the number of vehicles being assigned in Reverse logistics network with the minimum intervention time considered in collection plants. It analyses different scenarios and diverse types of network configuration. The WEEE types taken into consideration are small and large household appliances. As recovery methods, there are several options consisting repairing, refurbishing, remanufacturing, parts recovery, recycling, and incineration. This study is applied in Southern Italy, Rockwell Arena.

The MILP model proposed in (Wang, I.L., & Yang, W.C., 2007) combines the facility location problem of WEEE recycling network with its configuration problem. Its objective is to maximize the revenue which is obtained by subtracting the sum of fixed cost of opening storage sites and recycling facilities, transportation cost of the network, and operational cost from subsidy. It also focuses on maximizing the use of returned products. The algorithm suggested in this study is applied for Taiwan case to validate its efficiency and effectiveness. Based on the results, the algorithm is capable of finding near-optimal solutions in a shorter time compared with the existing solution methods and Cplex.

(Ahluwalia, P.K., & Nema, A.K., 2006) proposes a multi-time-step, multi criteria, integrated planning, and design model for reverse logistic network of computer waste management system in Delhi, India. The objective of this ILP model is to minimize the total cost including transportation, segregation, storage, treatment, recycling, capital, and fixed costs of opening facilities together with the minimization of total risk consisting of the risk caused by transportation and site risk. It uses Monte Carlo simulation method to handle the uncertainty related with waste quantities. The model and its results can help the solid waste manager in selecting the best configuration waste management facilities, allocating waste to them, selecting the optimum routes for transportation of waste, and minimizing the risk for a given budget.

Another beneficial study by (Chang, X., Huo, J., & Chen, S., 2006) suggests an MIP model to design a reverse logistics network for WEEE. The network is capable of dealing with all of reusable portion of WEEEs. It replaces the damaged parts in the reusable products, reprocesses the reusable part of products, and decomposes the reusable materials from WEEE and sends the output of all these processes to the market. The generated waste is also sent to disposals. The aim of this study is to find the optimal locations for reprocessing and disassembling facilities for the reverse logistic network of WEEE with a focus on the cost minimization consisting collection, transportation, operation, disposal, and fixed costs.

The study conducted by (Shih, L.H., 2001) proposes a mixed integer model to optimize the recovery network flow and infrastructure design of computers and home appliances in Taiwan. The aim is to minimize the cost which includes transportation, operation, disposal, landfill, and fixed cost of opening facilities, and the revenue obtained by selling reclaimed materials. It focuses to propose the best collection and recycling plan for EOL e-wastes. The optimal locations of storage sites and treatment facilities and the flows between different type of facilities are decided by solution of the model. The study also considers various scenarios based on different take-back rates and operating situations.

2.3.2. Product Recovery

(Qiang, S., & Zhou, X.-Z., 2016) proposes a forward-reverse logistics network for the recovery of products. The network consists of recovery places, recovery testing centers, remanufacturing centers, markets, and disposal centers. The aim is to find the best locations of recovery testing and disposal centers and the flows between different facilities. The objective is to minimize the cost for this single period, single product, multi-echelon RL network. It takes into account the effect of uncertainty in terms of customer's demand, quantity, and quality of returned products on the model. They use robust optimization approach.

(Assavapokee, T., & Wongthatsanekorn, W., 2012) proposes an MILP model. It is developed to design a strategic infrastructural reverse logistic network for Texas. The main purpose of the network is to recover the obsolete PC and monitors while trying to maximize the net profit coming from (total revenue) – (total cost). This network ignores the recycling processes. It just focuses on reusing, refurbishing, and remanufacturing of products. The revenue comes from selling these recovered products and the fees related to collection of them.

(Piplani, R., & Saraswat, A., 2012) proposes a deterministic MILP model to optimize the network of the computer selling company which is providing after sale services like repairing or refurbishing for its products in Asia pacific region. Solution of this model answers two questions: first one is “Where to open facilities?”, and the second one, “What is the flow between different facilities?”. There are some uncertain aspects in the problem. For instance, the number of returned products, percentage of faulty products, and warranty fraction of modules are some of them. In order to handle the uncertainty related with mentioned factors, a min-max robust optimization model is developed in the next step. The solution of this model gives an optimal network configuration.

(Kawa, A., & Golinska, P., 2010) develops a model based on agent technology and graph theory. The goal of this recovery supply chain arrangement model (RSCA) is to restructure the configuration of recycling recovery network for the end of life computers in a dynamic supply chain scenario where recycling companies depend on each other. The proposed model assists the companies by providing them with potential methods of finding economic supply chain paths by considering their individual capacities. Some of advantages of using this model is visualization of goods flow, easier closed-loop supply chain forming, fast detection, and exclusion of bottlenecks, and minimization of cost, delivery time, and stock.

A study by (Cagno, E., Magalini, F., & Trucco, P., 2008) develops an analytical model for recovery network of end of life refrigerators in Italy. This model is capable of evaluating the existing network used for recovery of refrigerators in terms of capacity and cost. Additionally, it can estimate the mentioned values for the future when possible developments will be carried out to satisfy the requirements stated in EU Directive.

Another study by (Srivastava, S.K., 2008) designs a multi-period value recovery network in India. Its corresponding model is a two level and multi-echelon system with an objective of maximizing total profit. In this case study, the e-waste types which are taken into account, are washing machines, passenger cars, and refrigerators. After evaluating the profitability of different scenarios for each of mentioned product categories, it is concluded that remanufacturing is not a valid and profitable proposition in the current situation of India for all of the product categories.

A network flow-based programming model is developed by (Lee, D.-H., & Dong, M., 2008) for recovery of end of lease computers. Existence of numerous constraints and variables in this model makes it very complex. To come over this complexity, the authors develop a bi-level heuristic approach in order to decompose the problem into two smaller problems. By use of the suggested heuristic, the integrated design of the multi-echelon forward and backward logistics distribution network is decomposed into a network flow problem and a location allocation problem. Different decisions are made at each step. A Tabu search algorithm is used to improve the results.

(Kara, S., Rugrungruang, F., & Kaebernick, H., 2007) suggests a simulation based reverse logistic network model. The purpose of the study is to address the problems related with RL networks. With the mentioned intention, first it designs the RL network which consists of transfer stations, drop of centers, and disassembly facilities. Next it makes use of simulation to calculate the collection cost in order to better understand the behavior of the designed system and identify the important factors affecting the network. The model is applied for end of life white goods in Sydney Metropolitan Area. It is also applicable for other types of EOL products and for other regions.

In a study by (Sodhi, M.S., & Reimer, B., 2001), a non-linear mathematical programming model is developed. The intention of assisting recyclers and processor is to optimize the recycling operations which consists of material recovery and disassembly. The objective is to minimize the total cost for economic sustainability of recycling processes of e-wastes.

(Krikke, H.R., Van Harten, A., & Schuur, P., 1999) suggests an SDP (stochastic dynamic programing) model for recycling PC monitors in Rotterdam, The Netherlands. It aims an optimum level of disassembly and the best disposal, recycling, and reusing options for the products that are not disassembled or for the components obtained by different disassembly levels. The major goal is to maximize the net profit, obtained by chosen recovery strategies. The chosen strategies in this paper are able to reduce the total cost of recycling system by 25% (caused by lowering the variable costs). It also indicates that the reduction percentage will reach 40% in the case which the location of facilities is changed (for instance, when they are located in cheaper locations), the technologies are improved or a DSS is developed to regularly re-determine optimum strategies, and etc.

2.3.3. Cost

(Yu, H., & Solvang, W.D., 2016) formulates a two-stage stochastic programming model to design and plan a reverse logistics system to maximize profit by consideration of uncertainty. Besides economic aspects, it considers the environmental impacts by considering carbon emission in the RL system. The multi-criteria scenario-based solution method is used. It is a method that has been improved during in this study in order to be applicable to all kinds of stochastic optimization problems (min-max, max-min, min-min, and max-max). The original version of it developed by (Soleimani, H, Seyyed-Esfahani, M., & Shirazi, M.A, 2013) is called sample average approximation method. This method is capable of solving only min-max and max-min stochastic optimization problems.

(Elbadrawy, R., Moneim, A.F.A., & Fors, M.N., 2015) designs a reverse logistics network with objective of cost minimization, in Egypt. The network consists of different facilities. E-wastes are collected through collection sites, they are transported to sorting facilities in order to be categorized. If a product is reusable, it will be repaired and distributed to the secondary market. If not, it will be recycled at the recycling facility. While sending valuable material to factories, it transmits the hazardous material to landfills to be recycled, incinerated or disposed of. It neglects to consider the processes that are considered to happen at the landfill and doesn't consider the recycling, incineration, and disposal of hazardous material. The model is solved by the use of the genetic algorithm to find the best location of recycling and repairing facilities, and the weighted flow of materials between different facilities.

(Yu, H., & Solvang, W.D., 2013) presents a reverse logistics network designed by a bi-objective MILP model. While one of the objectives considers the financial aspect of the network, the other one takes into consideration its environmental impacts by attempting to minimize the greenhouse gas emission originated by transportation. The suggested network is made up of diverse facilities named collection, pre-treatment, treatment, disposal, and markets. Collection points and markets are supposed to be known in terms of location and quantity. The locations of remaining facilities and the flows between them are going to be calculated during the solution procedure. Collection points are categorized into different types as retailers, public drop-off, and third-party service. Disassembly and sorting processes are done at pre-treatment facilities while treatment facilities are considered to be used for recycling, remanufacturing, repairing or reusing the products. At disposal facilities materials could be incinerated or disposed of. The model is solved by Lingo 11.0.

(Dat, L.Q., Truc Linh, D.T., Chou, S.-Y., & Yu, V.F., 2012) presents a mathematical programming model to design a reverse logistics network specifically for recycling process of multi-sourced WEEE. The suggested model is a single-objective one and concentrates on only economic dimension of the problem. It seeks for the optimum locations of facilities and the material flow in between, which results in minimum total processing cost. The facilities that are supposed to be built in this network are namely collection, disassembly, repairing, recycling, and disposal facilities and the major part of the total cost is the transportation cost between them. The article concludes that in order to improve the net profit, lowering the transportation cost plays an important role.

A single period multi objective linear programming model is developed in a study by (Achillas, C., Aidonis, D., Vlachokostas, C., Moussiopoulos, N., Banias, G., & Triantafillou, D., 2012) to be used in allocation of different types of carriers in the WEEE reverse logistic network. The aim of the study is to take into consideration both environmental and economical aspect of the network. In order to focus on its economical aspect, it tries to minimize the total cost of transportation. On the other hand, to consider its environmental aspect it aims to minimize the fossil fuel consumption together with carbon emission caused by use of different types of carriers. One differentiating feature of this study is to consider different carriers to be used in transportation network motivated by observing the various quantities and some restriction related with roads, and etc. The model is applied in central Macedonia, Greece and the mentioned objectives are estimated by use of the suggested model.

A nice study by (Cao, S., & Zhang, K., 2011) proposes an operational mathematical model with the objective of maximizing the total profit. The considered e-waste type in this study is solar photovoltaic waste. Though this waste type exists in small amounts, it is predicted to be increased very fast in the future based on information about the sold amounts and the product lifetime. The article suggests feasibility evaluation of recycling infrastructure and it aims to propose a framework for photovoltaic recycling managers to prevail over challenges existing in this area.

A study conducted by (Shanshan, W., & Kejing, Z., 2008) focuses on designing a recycling network for different types of e-wastes by using an integrated optimization model. It aims to minimize the total cost which includes the costs related to collection, disassembly, treatment, and transportation. The income is obtained through governmental subsidy and selling the parts of product which can be directly reused. It decides on the location of facilities and the flows between them. While e-waste is the input of the network, recovered valuable materials and hazardous materials are its outputs. The environmental aspect is not considered in this study.

2.3.4. Secondary market

A study conducted by (Liu, Y., Zhang, Y.F., & Jin, Y.X., 2014) recommends an evolutionary model for designing reverse logistics in China. Based on the suggested model, the logistics capability standard of companies is an important output measured. The multi-objective model makes use of the theory of constraints and is solved by LINDO 6. This study concludes that by improving the utilization of processing centers to its maximum, it is possible to reach the maximum profit that is obtained by selling recycled goods.

The paper by (Choi, J.K., & Fthenakis, V., 2010) proposes a method generated by combination of multi-attribute decision making and multi-criteria optimization. It is used to find the optimum flows between different type of facilities (collection points, storage sites, dismantling or testing centers, treatment facilities, markets, disposals) considered in reverse logistics network of WEEE. The proposed model aims to maximize the total profit, minimize the energy consumption, and the loss (it corresponds to the difference between input and output). First, the multi-criteria problem is solved by NSGA2, and the Pareto optimum solutions are obtained. The obtained solutions constitute the input of the multi-attribute decision making problem. The optimum solution is procured by solving it by the use of TOPSIS (The weights of each of criteria used in TOPSIS method are calculated by the Eigenvector together with the preferences of decision maker).

With the intention of evaluating different possible scenarios of WEEE management in Cyprus, a multi-objective decision-making model is proposed in the study of (Rousis, K., Moustakas, K., Malamis, S., Papadopoulos, A., & Loizidou, M., 2008). The model is solved by PROMETEE. Based on the results, it is concluded that the best scenario in the existing situation is to disassemble a part of e-wastes while selling the recyclable materials at secondary market and disposing of the residues at disposals.

A study by (Franke, C., Basdere, B., Ciupek, M., & Seliger, S., 2006) presents a generic planning method for capacities of the facilities which remanufacture cell phones. The suggested method also helps in planning of remanufacturing program by use of combinatorial optimization. The results about needed capacities and the remanufacturing program are used for assessment and qualification of current remanufacturing plants by means of discrete-event simulation. The uncertain aspects taken into consideration in this problem are the uncertainty related with the quality and quantity of cell-phones, capacity reliability, time of processing, and etc.

A multi-level network balance model is developed by (Nagurney, A., & Toyasaki, F., 2005) focusing on a recycling policy instrument. It is discovered that policy instruments involving original equipment manufacturers (OEMs) and integrating a classic supply chain network with recycling is the optimal situation in terms of efficiency and effectiveness.

(Nagel, C., & Meyer, P., 1999) proposes a novel approach that systematically models and evaluates end-of-life networks. It is a case in Germany which is a network for disassembly and recycling of end-of-life refrigerators, it takes into consideration both economic and environmental aspect of the problem.

A beneficial study by (Queiruga, D., Walther, G., González-Benito, J., & Spengler, T., 2008) proposes a technique which uses a discrete multi-objective method named PROMETHE to find the best locations to install recycling facilities for e-wastes in Spain. It considers numerous objectives in order to take into consideration all different aspects of the problem consisting of its infrastructural, economic, and legal aspects. It considers all the municipalities of Spain with more than 23000 inhabitants as its alternatives. All these alternatives are compared based on 10 different objectives. It makes use of Gaussian function to apply the PROMETHE method. For the case studied, the alternatives which are chosen as the most favorable ones are concentrated in a few regions.

The model proposed in (Gamberini, R., Gebennini, E., Manzini, R., & Ziveri, A., 2010) intends to optimize the WEEE transportation network of the North of Italy. It consists of each step required in the process of planning in order to efficiently support the decision maker. It aims to take into consideration both environmental and technical aspect of the problem. For technical aspect, it considers the vehicle working times and their capacity saturation.

CHAPTER 3

PROBLEM STATEMENT AND MODELING

Content of the chapter

Building an efficient reverse logistics network can empower countries to deal with the huge stream of EEE wastes. We aim to design an RL network for WEEE in Turkey, by considering the hazardous material used. It is regarded to benefit from the recycling of useful material in it while saving the environment from the potential threat of hazardous material utilized. To get known about the problem, some details are provided in this chapter. We will start the definition part by identifying distinct kinds of facilities required to design an efficient RL network and then we will focus on their interconnections and the processes that take place within each of them through the network. Next, we will represent the network and the flows between plants. Last, we will state the parameters, decision variables, and the mathematical model

3.1. Network Representation

A well-designed reverse logistics network is a crucial part of the efficient management of WEEE that should be carried out in a watchful manner. It should take into the processes and factors affecting the network as much as possible. In order to be capable of doing all that is mentioned above, it is aimed to design a comprehensive network, suitable for dealing with most of the electronic waste types. The suggested network includes nine types of facilities as shown in Table 3.1, while eight of them have physical existence the remaining one is supposed to be a fictitious facility. In order to start representing the network, it is better to first get known with the facilities considered in the network.

1. Generation points: These are the locations of houses, retailers or other places that generate WEEE. We do not have any control over them, therefore, we do not consider them in our study.
2. Collection points: Two types of collection points exist. The first type is the stationary collection points, which are organized and set by municipalities. They could be different kinds of containers placed at strategic locations, stores selling EE, etc. (Nowakowski, P., Szwarc, K., & Boryczka, U. 2018). The second type is the mobile collection points. In this type, vehicles which mandated to collect the waste, travel in special parts of the city. An alternative for this type of collection would be websites or companies that send their vehicles to take waste when it is requested (Nowakowski, P., Szwarc, K., & Boryczka, U. 2018). In our case, the locations of collection points are decided by the municipalities and they are given, hence we do not search for optimal locations for them.

Table 3.1 Types of facilities used in the suggested network

1	Generation point
2	Collection point
3	Storage site
4	WEEE recycling facility
5	Fictitious separation point
6	Hazardous material recycling facility
7	Hazardous material treatment facility
8	Disposal
9	Secondary market

3. Storage sites: For one-month periods the WEEEs get accumulated in storage facilities when the period ends, all of them get transferred to WEEE recycling facilities. We have different kinds of storage sites in terms of capacity.
4. WEEE recycling facilities: These are the facilities where WEEE recycling processes take place. The procedure is carried out in a manner that separates the useful material from hazardous one and prepares the useful material to be sold at the secondary market immediately after the process. The hazardous material recycling process cannot be done at this plant. It should be transferred

to another facility based on its type, if it is recyclable hazardous material it will be sent to the hazardous recycling facility, otherwise it will be sent to the treatment facility. To clearly comprehend what happens in this stage, we consider a fictitious separation node after this facility.

5. Fictitious separation facility: This is a facility with construction and annual cost of zero. The processes which are done at this facility also costs zero. This is a facility that is considered just to ease the understanding of material types and the flows that we have from the WEEE recycling facility to other facilities.
6. Hazardous material recycling facility: These are the facilities designed to implement the process of recycling hazardous materials. After the recycling process, we will have useful material and waste. The first one should be sent to the secondary market and the second one should be transferred to the disposal facility.
7. Treatment facilities: The treatable hazardous material are inputs of these facilities. These facilities are designed to treat the hazardous materials and minimize the threat of environmental risk that they potentially expose to nature. Following the implementation of the treatment process, wastes which are called as non-hazardous residues in the literature, are obtained. These waste residues are categorized into two groups. The first one which is recyclable waste residues is transferred to the hazardous material recycling facility and the next that is named non-recyclable waste residues should be disposed of at disposal facilities.
8. Disposal: The wastes which are no more hazardous are disposed of at these sites.
9. Secondary market: It is used to refer to the market which used goods or assets are sold. Also, in our problem, the used useful materials obtained by recycling processes are sent to these markets to be sold.

The suggested network of this study is inspired by the one designed by (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015) which is represented in Figure 3.1. In this network, it is considered that the WEEE's are transferred to two types of facilities after being recycled. The useful material obtained by the recycling process goes to the secondary market to be sold, while the hazardous material is taken to disposal facilities to be discarded. As it is known, hazardous materials are capable of being contaminating for the environment. For instance, CFC's that we have as one of the hazardous waste types in our problem, can deplete the ozone layer and intensify global warming. Table 3.2 shows the "Global Warming Potential, GWP" and "Ozone Depleting Potential, ODP" of some of the refrigerants (Devotta, S., Asthana, S., & Joshi, R., 2004).

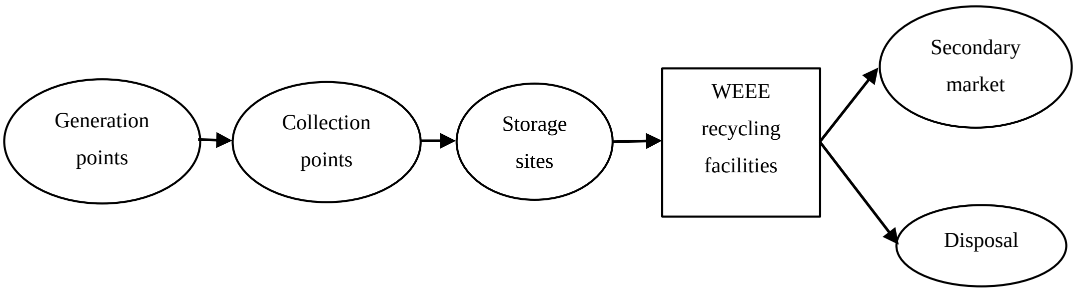

Figure 3.1 The reverse logistics network of WEEE in Turkey designed by (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015)

Table 3.2 "Global Warming Potential, GWP" and "Ozone Depleting Potential, ODP" of some of refrigerants. (Devotta, S., Asthana, S., & Joshi, R., 2004)

Species	Chemical formulation	ODP	100 years GWP
CFC-11	CCl3F	1	4000
CFC-12	CCl2F2	1	8500
HCFC-22	CHClF2	0.055	1700
HFC-134a	CH2FCF3	0	1300
HC-600a	CH(CH3)2CH3	0	3
HC-290	CH3CH2CH3	0	3

However, the network that we suggest, considers the threat of hazardous materials and as it is shown in Figure 3.2. It serves the opportunity of treating or recycling hazardous waste before disposing it off. Actually, it aims to include the environmental effects of the materials in the problem and consequently prevent the environment from being contaminated by directly disposing of them. The part of the network which differentiates the suggested one from the past one is highlighted by the dashed rectangular in Figure 3.2. In addition to the past network, we have different kinds of materials. While the past one considers just useful and hazardous materials, we will consider useful material, recyclable and treatable hazardous materials, recyclable and non-recyclable waste residues, and waste. The flows of the mentioned materials are illustrated in Figure 3.3. The facilities with specific processes are shown by rectangles, however, the ones including no processes are represented by ovals or circles.

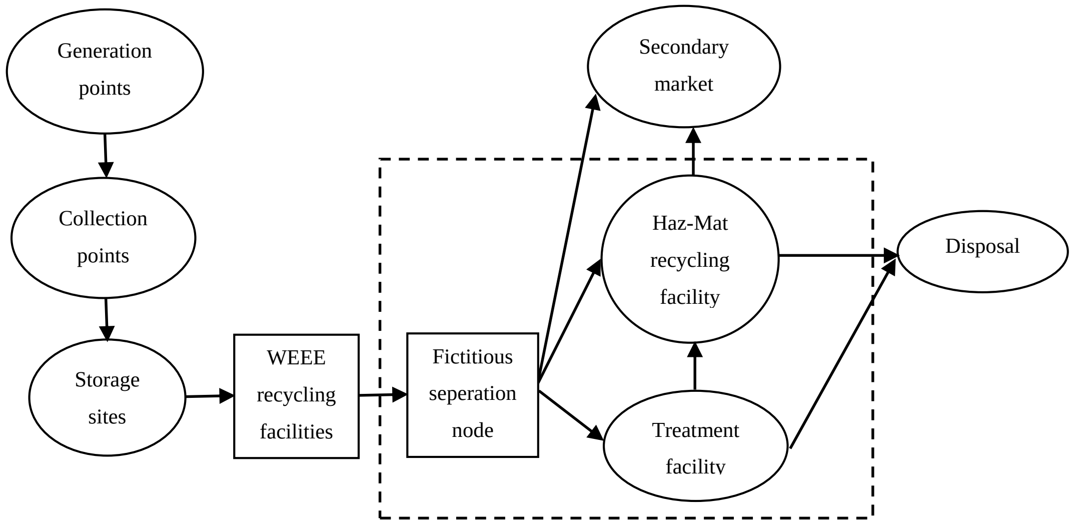

Figure 3.2 The extension of suggested network.

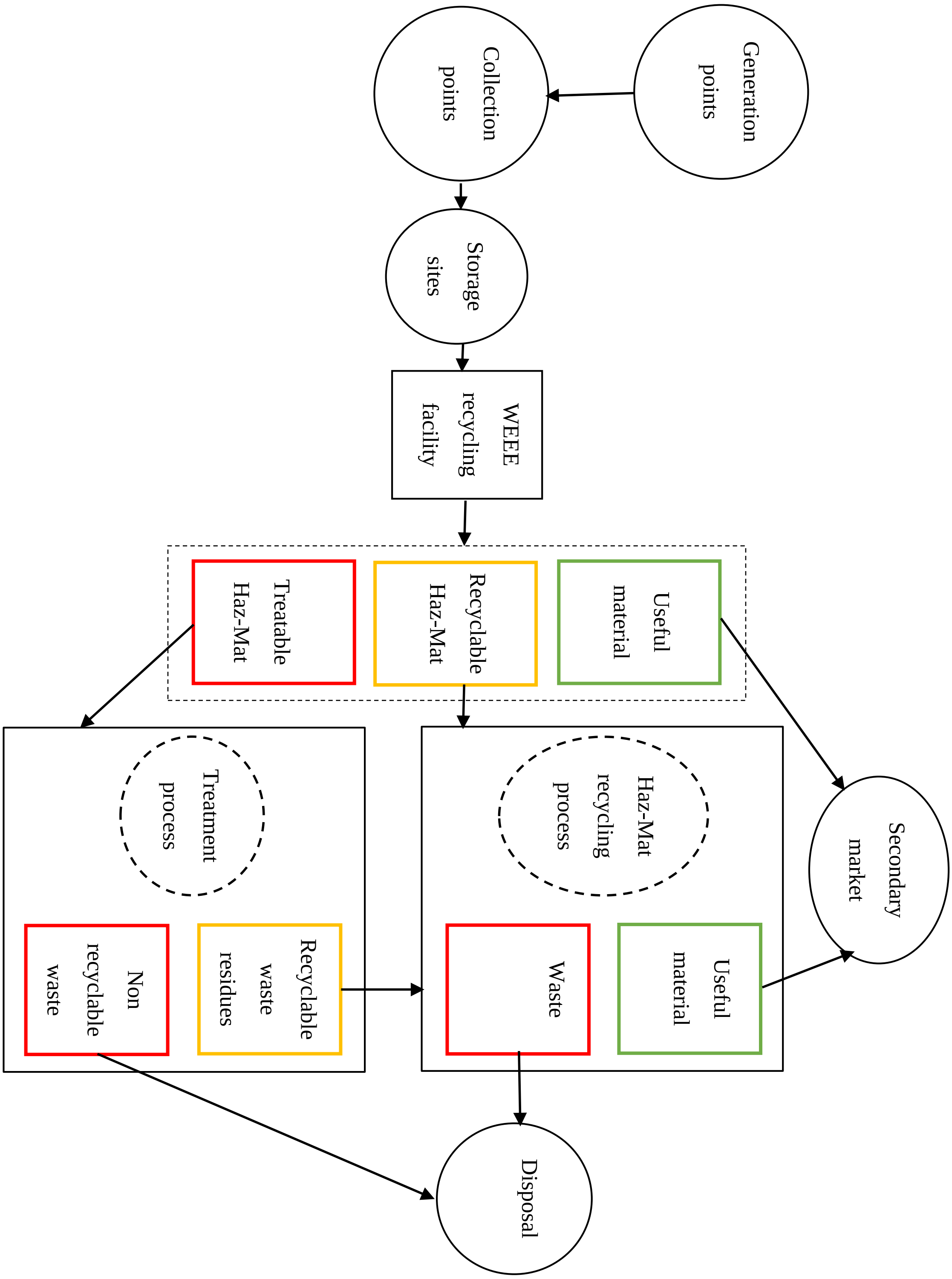

Figure 3.3 Flows of different types of materials in the suggested network

3.2. Model Explanation and Mathematical Formulation

3.2.1. Objectives and Decision Variables

Our main objective is to find the optimum locations of all facilities except generation points, collection points, secondary markets, and disposals, which are supposed to be given (the locations of collection points are set by the municipalities). Additionally, we will aim to find the flow between different facilities starting from collection points. While searching for all these, we will consider the effect of hazardous materials. We will try to find the location of the facilities and the flows in a way that minimizes the overall risk caused by these materials.

Decision variables

1. Location decisions (types, numbers, and locations of storage sites, WEEE-recycling facilities, Haz-Mat recycling facilities, and Haz-Mat treatment facilities)
2. Flow decisions (the network flow of product category through all facilities except generation and collection points)
3. The number of product categories to be allocated to storage, recycling, treatment facilities

Objective

- Minimizing total cost (transportation, handling, operation, fixed, disposal cost minus the revenue of selling useful materials)

3.2.2. The Model and Parameters

The model is developed as a single objective MILP. based on the network features stated above, in this part, the model, parameters, and decision variables will be defined.

$\boldsymbol{Index}$:

I : Collection point locations

J：Storage site locations

K：WEEE recycling facility locations

H：Hazardous material recycling facility locations

T：Treatment facility locations

L：Secondary market locations

M：Disposal locations

U： Product types

Q： Technology type

F：Useful material type

G：Hazardous material type

Parameters:

$distanceCS_{ij}$	The distance between collection points and storage sites
$distanceSW_{jk}$	The distance between storage sites and WEEE-recycling facilities
$distanceWS_{kl}$	The distance between WEEE-recycling facilities and secondary markets
$distanceWH_{kh}$	The distance between WEEE-recycling facilities and Haz-Mat recycling facilities
$distanceWT_{kt}$	The distance between WEEE-recycling facilities and treatment facilities
$distanceTH_{th}$	The distance between treatment facilities and Haz-Mat recycling facilities
$distanceHS_{hl}$	The distance between Haz-Mat recycling facilities and secondary markets
$distanceTD_{tm}$	The distance between treatment facilities and disposals

$distanceHD_{hm}$	The distance between Haz-Mat recycling facilities and disposals
$UTypeTransCost_u$	The transportation cost for u type product
$FTypeTransCost_f$	The transportation cost for f type useful material
$ZTypeTransCost$	The transportation cost for recyclable hazardous material
$NTypeTransCost$	The transportation cost for treatable hazardous material
$RWasteTransC$ost	The transportation cost for recyclable waste
$UsefulTransCost$	The transportation cost for useful material originated from Haz-Mat recycling facility
$NRwasteTransCost$	The transportation cost for non-recyclable waste
$HandlingCost_{ju}$	Handling cost of u type product at storage site j
$ProcessingCost_{ku}$	Recycling cost per kg of u at WEEE-recycling facility k
$RecyclingCostHR_h$	Recycling cost per kg of recyclable hazardous material at Haz-Mat recycling facility k
$TreatmentCost_{gq}$	Treatment cost per kg of treatable hazardous material type g by technology q
$PricePerKG$	Selling price per kg of useful material recycled at Haz-Mat recycling facility
$PricePerKGUseful_f$	Selling price per kg of useful material type f recycled at WEEE-recycling facility
$FixedCostTr_q$	Fixed cost of opening treatment facility with technology of q
$FixedCostHR_h$	Fixed cost of opening Haz-Mat recycling facility at site h

$FixedCostWEEE_k$	Fixed cost of opening WEEE-recycling facility at site k
$FixedCostSt_j$	Fixed cost of opening storage site facility at site j
a_{iu}	The number of u type product at collection point i
$weight_u$	Weight of product category u
$volume_u$	Volume of product category u
$PercUseful_{uf}$	Weight percentage of f type useful material at u type product
$RecRate_k$	Recycling rate of WEEE-recycling facility k
$MinRecRate_u$	Minimum recycling rate stated at EU directive for u type product
$PercHazar_{ug}$	Weight percentage of g type hazardous material at u type product
$PercUsefulHR_h$	The recycling rate of Haz-Mat recycling facility h
$WeightRed_{gq}$	Weight reduction percentage of treatable hazardous material g treated by technology q
$PercRecHazWaste_{gq}$	Weight percentage of recyclable waste obtained from g type hazardous material treatment process by technology q
$MinCapSt_j$	Minimum capacity of storage site j
$MaxCapSt_j$	Maximum capacity of storage site j
$MinCapWEEE_k$	Minimum capacity of WEEE recycling facility k

$MaxCapWEEE_k$	Maximum capacity of WEEE recycling facility k
$MinCapHR_h$	Minimum capacity of Haz-Mat recycling facility h
$MinCapHR_h$	Maximum capacity of Haz-Mat recycling facility h
$MinCapT_q$	Minimum capacity of treatment facility with the technology q
$MaxCapT_q$	Maximum capacity of treatment facility with the technology q
com_{gq}	Compatibility of technology q with hazardous material type g
$market_{lf}$	Compatibility of selling product type f at secondary market l
$treat_g$	Binary parameter that shows hazardous material type g can be treated or not
$recycle_g$	Binary parameter that shows hazardous material type g can be recycled or not

decision variables:

CS_{iju}	The flow of u type product from collection point i to storage site j.
SW_{jku}	The flow of u type product from storage site j to WEEE-recycling facility k.
WS_{klf}	The flow of f type useful material from WEEE-recycling facility k to secondary market l.
WH_{khg}	The flow of g type hazardous material from WEEE-recycling facility k to Haz-Mat recycling facility h.

WT_{ktg}	The flow of g type hazardous material from WEEE-recycling facility k to treatment facility t.
TH_{th}	The flow of recyclable wastes from treatment facility t to Haz-Mat recycling facility h.
HS_{hl}	The flow of useful material from Haz-Mat recycling facility h to secondary market l.
TD_{tm}	The flow of non-recyclable waste residues from treatment facility t to disposal site m.
HD_{hm}	The flow of wastes from Haz-Mat recycling facility h to disposal site m.
St_j	Binary variable showing that storage site j is opened or not.
W_k	Binary variable showing that WEEE-recycling facility k is opened or not.
HR_h	Binary variable showing that Haz-Mat recycling h is opened or not.
Tr_{tq}	Binary variable showing that treatment facility t with technology q is opened or not.
b_{ju}	The number of u type product at storage site j.
c_{ku}	The number of u type product at WEEE-recycling facility k.
$NRhazmatT_{tgq}$	The amount of g type hazardous material that is treated by technology q at treatment facility t
$TotalHR_h$	The total amount of material which is recycled at Haz-Mat recycling facility h.
$RhazmatHR_{hg}$	The amount of g type hazardous material that is recycled at Haz-Mat recycling facility h
$RwasteT_t$	The amount of recyclable waste that is obtained by the treatment process at treatment facility t

$RwasteHR_h$	The amount of recyclable waste that is recycled at Haz-Mat recycling facility h
$NRwasteT_t$	The amount of non-recyclable waste that is obtained by the process of treatment at treatment facility t
$WasteHR_h$	The amount of waste that is obtained by the process of recycling at Haz-Mat recycling facility h
$usefulHR_h$	The amount of useful material obtained by the recycling process at Haz-Mat recycling facility h
$usefulWR_{kf}$	The amount of useful material type f obtained by the recycling process at WEEE-recycling facility k
$soldHR_l$	The amount of useful material sold at secondary market l coming from Haz-Mat recycling facilities.
$soldWR_{lf}$	The amount of useful material type f sold at secondary market l coming from WEEE-recycling facilities.
$GtypeHazWaste_{kg}$	Amount of g type hazardous material at WEEE recycling facility k

All the parameters and decision variables are mentioned above. At the rest of this part the model will be given and described in details. In this model we have one objective function set to minimize the total cost and thirty-one constraints.

$$
\begin{aligned}
z = & \sum_i \sum_j \sum_u CS_{iju} * distanceCS_{ij} * UTypeTransCost_u \\
& + \sum_j \sum_k \sum_u SW_{jku} * distanceSW_{jk} * UTypeTransCost_u \\
& + \sum_k \sum_l \sum_f WS_{klf} * distanceWS_{kl} * FTypeTransCost_f \\
& + \sum_k \sum_h \sum_g WH_{khg} * distanceWH_{kh} * ZTypeTransCost \\
& + \sum_k \sum_t \sum_g WT_{ktg} * distanceWT_{kt} * NTypeTransCost \\
& + \sum_t \sum_h TH_{th} * distanceTH_{th} * RWasteTransCost \\
& + \sum_h \sum_l HS_{hl} * distanceHS_{hl} * UsefulTransCost \\
& + \sum_t \sum_m TD_{tm} * distanceTD_{tm} * NRwasteTransCost \\
& + \sum_h \sum_m HD_{hm} * distanceHD_{hm} * NRwasteTransCost \\
& + \sum_i \sum_j \sum_u CS_{iju} * HandlingCost_{ju} \\
& + \sum_j \sum_k \sum_u SW_{jku} * ProcessingCost_{ku} \\
& + \sum_t \sum_g \sum_q NRhazmatT_{tgq} * TreatmentCost_{gq} \\
& + \sum_h TotalHR_h * RecyclingCostHR_h \\
& + \sum_j St_j * FixedCostSt_j + \sum_k W_k * FixedCostWEEE_k \\
& + \sum_T \sum_q Tr_{tq} * FixedCostTr_{tq} + \sum_h HR_h * FixedCostHR_h \\
& - \sum_l soldHR_l * PricePerKG \\
& - \sum_l \sum_f soldWR_{lf} * PricePerKGUseful_f
\end{aligned}
\tag{3.1}
$$

Subjected to:

- Flow constraints: Constraints that balance flows between all facilities.

$$\sum_{j} CS_{iju} = a_{iu} \qquad \forall i, \forall u \qquad (3.2)$$

$$\sum_{i} CS_{iju} = b_{ju} \qquad \forall j, \forall u \qquad (3.3)$$

$$\sum_{k} SW_{jku} = b_{ju} \qquad \forall j, \forall u \qquad (3.4)$$

$$\sum_{j} SW_{jku} = c_{ku} \qquad \forall k, \forall u \qquad (3.5)$$

$$\sum_{u} c_{ku} * weight_{u} * PercUseful_{uf} * RecRate_{k} = usefulWR_{kf} \qquad \forall k, \forall f \qquad (3.6)$$

$$\sum_{l} WS_{klf} * market_{lf} = usefulWR_{kf} \qquad \forall k, \forall f \qquad (3.7)$$

$$\sum_{k} WS_{klf} * market_{lf} = soldWR_{lf} \qquad \forall l, \forall f \qquad (3.8)$$

$$\sum_{u} c_{ku} * weight_{u} * PercHazar_{ug} = GtypeHazarWaste_{kg} \qquad \forall k, \forall g \qquad (3.9)$$

$$\sum_{t} WT_{ktg} * treat_{g} + \sum_{h} WH_{khg} * recycle_{g} = GtypeHazarWaste_{kg} \qquad \forall k, \forall g \qquad (3.10)$$

$$\sum_{k} WT_{ktg} * treat_{g} = \sum_{q} NRhazmatT_{tgq} * com_{gq} \qquad \forall t, \forall g \qquad (3.11)$$

$$\sum_{k} WH_{khg} * recycle_{g} = RhazmatHR_{hg} \qquad \forall h, \forall g \qquad (3.12)$$

$$\sum_{g} \sum_{q} NRhazmatT_{tgq} * com_{gq} * (1 - WeightRed_{gq}) * PercRecHazWaste_{gq} = RwasteT_{t} \qquad \forall t \qquad (3.13)$$

$$\sum_{h} TH_{th} = RwasteT_t \qquad \forall t \qquad (3.14)$$

$$\sum_{t} TH_{th} = RwasteHR_h \qquad \forall h \qquad (3.15)$$

$$\sum_{g} \sum_{q} NRhazmatT_{tgq} * com_{gq} * \left(1 - WeightRed_{gq}\right) * \left(1 - PercRecHazWaste_{gq}\right) = NRwasteT_t \qquad \forall t \qquad (3.16)$$

$$\sum_{m} TD_{tm} = NRwasteT_t \qquad \forall t \qquad (3.17)$$

$$\sum_{g} RhazmatHR_{hg} + RwasteHR_h = TotalHR_h \qquad \forall h \qquad (3.18)$$

$$TotalHR_h * (1 - PercUsefulHR_h) = WasteHR_h \qquad \forall h \qquad (3.19)$$

$$\sum_{m} HD_{hm} = WasteHR_h \qquad \forall h \qquad (3.20)$$

$$TotalHR_h * PercUsefulHR_h = usefulHR_h \qquad \forall h \qquad (3.21)$$

$$\sum_{l} HS_{hl} = usefulHR_h \qquad \forall h \qquad (3.22)$$

$$\sum_{h} HS_{hl} = soldHR_l \qquad \forall l \qquad (3.23)$$

- Capacity constraints:

$$\sum_{u} b_{ju} * volume_u \geq MinCapSt_j * St_j \qquad \forall j \qquad (3.24)$$

$$\sum_{u} b_{ju} * volume_u \leq MaxCapSt_j * St_j \qquad \forall j \qquad (3.25)$$

$$\sum_{u} c_{ku} * volume_u \geq MinCapWEEE_k * W_k \qquad \forall k \qquad (3.26)$$

$$\sum_{u} c_{ku} * volume_u \leq MaxCapWEEE_k * W_k \qquad \forall k \qquad (3.27)$$

$$TotalHR_h \geq MinCapHR_h * Hr_h \qquad \forall h \qquad (3.28)$$

$$TotalHR_h \leq MinCapHR_h * Hr_h \qquad \forall h \qquad (3.29)$$

$$\sum_g NRhazmatT_{tgq} \geq \sum_g MinCapT_{tq} * Tr_{tq} * com_{gq} \qquad \forall t, \forall q \qquad (3.30)$$

$$\sum_g NRhazmatT_{tgq} \leq \sum_g MaxCapT_{tq} * Tr_{tq} * com_{gq} \qquad \forall t, \forall q \qquad (3.31)$$

- Minimum recycling rate constraint:

$$\sum_k c_{ku} * weight_u * RecRate_u \Big/ \sum_i a_{iu} weight_u \geq MinRecRate_u \qquad \forall u \qquad (3.32)$$

The objective shown by equation (3.1) is to minimize the total cost. The total cost consists of transportation costs, handling costs, recycling costs, treatment costs, and fixed costs minus the revenue gained by selling products. The constraints (3.2) and (3.3) corresponds to the flow between collection points and storage sites, while (3.4) and (3.5) balance the product flows between storage sites and WEEE-recycling facilities. Products do not expose to any kind of process until they come to WEEE recycling facilities. That is why we have one extra constraint as a flow balancer for the facilities where some special processes are implemented. The constraint (3.6) corresponds to the recycling process that is carried out at the WEEE-recycling facility. Each type of product category u contains a special weight percentage of type useful material that can be sold at the secondary market concerning the recycling rate of the facility, that is why we need to have the constraint (3.6). (3.7) and (3.8) are the remaining constraints responsible for balancing the flow between WEEE-recycling facilities and secondary markets.

Constraint (3.9) calculates the amount of each of hazardous material type by considering their weight percentages and the recycling process, (3.10) forces the hazardous material to be sent to hazardous material recycling facilities or treatment facilities, it takes into consideration the compatibility of each type of the hazardous material with recycling and treating processes. (3.11) shows the flow of treatable hazardous material coming from WEEE recycling facility, it also considers the compatibility of each treatable material with treatment technology. The constraint (3.12) also shows the flow of recyclable hazardous material originated from WEEE recycling facilities. Constraints (3.13) to (3.15) correspond to the flow between treatment facilities and hazardous material recycling facility, the first one again refers to the treatment procedure, which reduces the amount of hazardous material by weight reduction rate and subsequently sends the non-recyclable waste residues to the disposal centers by use of constraints (3.16) and (3.17).

Constraint (3.18) indicates the total flow to the hazardous material recycling facilities which is the input of the recycling process. After the hazardous material recycling process, useful materials and wastes are obtained, while wastes are transmitted to disposal facilities by constraints (3.19) to (3.20), the useful materials are sent to secondary markets by constraints (3.21) to (3.23). The constraints (3.24) to (3.31) are considered to control the minimum and maximum capacity limits and the last constraint is for making sure that the recycled amounts satisfy the minimum recycling rates indicated by (EU Directive, 2002).

CHAPTER 4

COMPUTATIONAL STUDIES

4.1. Data Description

The model is applied countrywide, considering all 81 cities of Turkey as generation points. Based on the assumptions in each generation point there exists one stationary collection point which is uncapacitated and its location is given and determined by the municipality. Therefore, we do not make any decision concerning the locations of collection points. The flow between these two points (generation points and collection points) is also not considered in this study, because the owners of WEEEs are in charge of bringing their e-wastes to collection points, and the system does not bear any cost in this stage.

4.1.1. Data related with collection points

Before providing the information and the data regarding collection points, it is important to get known with different types of WEEE. According to the EU directive, there are ten types of WEEE categories which are as follows:

- Large household appliances
- Small household appliances
- IT and telecommunications equipment
- Consumer equipment
- Lighting equipment
- Electrical and electronic tools (except large-scale stationary industrial tools)
- Toys, leisure, and sports equipment

- Medical devices (except all implanted and infected products)
- Monitoring and control instruments
- Automatic dispensers

The ones which are considered in this study are small and large household appliances, TV’s and monitors, and cooling and freezing appliances. They are the most common domestic e-waste types. The occurrence rates of these categories in collected WEEEs are as shown in Chart 4.1.

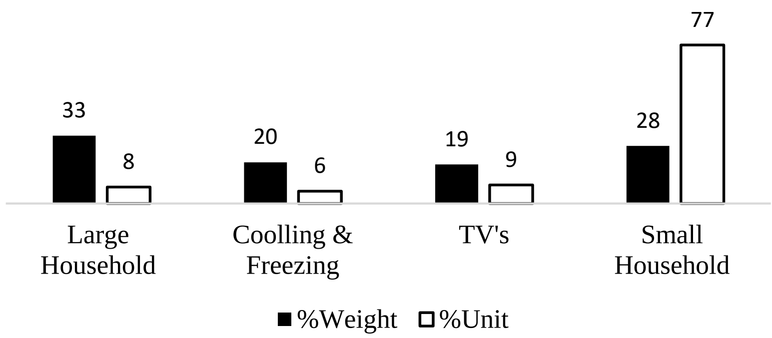

Chart 4.1 Occurrence rates of different types of WEEE in weight and unit percent

Based on (EU Directive, 2002) the target amount of WEEE collection for countries is 4kg/per capita, therefore, the desired total amount of collected WEEE in each city is the multiplication of the city population with 4. As it is shown in Figure 4.1 most of the eastern cities of Turkey are generating WEEE less than 4kg/capita, so there is no probability of collecting the target amount there. To handle this issue, the maximum collected WEEE amount in each city is computed as follows, for the cities whose estimation of WEEE generation is more than 4 kg/capita, the population is multiplied by 4 for the remaining ones, with generation estimation rate of smaller than 4 kg/capita, the population is multiplied by the generation estimation rate itself. By multiplication of the weight percentages of different categories stated in Chart 4.1 with the calculated collected WEEE amounts of cities in the previous step, the total weight of each product category in each collection point is computed. To obtain the number of products, the amounts are divided by the mean weights of each category which is 60, 45, 30, and 5kg for large household appliances, cooling and freezing, TV’s, and small household appliances respectively (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015). These calculated numbers are rounded to the nearest integers to be capable of representing the number of units of each product category for each collection point.

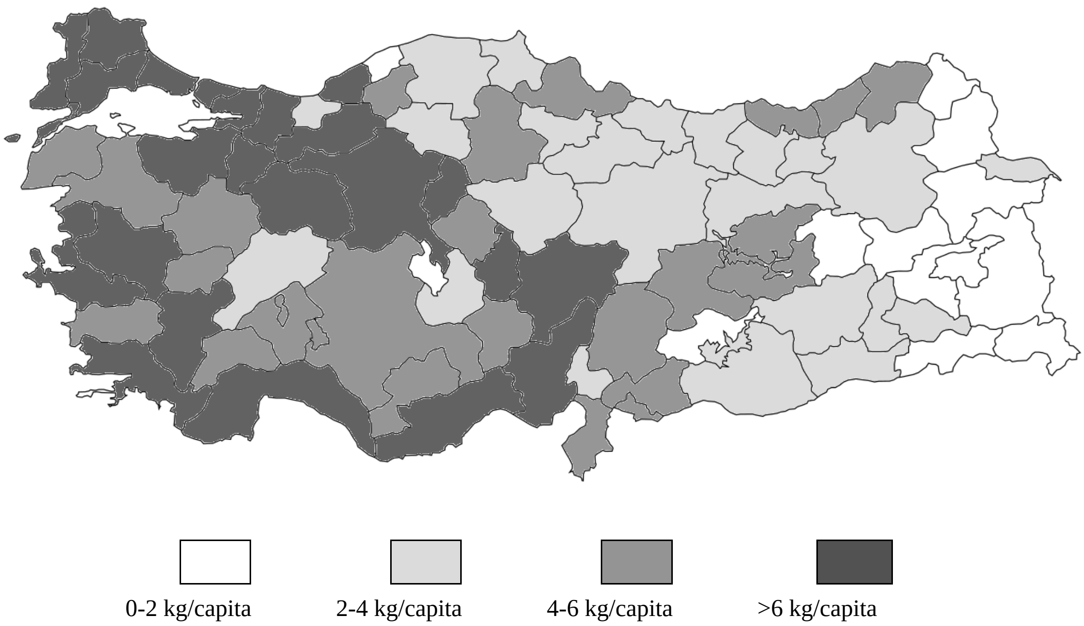

Figure 4.1 WEEE generation estimation in Turkey.

4.1.2. Data related with storage sites

The products existing in collection points are supposed to be transferred to storage sites. The suitable locations for storage sites are chosen among 21 cities, and in each city they can be built in 4 to 6 distinct types based on their capacities. Building more than one storage site in the same city is allowed. The other information related with storage sites is given in Table 4.1. As shown, the capacity limitations of the storage sites are volume type. In order not to exceed these capacities we need to have the volume of product categories which are given in Table 4.2. The minimum recycling rates which should be satisfied are determined by the EU directive and given in the first column of the table for each of product categories. The transportation costs of product categories (the transportation between collection points & storage sites, and storage sites & WEEE recycling facilities) are also given in the last column. The information about fixed costs and variable costs of storage sites are given in Table 4.3.

Table 4.1 Types and Capacities information of storage sites

Storage site	Type					
	Type**1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**
Adana	*	*	*			
Ankara	*	*	*	*	*	*
Antalya	*	*	*			
Bursa	*	*	*	*	*	*
Çanakkale	*	*	*			
Denizli	*	*	*			
Diyarbakır	*	*	*			
Elazig	*	*	*			
Erzurum	*	*	*			
Eskişehir	*	*	*			
Hatay	*	*	*			
Mersin	*	*	*			
İstanbul	*	*	*	*	*	*
İzmir	*	*	*	*	*	*
Kayseri	*	*	*			
Kocaeli	*	*	*	*	*	*
Konya	*	*	*			
Samsun	*	*	*			
Trabzon	*	*	*			
Van	*	*	*			
Zonguldak	*	*	*			
Min.capacity (m3)	**38,400**	**76,800**	**115,200**	**153,600**	**192,000**	**230,400**
Max.capacity (m3)	**48,000**	**96,000**	**144,000**	**192,000**	**240,000**	**288,000**

Table 4.2 Minimum recycling rates, volume, and transportation cost of product categories

Product categories	**Minimum recycling rate**	**Dimension (m^3)**	**Volume (m^3)**	**Transportation cost D/(product*km)**
Large household appliances	75%	0.6*0.6*0.9	0.324	0.0055
Cooling and freezing appliances	75%	0.6*0.6*1.5	0.54	0.0092
TV's and monitors	65%	0.4*0.4*0.5	0.08	0.0014
Small household appliances	50%	0.3*0.3*0.3	0.027	0.0005

Table 4.3 Fixed and variable costs of storage sites

Storage site type	**Fixed costs**			**Variable costs for each product category**			
	West	**Middle**	**East**	**C1**	**C2**	**C3**	**C4**
1	49,750	42,250	35,650	0.0972	0.162	0.024	0.0081
2	65,000	56,500	49,500	0.0486	0.081	0.012	0.0041
3	50,250	70,750	63,350	0.0432	0.072	0.0107	0.0036
4	103,000	92,500	84,700	0.0405	0.0675	0.01	0.0034
5	118,250	106,750	98,550	0.0324	0.054	0.008	0.0027
6	133,500	121,000	112,400	0.0324	0.054	0.008	0.0027

The following map depicts the candidate locations of storage sites. It has been tried to choose the candidate locations in a way that spread across the whole country.

Figure 4.2 Map of candidate locations for storage sites

4.1.3. Data related with WEEE-recycling facilities

The next facility is the WEEE-recycling facility. We have 21 of these capacitated facilities and there are 4 distinct types of them in terms of technology. While we have 2 types of manual recycling facilities, there are also 2 types of automatic ones. The candidate locations and capacity limitations of WEEE-recycling facilities are as presented in Table 4.4. Processing costs and fixed costs change based on technology type, as it is reflected in Table 4.5 the manual type technologies have lower annual fixed costs because of less complicated equipment but have higher processing costs because of the labour force. The recycling rates are determined as 93% for manual systems and 60% for automatic systems with shredders (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015) (Yuksel T, & Baylakoglu I., 2007).

Table 4.4 Candidate locations, types, and Minimum/Maximum capacity of WEEE-recycling facilities

WEEE-recycling facility	Type			
	Manual 1	Manual 2	Automatic 1	Automatic 2
Ankara	*	*	*	*
Bursa	*	*	*	*
Çanakkale	*		*	*
Diyarbakır	*			
Eskişehir	*		*	
Hatay	*			
Mersin	*			
İstanbul	*	*	*	*
İzmir	*	*	*	*
Kayseri	*		*	*
Kocaeli	*	*	*	*
Trabzon	*			
Min. capacity (kg/year)	3,200,000	6,400,000	6,400,000	12,800,000
Max. capacity (kg/year)	12,000,000	24,000,000	24,000,000	48,000,000

Table 4.5 Annual fixed costs and processing costs of different types of WEEE-recycling facilities

Recycling facility type	Annual fixed cost	Processing cost per kg
Manual 1	150,000	0,25
Manual 2	250,000	0,25
Automatic 1	500,000	0,1
Automatic 2	900,000	0,1

The following map shows the candidate location of WEEE-recycling facilities. As you see the candidate locations are chosen in a way that mostly cover the part of country with high amount of WEEE generation.

Figure 4.3 Map of candidate locations for WEEE-recycling facilities

4.1.4. Data related with secondary markets

After being recycled at WEEE recycling facilities, the obtained useful materials are sent to secondary markets to be sold, however, there are some limitations for it because each of useful materials can be sold at specific secondary markets. The market locations of useful materials are shown in Table 4.6.

Table 4.6 Market location for each type of useful material

Materials	Market
Ferrous metals	Hatay, Zonguldak, Karabük
Aluminum	Konya
Copper	Artvin, Diyarbakır, Samsun
Plastic, glass, and others	Bursa, İstanbul, İzmir, Kocaeli

Based on the table above a parameter named $marketlf$ is defined and shown in Table 4.7. This parameter shows the compatibility of useful material with the secondary market and is used in flow constraints between WEEE recycling facilities and secondary markets.

Table 4.7 Compatibility of useful materials with secondary markets

$market_{lf}$	Ferrous	Aluminium	Copper	Plastic	Glass	Others
Artvin	0	0	1	0	0	0
Diyarbakır	0	0	1	0	0	0
Hatay	1	0	0	0	0	0
Konya	0	1	0	0	0	0
Samsun	0	0	1	0	0	0
Zonguldak	1	0	0	0	0	0
Karabük	1	0	0	0	0	0
Bursa	0	0	0	1	1	1
İstanbul	0	0	0	1	1	1
İzmir	0	0	0	1	1	1
Kocaeli	0	0	0	1	1	1

The revenue gained by selling these materials and the transportation costs are as indicated in Table 4.8. As you see we do not decide on the locations of secondary markets and we are not charged for using them. They do not have any capacity limitations or fixed costs.

Table 4.8 Revenue and transportation cost of useful materials

Materials	Revenue (per KG)	Transportation cost/(ton*km)
Ferrous	0.2	0.048
Aluminum	1	0.083
Copper	4	0.083
Plastic	0.2	0.167
Glass	0.1	0.048

4.1.5. Data related with treatment facilities and hazardous material recycling facilities

The other materials that are obtained by the recycling process are hazardous materials. In this study, we have two types of them, chlorofluorocarbons and circuit boards. The materials have two ways to follow, the recyclable materials are sent to hazardous material recycling facility while the non- recyclable ones are transferred to treatment facilities. If the material is both recyclable and treatable, then the model decides on its amounts for being treated and recycled, otherwise, it will be directly brought to the facility which is compatible with its properties. The candidate locations of both treatment and hazardous recycling facilities are the same and are Bingöl, Burdur, Çankırı, Kirsehir, Tunceli, Bayburt, and Kırıkkale. The cities are chosen among less populated cities (to expose minimum number of people to threat of hazardous materials), with the maximum area coverage possible.

4.1.5.1. Properties of treatment facilities

In the treatment facility, we have two types of technologies, chemical treatment and incineration. The weight reduction rate (the percentage of reduction in weight of a material after the treatment process is called weight reduction rate) of the incineration is higher compared with the rate of chemical treatment, however, its fixed cost and processing cost is much less than the other one. As can be understood from Table 4.9, circuit boards are assumed to be non-treatable, however, CFCs are both treatable and recyclable and they are compatible with both treatment technologies.

Table 4.9 Properties of treatment facilities and hazardous materials

	incineration	**chemical treatment**
Min capacity of technology	20,000	150,000
Max capacity of technology	50,000	200,000
Fixed cost of treatment technology	10,000	22,000
Treatment Cost of hazardous material with technology q		
circuit board	-	-
CFC	0.09	0.27
Compatibility of hazardous material with technology q		
circuit board	-	-
CFC	1	1
Weight Reduction of hazardous material treated by technology q		
circuit board	-	-
CFC	0.85	0.05

4.1.5.2. Properties of hazardous material recycling facilities

Hazardous material recycling facilities are spread in 7 candidate locations and have 4 different types. All candidate cities are allowed to have all types and there is no limitation about having more than one facility in the same city. These types vary in capacities, the more the capacity increases, fixed cost swells however it causes the variable cost to decrease. The Table 4.10 provides some information about them.

Table 4.10 Capacity and cost information of Haz-Mat recycling facilities

	Fixed cost	**Min capacity**	**Max capacity**	**Variable recycling cost**
type1	273,440	1,400,000	2,304,000	0.255
type2	325,453	2,880,000	3,456,000	0.223
type3	431,085	4,032,000	4,608,000	0.2425
type4	495,715	5,760,000	6,912,000	0.198

The following map depicts the candidate locations of treatment facilities and hazardous material recycling facilities. These cities are chosen among the first 20 cities of Turkey with the least population. The ones which are located at borders of Turkey, like Kilis, Ardahan, Igdir, Kırklareli, and so on, are deleted because of political issues, and between the remaining ones, the mentioned seven locations are chosen.

Figure 4.4 Candidate locations of Haz-Mat recycling, and treatment facilities

Based on the performance of the treatment facility which is determined by $PercRecHazWasteng$ parameter, recyclable amounts of waste residues are sent to hazardous material recycling facilities. The remaining amount also is sent to disposals which are located at İstanbul, Bursa, İzmir, and Kocaeli. Disposal facilities have no cost, and we don’t decide about their locations. The disposal of the materials also costs nothing based on our assumptions.

For sake of simplicity, in the rest of the study, we will call the WEEE-recycling facility as WR, the treatment facility as TR, and the Haz-Mat recycling facility as HR.

4.2. Computational results and discussion

4.2.1. Definition of scenarios

Our main aim is to study the effect of hazardous material on reverse logistics network design of WEEE. For this purpose, we considered 36 scenarios differing in the values of parameters stated in Table 4.11 and applied them to check their effects on the network.

Table 4.11 Parameters of scenarios

Collection rate	Treatment facility rate	Hazardous material recycling facility rate
20% (low)	10% (low)	20% (low)
50% (medium)	30% (medium)	50% (medium)
70% (high)	90% (high)	90% (high)
100% (max)		

Before evaluating the results, some clarifications are required about the table of results. It shows the chosen facilities for all scenarios under a specific collection rate. Additional to optimum location, it includes information about number and types of facilities as well. In the last six rows of the table, some information is provided to compare the results, the first row shows the objective value, the second row gives the value of transportation cost for the whole network including all of the flows, the third row provides the WEEE-related cost, it is the summation of all cost except the ones which concerns hazardous materials, a more detailed explanation of last four columns is as follows:

(WEEE-related cost) = (Transportation cost of WEEEs from collection points to storage sites) (Handling cost of WEEEs at storage sites) + (Fixed cost of storage sites) + (transportation cost of WEEEs from storage sites to WR) + (fixed cost of WR) + (Processing cost at WR) + (Transportation cost of useful material obtained by WR processes to secondary markets)

(WEEE-related revenue) = (Revenue by selling useful material originated from WR)

(Haz-Mat-related cost) = (Fixed cost of TRs) + (Transportation of hazardous materials from WRs to TR) + (Treatment cost at TRs) + (Transportation cost from TRs to HRs) + (Transportation of wastes from TRs to disposals) + (Fixed cost of HRs) + (Recycling cost of hazardous materials at HRs) + (Transportation cost of useful material obtained by HR processes to secondary markets) + (Transportation of wastes from HRs to disposals)

(Haz-Mat-related revenue) = (Revenue by selling useful material originated from HR)

After clarifying these terms in tables, the results can be interpreted.

4.2.2. The results for scenarios with 20% collection rate

The results of the runs with the low collection rate are provided in Table 4.12. Accordingly, when the collection rate is low, the network is not affected by the performance of TR and HR, in terms of the number of selected facilities, however, the location of HR changes when its process is implemented inefficiently (performance level of 20%). Because of the low collection rate, the network prefers to have only HR and it neglects TR. Expectedly, in the constant collection rate and non-existence of TRs, the HR rate becomes the only affecting and determinant factor for the whole network. As demonstrated by Table 4.12, by the improvement of HR performance, the objective function also improves while the transportation cost, HR-related cost and revenue increase due to more useful material which is generated at the HR. Maps show the results for all scenarios with the collection rate of 20%.

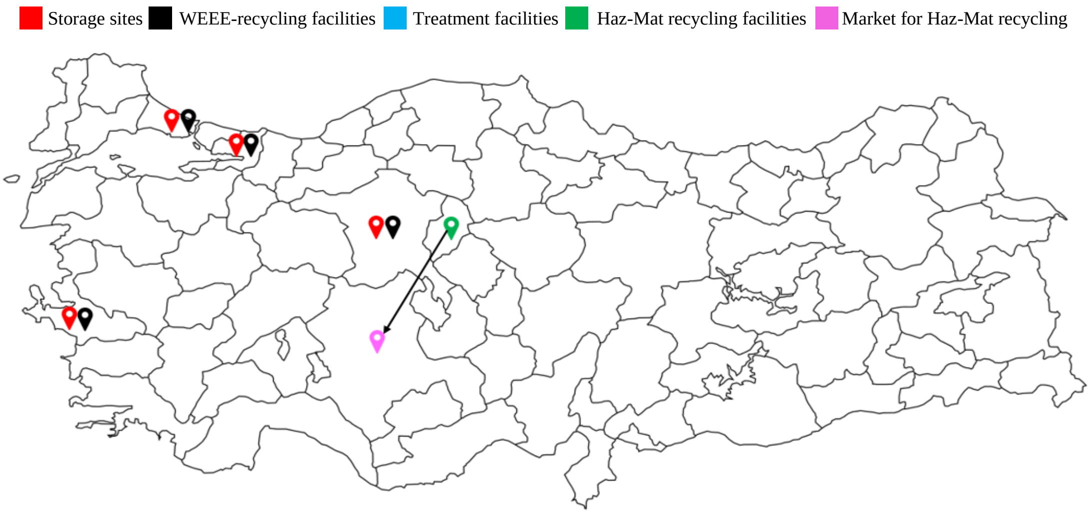

Figure 4.5 The map of the results for collection rate 20%, HR 20%, TR (10%, 30%, 90%)

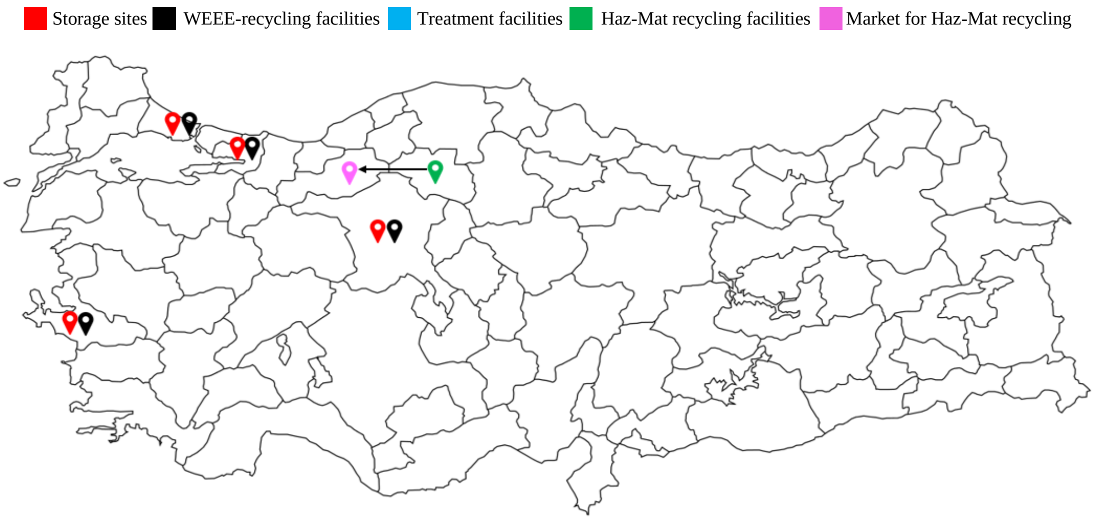

Figure 4.6 The map of the results for collection rate 20%, HR (50%, 90%), TR (10%, 30% ,90%)

Table 4.12 Results of scenarios with collection rate of 20%

Collection rate	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**
Treatment rate	**90**	**90**	**90**	**30**	**30**	**30**	**10**	**10**	**10**
Hazmat rate	**90**	**50**	**20**	**90**	**50**	**20**	**90**	**50**	**20**
Storage site									
Ankara type 3	1	1	1	1	1	1	1	1	1
İstanbul type 1	1	1	1	1	1	1	1	1	1
İzmir type 1	1	1	1	1	1	1	1	1	1
Kocaeli type 3	1	1	1	1	1	1	1	1	1
Total	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**
WR									
Ankara Automatic 1	1	1	1	1	1	1	1	1	1
İstanbul Manual 1	1	1	1	1	1	1	1	1	1
İzmir Manual 1	1	1	1	1	1	1	1	1	1
Kocaeli Manual 2	1	1	1	1	1	1	1	1	1
Total	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**
HR									
Çankırı type 1	1	1	0	1	1	0	1	1	0
Kırıkkale type 1	0	0	1	0	0	1	0	0	1
Total	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Objective	(2,538,515)	(2,067,917)	(1,734,314)	(2,538,515)	(2,067,917)	(1,734,314)	(2,538,514)	(2,067,917)	(1,734,314)
Transportation cost	3,913,717	3,795,721	3,687,879	3,913,715	3,795,721	3,687,879	3,913,716	3,795,721	3,687,879
WEEE-related cost	16,539,359	16,539,359	16,539,056	16,539,357	16,539,359	16,539,056	16,539,363	16,539,359	16,539,056
WEEE-related revenue	19,072,442	19,072,442	19,072,442	19,072,440	19,072,442	19,072,442	19,072,444	19,072,442	19,072,442
Haz-Mat-related cost	1,318,902	1,200,907	1,093,368	1,318,903	1,200,907	1,093,368	1,318,902	1,200,907	1,093,368
Haz-Mat-related revenue	1,324,335	735,742	294,297	1,324,335	735,742	294,297	1,324,335	735,742	294,297

4.2.3. The results for scenarios with 50% collection rate

To observe the effect of collection rate improvement, we ran the model for another 9 scenarios with the collection rate of 50%. The results are provided in Table 4.13. Expectedly, by the increase in the collection rate, the number of opened facilities increases. The number of storage sites reaches to 7 from 4, and by opening 3-4 more WRs, its number increases to 7-8 as well. When the collection rate is 50%, the network needs 2 HRs, however, it still doesn't include any TR, therefore its performance has no impact on the network. As can be inferred by the results, the change in performance of HR affects WR in terms of type and quantity, when HR performance is high, one more WR opens at Kocaeli. It also can affect the network to choose different locations for HR. According to the results, when HR processes are not implemented very well (20% and 50%), the network prefers to locate it in Burdur and Kırıkkale. Whenever its performance increases to its maximum, its location alters to Çankırı and Kırıkkale. The following maps show the location information of chosen facilities for 50% collection rate.

In the light of results it is comprehended that by improvement of HR performance and production of more useful material, transportation cost and HR- related cost increases, however, the objective improves.

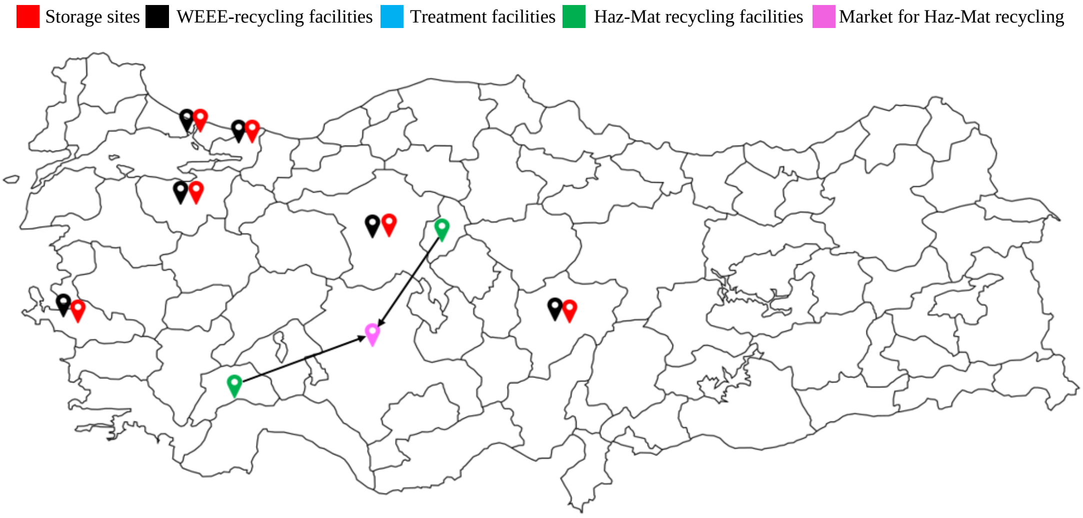

Figure 4.7 The map of the results for collection rate 50%, HR (20%, 50%), TR (10%, 30%, 90%)

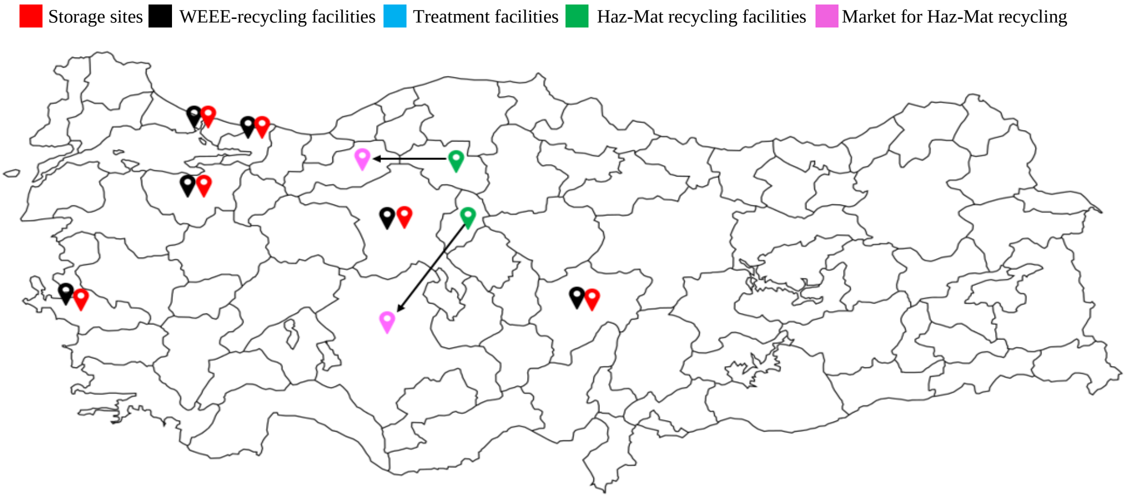

Figure 4.8 The map of the results for collection rate 50%, HR 90%, TR (10%, 30%, 90%)

Table 4.13 Results of scenarios with collection rate of 50%

Collection rate	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
Treatment rate	**90**	**90**	**90**	**30**	**30**	**30**	**10**	**10**	**10**
Hazmat rate	**90**	**50**	**20**	**90**	**50**	**20**	**90**	**50**	**20**
Storage site									
Ankara type 3	1	1	1	1	1	1	1	1	1
Bursa type 3	1	1	1	1	1	1	1	1	1
İstanbul type 4	1	1	1	1	1	1	1	1	1
İzmir type 3	1	1	1	1	1	1	1	1	1
Kayseri type 2	1	1	1	1	1	1	1	1	1
Kayseri type 3	1	1	1	1	1	1	1	1	1
Kocaeli type 3	1	1	1	1	1	1	1	1	1
Total	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**
WR									
Ankara Manual 1	1	1	1	1	1	1	1	1	1
Ankara Automatic 1	1	1	1	1	1	1	1	1	1
Bursa Manual 2	1	0	0	1	0	0	1	0	0
Bursa Automatic 1	0	1	1	0	1	1	0	1	1
İstanbul Manual 2	1	1	1	1	1	1	1	1	1
İzmir Manual 1	1	0	0	1	0	0	1	0	0
İzmir Manual 2	0	1	1	0	1	1	0	1	1
Kayseri Automatic 1	1	1	1	1	1	1	1	1	1
Kocaeli Manual 1	1	0	0	1	0	0	1	0	0
Kocaeli Manual 2	0	1	1	0	1	1	0	1	1
Kocaeli Automatic 1	1	0	0	1	0	0	1	0	0
Total	**8**	**7**	**7**	**8**	**7**	**7**	**8**	**7**	**7**
HR									
Burdur type1	0	1	1	0	1	1	0	1	1
Çankırı type1	1	0	0	1	0	0	1	0	0
Kırıkkale type1	1	1	1	1	1	1	1	1	1
Total	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Objective	(7,611,343)	(6,515,987)	(5,734,229)	(7,611,343)	(6,515,987)	(5,734,229)	(7,611,343)	(6,515,987)	(5,734,229)
Transportation cost	9,351,550	9,025,435	8,703,574	9,351,550	9,025,435	8,703,574	9,351,550	9,025,435	8,703,574
WEEE-related cost	38,629,037	38,521,469	38,519,073	38,629,037	38,521,469	38,519,073	38,629,037	38,521,469	38,519,073
WEEE-related revenue	46,356,319	46,356,319	46,356,310	46,356,319	46,356,319	46,356,310	46,356,319	46,356,319	46,356,310
Haz-Mat-related cost	3,426,778	3,158,218	2,838,750	3,426,778	3,158,218	2,838,750	3,426,778	3,158,218	2,838,750
Haz-Mat-related revenue	3,310,838	1,839,354	735,742	3,310,838	1,839,354	735,742	3,310,838	1,839,354	735,742

4.2.4. The results for scenarios with 70% collection rate

The next group of the results which are provided in Table 4.13 corresponds to the scenarios with the collection rate of 70%. As the table shows, when the collection rate increments, the network becomes more sensitive about the performances of HR and TR. As can be observed, this time changes in performances of TR and HR can affect the locations and types of all facilities. The maps demonstrate that when HR does not perform very well, and its rate is 20% the network prefers to have one storage site and WR at Eskişehir instead of Diyarbakır. Also, it locates the HR at Burdur and Kırıkkale. The reason is that when its rate is low, and low amount of useful material can be produced by the processes, HR tries to collect the hazardous material from the nearest cities possible because of minimizing transportation costs of hazardous materials (as shown on the table the transportation cost for scenarios with 20% HR performance, are the least in comparison with the other scenarios), so the network chooses facilities in a limited area which is the western part of Turkey. Based on the results given in the table, in scenarios with the 20% performance level of HR, the HR-related cost is much higher than its revenue, though the WRs are chosen very close to it. When the performance level of HR is medium, it becomes able to collect materials from far cities, because now its potential income from selling useful material is almost tripled (50%/20%=2.5). That is why the network opens the storage site and WR in Diyarbakır. As the performance of the HR process is not still so high (Despite sensible improvements, still HR-related cost is higher than its revenue when its rate is 50%), the network considers a TR close to Diyarbakır in Bingöl, to diminish the transportation cost. By the treatment process, its amount drops down to 15% of its initial amount (because of the weight reduction rate of incineration), and it positively affects the transportation costs. In the last part of these scenarios, when we increase the HR performance level to 90%, for the first time HR-based revenue exceeds its cost. This time as the performance level of HR is so high, the recycling of wastes coming from WR becomes profitable, and the network becomes able to collect WEEE's from far cities like Diyarbakır, and as it can produce useful materials in high amounts, it wants the coming amounts to be the maximum, that is why the network does not open any treatment facility.

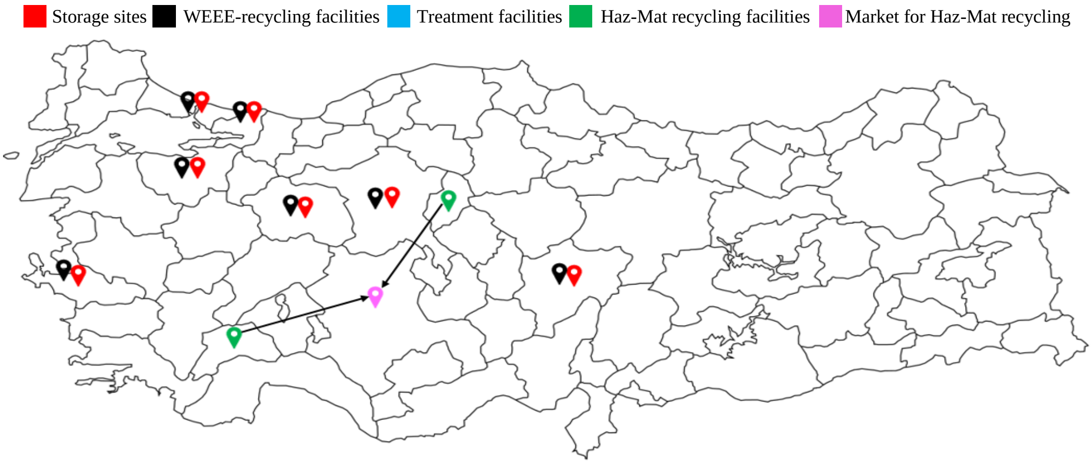

Figure 4.9 The map of the results for collection rate 70% HR 20%, TR (10%, 30%, 90%)

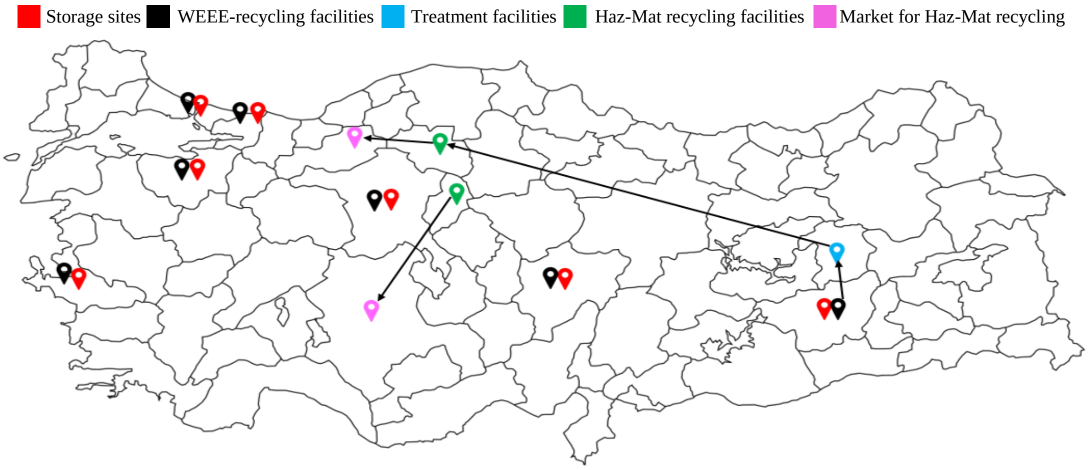

Figure 4.10 The map of the results for collection rate 70% HR 50%, TR (10%, 30%, 90%)

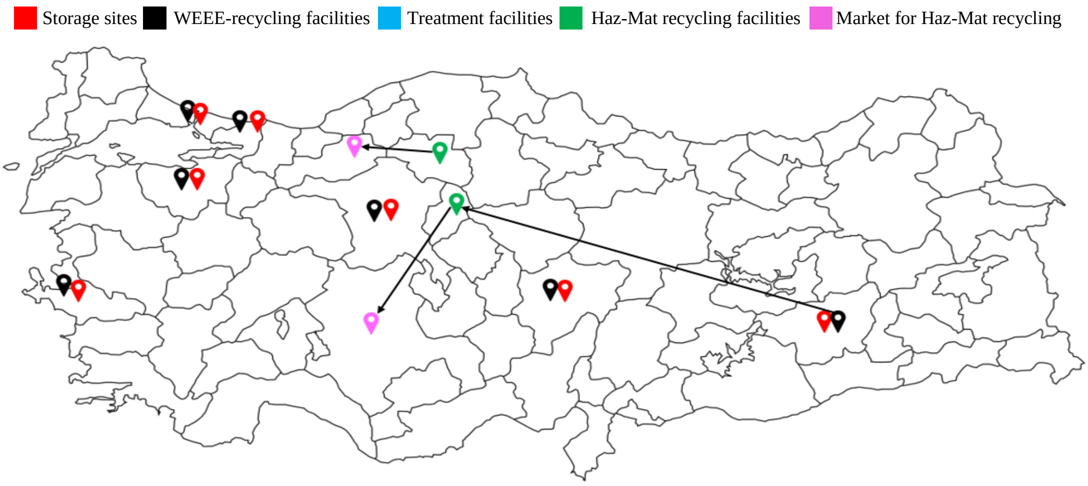

Figure 4.11 The map of the results for collection rate 70% HR 90%, TR (10%, 30%, 90%)

Table 4.14 Results of scenarios with collection rate of 70%

Collection rate	**70**	**70**	**70**	**70**	**70**	**70**	**70**	**70**	**70**
Treatment rate	**90**	**90**	**90**	**30**	**30**	**30**	**10**	**10**	**10**
Hazmat rate	**90**	**50**	**20**	**90**	**50**	**20**	**90**	**50**	**20**
Storage sites									
Ankara type 3	1	1	1	1	1	1	1	1	1
Ankara type 5	1	1	1	1	1	1	1	1	1
Bursa type 3	1	1	1	1	1	1	1	1	1
Diyarbakır type 1	1	1	0	1	1	0	1	1	0
Eskişehir type 3	0	0	1	0	0	1	0	0	1
İstanbul type 2	0	0	1	0	0	1	0	0	1
İstanbul type 3	1	1	1	1	1	1	1	1	1
İstanbul type 4	1	1	0	1	1	0	1	1	0
İzmir type 3	0	0	1	0	0	1	0	0	1
İzmir type 4	1	1	0	1	1	0	1	1	0
Kayseri type 1	1	1	0	1	1	0	1	1	0
Kayseri type 2	0	0	1	0	0	1	0	0	1
Kayseri type 3	1	1	1	1	1	1	1	1	1
Kocaeli type 3	1	1	1	1	1	1	1	1	1
Total	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**
WR									
Ankara Manual 2	1	1	1	1	1	1	1	1	1
Ankara Automatic 2	1	1	1	1	1	1	1	1	1
Bursa Manual 2	1	1	1	1	1	1	1	1	1
Diyarbakır Manual 1	1	1	0	1	1	0	1	1	0
Eskişehir Automatic 1	0	0	1	0	0	1	0	0	1
İstanbul Manual 1	0	0	1	0	0	1	0	0	1
İstanbul Manual 2	1	1	1	1	1	1	1	1	1
İstanbul Automatic 1	1	1	0	1	1	0	1	1	0
İzmir Manual 2	1	1	1	1	1	1	1	1	1
Kayseri Automatic 1	1	1	1	1	1	1	1	1	1
Kocaeli Manual 2	1	1	1	1	1	1	1	1	1
Total	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**

Table 4.15 Results of scenarios with collection rate of 70% (continued)

Collection rate	**70**	**70**	**70**	**70**	**70**	**70**	**70**	**70**	**70**
Treatment rate	**90**	**90**	**90**	**30**	**30**	**30**	**10**	**10**	**10**
Hazmat rate	**90**	**50**	**20**	**90**	**50**	**20**	**90**	**50**	**20**
HR									
Burdur type1	0	0	1	0	0	1	0	0	1
Çankırı type1	0	1	0	0	1	0	0	1	0
Çankırı type2	1	0	0	1	0	0	1	0	0
Kırıkkale type1	1	0	0	1	0	0	1	0	0
Kırıkkale type2	0	1	1	0	1	1	0	1	1
Total	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
TR									
Bingöl incineration	0	1	0	0	1	0	0	1	0
Total	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**
Objective	(11,096,863)	(9,532,984)	(8,405,711)	(11,096,863)	(9,532,606)	(8,405,711)	(11,096,863)	(9,532,496)	(8,405,711)
Transportation cost	12,874,914	12,359,117	12,031,906	12,874,914	12,358,815	12,031,906	12,874,914	12,358,705	12,031,906
WEEE-related cost	54,427,851	54,446,708	54,531,496	54,427,851	54,446,749	54,531,496	54,427,850	54,446,728	54,531,497
WEEE-related revenue	65,501,090	65,501,090	65,500,628	65,501,090	65,501,110	65,500,628	65,501,090	65,501,102	65,500,628
Haz-Mat-related cost	4,611,539	4,082,268	3,593,457	4,611,538	4,081,147	3,593,458	4,611,539	4,080,775	3,593,456
Haz-Mat-related revenue	4,635,162	2,560,870	1,030,036	4,635,162	2,559,391	1,030,036	4,635,162	2,558,898	1,030,036

When we compare the results of the scenarios with 90% and 50% rate of HR performances, the only observed difference is the existence of TR. In the scenario with lower performance, there is a treatment facility at Bingöl which receives hazardous materials from WR in Diyarbakır, after the treatment processes it transmits the recyclable waste residues to the HR in Çankırı. For the scenario with the higher performance of HR, there is no TR and the hazardous materials are directly sent to HR in Kırıkkale. To observe what happens that makes including TR profitable for one of them, and non-profitable for the other one, we calculated the cost for each of the situations for both HR rates. Table 4.16 provides details about the calculations and the results. According to the results, when the HR performance level is 50%, by the existence of a treatment facility the network saves more than 2000 TRY, however, when the HR rate is 90%, by the non-existence of the treatment facility, network saves more than 9000 TRY. Though these costs are so little in comparison with the total cost, but despite being small they can change the network structure.

Table 4.16 comparison of costs for two different locations when collection rate is 70%

		For 90% TR and 50% HR	**For 90% TR and 90% HR**
With treatment facility in Bingöl	**Transportation from WR(Diyarbakır) to TR(Bingöl)**	35,200*0.00094*142	35,200*0.00094*142
	Fixed cost of opening TR(Bingöl)	10,000	10,000
	Treatment cost at TR(Bingöl)	35,200*0.09	35,200*0.09
	Transportation cost from TR(Bingöl) to HR(Çankırı)	35,200*0.15***(0.9)***850* 0.000019	35,200*0.15***(0.9)***850* 0.000019
	Recycling process at HR(Çankırı)	35,200*0.15***(0.9)***0.255	35,200*0.15***(0.9)***0.255
	Revenue earned by selling useful material at HR(Çankırı)	35,200*0.15*0.9***(0.5)***0.93 4	35,200*0.15*0.9***(0.9)***0.934
	Cost	**16,935.81**	**15,160.46**
Without treatment facility	**Transportation from WR(Diyarbakır) to HR(Kırıkkale)**	35,200*806*0.00094	35,200*806*0.00094
	Recycling process at HR(Kırıkkale)	35,200*0.255	35,200*0.255
	Revenue earned by selling useful material at HR(Kırıkkale)	35,200***(0.5)***0.934	35,200***(0.9)***0.934
	Cost	**19,206.52**	**6,055.8**

4.2.5. The results for scenarios with 100% collection rate

In the last part, the results of scenarios with the collection rate of 100% are provided. The number of storage sites and WR increases by the improvement of the collection rate. Though the number of HR remains the same as previous scenarios when the collection rate was 70% or 50%, their types change to the ones with much higher capacities. Based on the results, in these scenarios, the changes in performances of HR and TR can influence the network in terms of location, type and the number of facilities. When HR performs at its lowest level and its processes are not profitable, the model chooses one more WR in İstanbul. In this situation it locates the HRs at Burdur and Kırıkkale but whenever its performance improves to 50% or 90%, the extra WR facility at İstanbul is closed and locations of HR are selected as Burdur and Çankırı. The results show that the improvement of TR performance has almost no effect on the objective. In contradiction with it, the improvement of HR can have a sensible positive impact on the objective function value. The following maps depict the results of these scenarios.

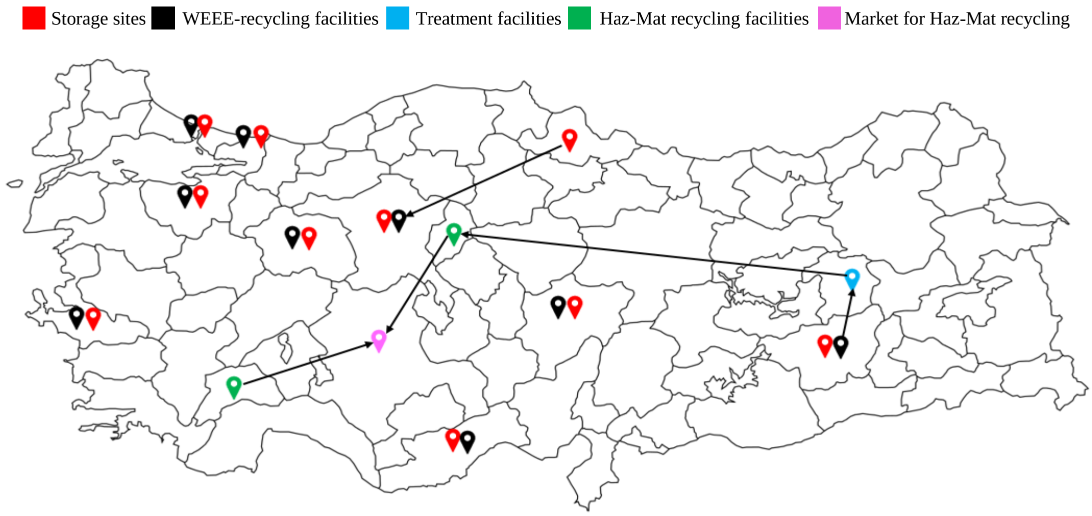

Figure 4.12 The map of results for collection rate 100%, HR 20%, TR (10%, 30%, 90%)

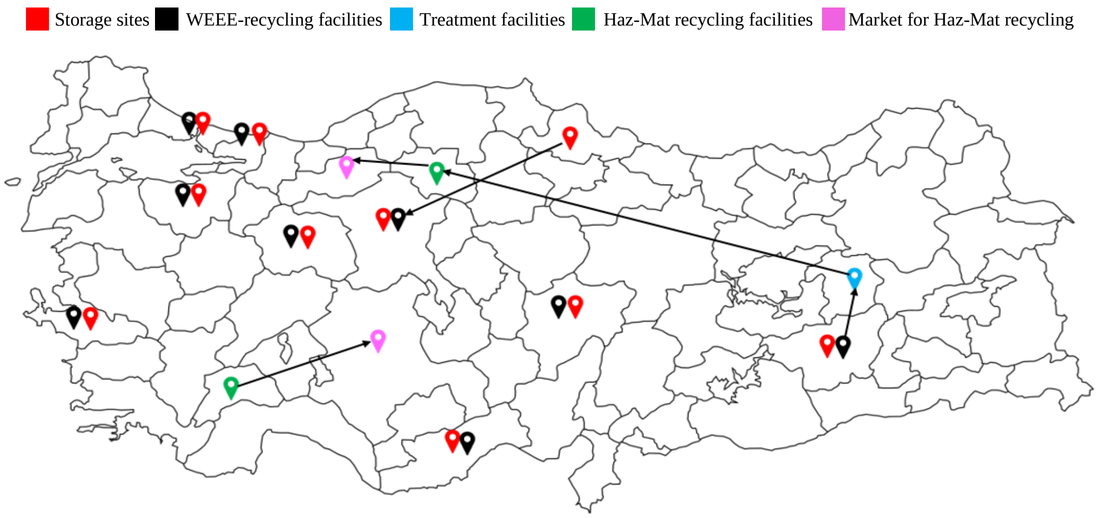

Figure 4.13 The map of results for collection rate 100%, HR (50%, 90%), TR (10%, 30%, 90%)

Table 4.17 Results of scenarios with collection rate of 100%

Collection rate	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Treatment rate	**90**	**90**	**90**	**30**	**30**	**30**	**10**	**10**	**10**
Hazmat rate	**90**	**50**	**20**	**90**	**50**	**20**	**90**	**50**	**20**
Storage site									
Ankara type 3	1	1	1	1	1	1	1	1	1
Ankara type 6	1	1	1	1	1	1	1	1	1
Bursa type 3	1	1	1	1	1	1	1	1	1
Diyarbakır type 2	1	1	1	1	1	1	1	1	1
Eskişehir type 3	1	1	1	1	1	1	1	1	1
Mersin type 2	1	1	1	1	1	1	1	1	1
İstanbul type 3	1	1	1	1	1	1	1	1	1
İstanbul type 6	1	1	1	1	1	1	1	1	1
İzmir type 2	1	1	1	1	1	1	1	1	1
İzmir type 3	1	1	1	1	1	1	1	1	1
Kayseri type 3	1	1	1	1	1	1	1	1	1
Kocaeli type 3	1	1	1	1	1	1	1	1	1
Samsun type 2	1	1	1	1	1	1	1	1	1
Total	13	13	13	13	13	13	13	13	13
WR									
Ankara Manual 2	1	1	1	1	1	1	1	1	1
Ankara Automatic 1	1	1	1	1	1	1	1	1	1
Ankara Automatic 2	1	1	1	1	1	1	1	1	1
Bursa Manual 2	1	1	1	1	1	1	1	1	1
Diyarbakır Manual 1	1	1	1	1	1	1	1	1	1
Eskişehir Manual 1	1	1	0	1	1	0	1	1	0
Eskişehir Automatic 1	0	0	1	0	0	1	0	0	1
Mersin Manual 1	1	1	1	1	1	1	1	1	1
İstanbul Manual 1	0	0	1	0	0	1	0	0	1
İstanbul Manual 2	1	1	1	1	1	1	1	1	1
İstanbul Automatic 1	0	0	1	0	0	1	0	0	1
İstanbul Automatic 2	1	1	0	1	1	0	1	1	0
İzmir Manual 1	1	1	1	1	1	1	1	1	1
İzmir Manual 2	1	1	1	1	1	1	1	1	1
Kayseri Automatic 1	1	1	1	1	1	1	1	1	1
Kocaeli Manual 1	1	1	1	1	1	1	1	1	1
Kocaeli Manual 2	1	1	1	1	1	1	1	1	1
Total	**14**	**14**	**15**	**14**	**14**	**15**	**14**	**14**	**15**

Table 4.18 Results of scenarios with collection rate of 100% (continued)

Collection rate	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Treatment rate	**90**	**90**	**90**	**30**	**30**	**30**	**10**	**10**	**10**
Hazmat rate	**90**	**50**	**20**	**90**	**50**	**20**	**90**	**50**	**20**
HR									
Burdur type 1	1	1	1	1	1	1	1	1	1
Çankırı type 4	1	1	0	1	1	0	1	1	0
Kırıkkale type 4	0	0	1	0	0	1	0	0	1
Total	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
TR									
Bingöl incineration	1	1	1	1	1	1	1	1	1
Total	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Objective	(16,207,275)	(13,934,700)	(12,307,349)	(16,205,576)	(13,934,700)	(12,308,758)	(16,204,960)	(13,934,536)	(12,308,136)
Transportation cost	18,209,100	17,553,923	16,891,399	18,208,160	17,553,923	16,890,331	18,207,903	17,553,770	16,891,059
WEEE-related cost	77,148,563	77,148,438	77,204,111	77,148,432	77,148,438	77,203,356	77,148,418	77,148,418	77,223,241
WEEE-related revenue	93,260,128	93,260,128	93,260,029	93,260,128	93,260,128	93,260,128	93,260,128	93,260,128	93,260,133
Haz-Mat-related cost	6,489,582	5,833,384	5,211,967	6,487,629	5,833,384	5,210,572	6,487,000	5,832,868	5,191,034
Haz-Mat-related revenue	6,585,293	3,656,395	1,463,398	6,581,510	3,656,395	1,462,558	6,580,249	3,655,694	1,462,278

4.3. Evaluating the environmental aspect of the proposed network

We have 36 scenarios, categorized in four groups based on collection rates, each of these four groups has 9 diverse scenarios based on HR and TR rates (3*3 = 9). To observe the environmental aspect of the problem, we choose the optimum of each of these groups and run the model for these four optimum scenarios with another dataset. In the new dataset everything is the same as the old one except the candidate locations of HR and TR. As previously mentioned in the Data description part, in the old dataset the candidate locations of HR and TR are chosen in a way that includes the least populated cities as much as possible. The purpose behind that is to protect the maximum number of people from the threat of hazardous material, and to minimize the population exposure. We know that in this situation, the network would bear an extra cost because of the higher transportation costs.

As you remember, the amount of collected WEEE is calculated by multiplication of estimation of WEEE generation by population, therefore, populated cities have more collected WEEE, and most probably facilities like storage sites, and WRs tend to be located in these cities to reduce the transportation cost. Additionally, secondary markets, and disposals are also located in densely populated cities, so if we let the network choose the Haz-Mat recycling and treatment facility among crowded cities, the transportation cost will be lower, however much more people will be exposed to the danger of hazardous material. To compare the result of these two datasets, to observe the burden of hazardous material on the network, and to check the revenue which is sacrificed for having an environment-friendly network, the results are provided in tables. We have three assupmtions here: First, we do not have any specific radius of influence for haz-mat recycling and haz-mat treatment facilities to obtain the number of exposed people to the threat of hazardous materials, therefore, we assumed that the population exposure of a chosen city is proportional to its density of inhabitants which is calculated by population of city / area of city. Second, the population of all cities are evenly distributed.

Before checking the results, we will define the differences between the two datasets. The new dataset has four more location options for treatment and hazmat recycling facilities, which are İstanbul, İzmir, Kocaeli, and Bursa. The fixed costs of opening HRs are higher for these cities (prices are higher for bigger and crowded cities) and are as follow (The remaining properties of HRs are the same).

Table 4.19 The fixed cost of opening HRs at recently added candidate locations in new dataset

Type of HR facility	Fixed cost
type1	373,440
type2	442,120
type3	559,657
type4	606,826

4.3.1. The results for scenarios with 20% collection rate

After getting known with the new dataset, now we can evaluate the results. The first group of results corresponds to the collection rate of 20%. The optimum scenario in the old dataset for the 20% collection rate is the ones with the HR rate of 90%, no matter what the treatment rate is. We consider the one with the treatment rate of 90% as the optimum. Table 4.20 and Table 4.21 compare the results of the optimum scenario and the results of the same scenario in the new dataset. Based on the results, the difference between the results of the new dataset and the old one is related with the location of HRs and types of some of the facilities. As you see, even one facility and its location can make big differences in terms of revenue and environmental issues. As it is shown on the table, when the collection rate is 20%, by sacrificing 379,176 TRY of the revenue, we can build hazardous material recycling facilities in much safer locations. Based on the results of new dataset, the HR is decided to be built in Kocaeli with the population exposure of 1,906,391/3,626=525.755 people per km^2, however, if we consider the potential threat of hazardous materials and select their locations from less populated cities, Çankırı will be chosen as the suitable location for HR which its corresponding population exposure is 216,362/1,347 =160.625 people per km^2. It means that just because of having 15%

more revenue, we threat 365.13 more people per km^2 by the hazard of these materials, which is 227% more than population exposure of the environment friendly network. Results shows that the decrease in transportation cost in new dataset is 13% which it is caused by 35% decrease in the cost of Haz-Mat related parts. As you see on the table, the revenues do not change, additionally there is no change in the cost related with non-hazardous part of the network which is called WEEE-related cost in this problem.

Table 4.20 Comparisons of selected facilities in old and new datasets for collection rate 20%.

Results of old dataset for collection rate of 20%	Results of new dataset for collection rate of 20%
Storage site	
Ankara type 3	Ankara type 3
İstanbul type 1	İstanbul type 2
İzmir type 1	İzmir type 1
Kocaeli type 3	Kocaeliv3
Total = 4	**Total = 4**
WR	
Ankara Automatic 1	Ankara Manual 1
İstanbul Manual 1	İstanbul Manual 2
İzmir Manual 1	İzmir Manual 3
Kocaeli Manual 2	Kocaeli Manual 4
Total = 4	**Total = 4**
HR	
Çankırı type 1	Kocaeli type 1
Total = 1	**Total = 1**

Table 4.21 Comparisons of results in old and new datasets for collection rate 20%.

	Results of old dataset for collection rate of 20%	Results of new dataset for collection rate of 20%	Difference
Objective	(2,538,515)	(2,917,691)	**15%**
Transportation cost	3,913,717	3,404,319	**-13%**
WEEE-related cost	16,539,359	16,646,353	**1%**
WEEE-related revenue	19,072,442	19,092,216	**0%**
Haz-Mat-related cost	1,318,902	852,508	**-35%**
Haz-Mat-related revenue	1,324,335	1,324,335	**0%**
Population exposure per km^2	160.625	525.755	**227%**

4.3.2. The results for scenarios with 50% collection rate

After comparing the results for the collection rate of 20%, we evaluate the results of the collection rate 50% which are provided in Table 4.22 and Table 4.23. The optimum scenario in this category is the one with 90% HR rate and 90% TR rate. We ran the same scenario for the new dataset as well. Based on the provided results, we observe just some minor differences in types of storage sites and WEEE-recycling facilities in the optimum solutions of the model. Expectedly the locations of HRs completely differ from the old dataset in the new one. As you see when the HR location is limited to less populated cities, the network tends to have two WRs at Ankara which is very close to selected HR in Kırıkkale and Çankırı, but in the new dataset it opens that WR in İzmir instead of Ankara, because one of the chosen HR is located there. By letting the model choose facilities in populated cities, the revenue of the network will increase about 17% which is affected by a 17% decrease in transportation cost. Again, the revenues of Haz-Mat related part and WEEE-related part do not change, just we have a significant decrease in Haz-Mat related cost which is caused by transportation. As mentioned, in the old dataset, two HRs are chosen to be opened at Çankırı and Kırıkkale which means population exposure of (216,362/1,347) + (286,602/4,365) = 226.284 people per km^2. In the new one İzmir and Kocaeli are selected which expose (1,906,391/3,626) + (4.320.519/7,340) = 1,114.381 people per m^2 to hazardous material. The population exposure in the new dataset is extremely high and it is 392% more than the old one. Therefore, in the collection rate of 50%, to increase the revenue about 17%, we have to expose 392% of more people per m^2 to the danger of hazardous materials.

Table 4.22 Comparisons of selected facilities in old and new datasets for collection rate 50%.

Results of old dataset for collection rate of 50%	Results of new dataset for collection rate of 50%
Storage site	
Ankara type 3	Ankara type 3
Bursa type 3	Bursa type 2
İstanbul type 4	İstanbul type 4
İzmir type 3	İzmir type 4
Kayseri type 2	Kayseri type 2
Kayseri type 3	Kayseri type 3
Kocaeli type 3	Kocaeli type 3
Total = 7	**Total = 7**
WR	
Ankara Manual 1	Ankara Manual 1
Ankara Automatic 1	Bursa Manual 1
Bursa Manual 2	İstanbul Manual 2
İstanbul Manual 2	İzmir Manual 1
İzmir Manual 1	İzmir Automatic 1
Kayseri Automatic 1	Kayseri Automatic 1
Kocaeli Manual 1	Kocaeli Manual 2
Kocaeli Automatic 1	Kocaeli Automatic 1
Total = 8	**Total = 8**
HR	
Çankırı type 1	İzmir type 1
Kırıkkale type 1	Kocaeli type 1
Total = 2	**Total = 2**

Table 4.23 Comparisons of results in old and new datasets for collection rate 50%.

	Results of old dataset for collection rate of 50%	Results of new dataset for collection rate of 50%	Difference
Objective	(7,611,342)	(8,904,679)	**17%**
Transportation cost	9,351,549	7,790,986	**-17%**
WEEE-related cost	38,629,037	38,717,103	**0%**
WEEE-related revenue	46,356,319	46,356,319	**0%**
Haz-Mat-related cost	3,426,777	2,045,375	**-40%**
Haz-Mat-related revenue	3,310,838	3,310,838	**0%**
Population exposure per km^2	226.284	1,114.381	**392%**

4.3.3. The results for scenarios with 70% collection rate

The next set of scenarios is the ones with the collection rate of 70%. The optimum scenario for this category is the one with 90% HR performance (notice that as treatment facility is not selected in these scenarios, the TR performance does not affect the objective and it is the same for all scenarios with 90% HR performance). If we want to compare the results of these two datasets, we have an additional location for selected storage sites and WR which is Diyarbakır. The selected facilities in Diyarbakır have the least capacities. The selected HRs are located at Çankırı and Kırıkkale, which together expose 226.284 people per km^2 to the hazardous material. For the new dataset, the facilities are concentrated in the middle and western parts of Turkey and we do not have any eastern city like Diyarbakır in it. The number of opened WRs is more than its number in old dataset results and it considers more WEEE-recycling facilities in İzmir and Kocaeli where HRs are also located. The population exposure of the new dataset is 1,114.381 people per m^2. All in all, when the collection rate is 70%, by neglecting the environmental issues of the problem, we can have 16% more income, however, the network will expose 392% more people to hazardous material. Similar to the previous group of scenarios, the revenues of the Haz-Mat and WEEE parts do not change, but there is a significant change in Haz-Mat based cost, which is caused by transportation costs. Based on the tables by sacrificing 1,182,196 TRY of the revenue which contributes to 14% of it, we can have a much safer network which exposes much fewer people to the threat of hazardous materials.

Table 4.24 Comparisons of selected facilities in old and new datasets for collection rate 70%.

Results of old dataset for collection rate of 70%	**Results of new dataset for collection rate of 70%**
Storage site	
Ankara type 3	Ankara type 3
Ankara type 5	Ankara type 4
Bursa type 3	Bursa type 3
Diyarbakır type 1	İstanbul type 3
İstanbul type 3	İstanbul type 4
İstanbul type 4	İzmir type 2
İzmir type 4	İzmir type 3
Kayseri type 1	Kayseri type 2
Kayseri type 3	Kayseri type 3
Kocaeli type 3	Kocaeli type 3
Total = 10	**Total = 10**
WR	
Ankara Manual 2	Ankara Manual 2
Ankara Automatic 2	Ankara Automatic 1
Bursa Manual 2	Bursa Manual 2
Diyarbakır Manual 1	İstanbul Manual 1
İstanbul Manual 2	İstanbul Manual 2
İstanbul Automatic 1	İzmir Manual 2
İzmir Manual 2	İzmir Automatic 1
Kayseri Automatic 1	Kayseri Automatic 1
Kocaeli Manual 2	Kocaeli Manual 2
	Kocaeli Automatic 1
Total = 9	**Total = 10**
HR	
Çankırı type 2	İzmir type 1
Kırıkkale type 1	Kocaeli type 2
Total = 2	**Total = 2**

Table 4.25 Comparisons of results in old and new datasets for collection rate 70%.

	Results of old dataset for collection rate of 70%	**Results of new dataset for collection rate of 70%**	**Difference**
Objective	(11,096,863)	(12,923,059)	**16%**
Transportation cost	12,874,913	10,760,959	**-16%**
WEEE-related cost	54,427,850	54,546,036	**0%**
WEEE-related revenue	65,501,090	65,501,090	**0%**
Haz-Mat-related cost	4,611,538	2,667,155	**-42%**
Haz-Mat-related revenue	4,635,161	4,635,161	**0%**
Population exposure per km^2	226.284	1,114.381	**392%**

4.3.4. The results for scenarios with 100% collection rate

In the last part we will discuss the results for the 100% collection rate. The optimum scenario for this group of collection rate is the one with 90% HR and TR performances. We applied the same scenario to the new dataset and we obtained the results. based on the results, the old dataset tends to have low capacity facilities at more locations, however, the new dataset tries to have high capacity facilities in densely populated cities. As you see on the table, again we have one more location for storage sites of the old dataset which is Samsun and it has the lowest possible capacity. Additionally, by the improvement of collection rate, the new dataset prefers to have more WR, for instance here in the new dataset it decides to have 3 WRs at Kocaeli where the HRs are also located. It is concluded from the table that if we want to build all facilities in densely populated cities, we will benefit from earning 17% more revenue mostly caused by a 17% decrease in transportation cost. The costs related with Haz-Mat part will decrease by 44%, while the WEEE-related cost remains the same. There is also no change in terms of income earned by Haz-Mat recycling and WEEE-recycling processes, However, there is again an extreme change in population exposure. While the population exposure in old dataset is (216,362/1,347) + (286,602/4,365) + (281,205/8,125) = 260.893 people per km^2 , for the new one it is (1,906,391/3,626) + (4.320.519/7,340) + (281,205/8,125) = 1,148.990 people per m^2. In the new dataset just because of having 17% higher revenue, we will expose 340% more people to hazardous material.

Table 4.26 Comparisons of selected facilities in old and new datasets for collection rate 100%.

Results of old dataset for collection rate of 100%	Results of new dataset for collection rate of 100%
Storage site	
Ankara type 3	Ankara type 3
Ankara type 6	Ankara type 5
Bursa type 3	Bursa type 3
Diyarbakır type 2	Diyarbakır type 2
Eskişehir type 3	Eskişehir type 3
Mersin type 2	Mersin type 2
İstanbul type 3	İstanbul type 3
İstanbul type 6	İstanbul type 6
İzmir type 2	İzmir type 3
İzmir type 3	İzmir type 4
Kayseri type 3	Kayseri type 3
Kocaeli type 3	Kocaeli type 3
Samsun type 2	
Total = 13	**Total = 12**
WR	
Ankara Manual 2	Ankara Manual 2
Ankara Automatic 1	Ankara Automatic 1
Ankara Automatic 2	Bursa Manual 2
Bursa Manual 2	Diyarbakır Manual 1
Diyarbakır Manual 1	Eskişehir Manual 1
Eskişehir Manual 1	Mersin Manual 1
Mersin Manual 1	İstanbul Manual 1
İstanbul Manual 2	İstanbul Manual 2
İstanbul Automatic 2	İstanbul Automatic 1
İzmir Manual 1	İzmir Manual 2
İzmir Manual 2	İzmir Automatic 1
Kayseri Automatic 1	Kayseri Automatic 1
Kocaeli Manual 1	Kocaeli Manual 1
Kocaeli Manual 2	Kocaeli Manual 2
	Kocaeli Automatic 2
Total = 14	**Total =15**
HR	
Burdur type 1	İzmir type 1
Çankırı type 4	Kocaeli type 4
Total = 2	**Total = 2**
TR	
Bingöl incineration	Bingöl incineration
Total = 1	**Total = 1**

Table 4.27 Comparisons of results in old and new datasets for collection rate 100%.

	Results of old dataset for collection rate of 100%	**Results of new dataset for collection rate of 100%**	**Differences**
Objective	(16,207,275)	(19,032,582)	**17%**
Transportation cost	18,209,100	15,043,548	**-17%**
WEEE-related cost	77,148,563	77,176,974	**0%**
WEEE-related revenue	93,260,128	93,260,133	**0%**
Haz-Mat-related cost	6,489,582	3,630,826	**-44%**
Haz-Mat-related revenue	6,585,293	6,580,249	**0%**
Population exposure per km^2	260.893	1,148.990	**340%**

4.4. Summary of the chapter

In this chapter, the results for 36 different scenarios are provided. As the collection rate extremely affects the network, to observe the effect of other chosen parameters, by fixing the collection rate, four groups of results are obtained, each including 9 scenarios with equal collection rates. The comparison-based analysis is done inside each of the groups. Additionally, the results of each group are compared with its superior group (for instance, the results of 20% collection rate group is compared with 50% collection rate one). In the last part to evaluate the environmental aspect of the problem, the optimum scenario of each group is compared with results of the same scenario by non-environmental-friendly dataset. Some of obtained results are as follows:

- The environmental benefits of having HRs and TRs in less populated cities are incomparably high from its economic burden on the network. By just spending a little more on transportation cost, the network becomes able to save millions of people from the danger exposed by hazardous materials.

- The most affecting parameter of the network is its collection rate. Its variations can extremely affect the locations, number and types of facilities, the total revenue, the transportation cost.

- The second affecting parameter is the performance level of HR. It also affects the network as the collection rate does, but its impact is less intense in comparison with the collection rate.

- TR performance is the least significant parameter. It can cause little and almost indiscernible changes in objective and it has no impact on types and locations of facilities. It is opened in high collection rate whenever the HR performance is not good nor bad, to reduce the transportation cost of hazardous materials originating from WRs far from HRs, or to reduce the amount of materials and build the network with a minimum fixed cost of opening facilities when the collection rate is maximum.

- It is revealed by the results that having consortiums for companies will be much profitable. For instance, when a company wants to establish this network and collect 50% of e-wastes, its revenue will be 7,611,343 TRY, however, if it collects the same amount of WEEE in a consortium with a collection rate of 100%, it will earn 16,207,275/2= 8,103,638 TRY. The reason is that the increase in the collection rate improves the revenue per unit of WEEE.

- As the transportation cost of WEEEs from collection points to storage sites is the same as this cost from storage sites to WRs, and there are no big differences in the fixed costs of storage sites in different locations, for all collection rates except 100% the model locates storage sites always in cities which WRs are located. Otherwise, if it locates the storage site and WR in different cities, it will result in higher transportation cost, by not transferring the WEEEs directly to the destination point. Therefore, when the fixed costs of storage sites are so close to each other, for lower collection rates we can consider only the candidate locations of storage sites that are mutual with candidate locations of WR. In this study, we have 21 candidate cities for storage sites and 12 cities for WRs which are all mutual with the previous one. Therefore, we can eliminate the 9 extra candidate cities and their corresponding types in the set of storage sites. As the computational time for some of the runs exceeds 60 hours, it will extremely assist in reducing it.

- As a summary, the HR performance effects on the network for different collection rates are provided in Table 4.23. As you see its effect increases from 20% collection rate to 70% collection rate, however, in the maximum collection rate when most of the cities are chosen its effect diminishes.

Table 4.28 Summery of effect of HR performance on the facilities of network for different collection rates.

Effect of HR performance	**collection rate**			
Facilities	**20%**	**50%**	**70%**	**100%**
storage sites	-	-	Location	-
WRs	-	Types	Location	Types and Numbers
HRs	Location	Location	Location	Location
TRs	-	-	To open or not	-

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this study, a reverse logistics network design problem for waste of electric and electronic equipment has been modeled and implemented to the whole country including all its 81 cities in Turkey. The results provide answers regarding the location of different facilities, their corresponding types, the flows between all facilities of the network, and the effect of performance levels of treatment facilities and hazardous material recycling facilities.

First of all, a deterministic mixed-integer linear programming model is developed for our problem based on real data. The differentiating aspect of this study is including treatment and Haz-Mat recycling facilities in the network in order to check its performance effect on the network in terms of location of facilities and revenue. We ran 36 scenarios, changing in collection rate of WEEEs, treatment and Haz-Mat recycling facility performances. As the effect of collection rate is undeniably intense and it plays a significant role in the network, to compare the results, scenarios are studied nine by nine, under four categories based on the collection rates. Next, to observe the environmental aspect of the suggested problem, the optimum scenario of each category is compared to the results of the same category in a non-environment friendly dataset. The factors which are used to compare the environmental aspect, are population exposure (population of locations which are chosen for treatment and recycling of hazardous materials) and the collection rate itself. There are some estimations in parameters, for instance, the transportation cost, and revenue of useful material which is obtained from the Haz-Mat recycling process are estimated. The remaining part of the data is obtained from different studies (Akçalı, E., Çetinkaya, S., & Üster, H., 2009), (Kilic, H.S., Cebeci, U., & Ayhan, M.B., 2015), (EC Directive 2002), (Turkey, R. E. C., 2011), and professionals of the hazardous material recycling sector, therefore this study reflects realistic results.

This thesis can be improved in several ways as follows:

- This model includes uncertainties only about performance levels of hazardous material recycling, and treatment facilities. However, there are so many other uncertain aspects in this problem. For instance, city-based WEEE generation rates are completely estimated and used as deterministic values; as it is an extremely effective factor in designing a network, the model can be developed by considering stochastic parameters.
- The factor used in this study to evaluate the environmental effect of the problem is population exposure, however, hazardous material can threat the population during the transportation stage, this aspect can be included by hazardous material routing problem.
- The WEEEs are considered to be at the same level in terms of quality, however, it could vary from one e-waste to another. Some of them may be unrecyclable, additionally the weight percent of useful material is considered to be constant for each category of WEEE, however, we know that it can vary. Including details like this can assist in more in-depth analysis.
- As the input data is very large and the problem considers the whole country, the computational time for some of the scenarios exceeds 60 hours, some heuristics can be developed to reduce the computational time.

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APPENDICES

A. Population information of Turkey

City	Population	City	Population
İstanbul	15.067.724	**Osmaniye**	534.415
Ankara	5.503.985	**Şırnak**	524.19
İzmir	4.320.519	**Giresun**	453.912
Bursa	2.994.521	**Isparta**	441.412
Antalya	2.426.356	**Yozgat**	424.981
Adana	2.220.125	**Aksaray**	412.172
Konya	2.205.609	**Edirne**	411.528
Şanlıurfa	2.035.809	**Muş**	407.992
Gaziantep	2.028.563	**Düzce**	387.844
Kocaeli	1.906.391	**Kastamonu**	383.373
Mersin	1.814.468	**Uşak**	367.514
Diyarbakır	1.732.396	**Niğde**	364.707
Hatay	1.609.856	**Kırklareli**	360.86
Manisa	1.429.643	**Bitlis**	349.396
Kayseri	1.389.680	**Rize**	348.608
Samsun	1.335.716	**Amasya**	337.508
Balıkesir	1.226.575	**Siirt**	331.67
Kahramanmaraş	1.144.851	**Bolu**	311.81
Van	1.123.784	**Nevşehir**	298.339
Aydın	1.097.746	**Kars**	288.878
Tekirdağ	1.029.927	**Kırıkkale**	286.602
Denizli	1.027.782	**Hakkari**	286.47
Sakarya	1.010.700	**Bingöl**	281.205
Muğla	967.487	**Burdur**	269.926
Eskişehir	871.187	**Yalova**	262.234
Mardin	829.195	**Karaman**	251.913
Trabzon	807.903	**Karabük**	248.014
Malatya	797.036	**Kırşehir**	241.868
Ordu	771.932	**Erzincan**	236.034
Erzurum	767.848	**Bilecik**	223.448
Afyonkarahisar	725.568	**Sinop**	219.733
Sivas	646.608	**Çankırı**	216.362
Adıyaman	624.513	**Bartın**	198.999
Tokat	612.646	**Iğdır**	197.456
Zonguldak	599.698	**Artvin**	174.01
Batman	599.103	**Gümüşhane**	162.748
Elazığ	595.638	**Kilis**	142.541
Kütahya	577.941	**Ardahan**	98.907
Çanakkale	540.662	**Tunceli**	88.198
Ağrı	539.657	**Bayburt**	82.274
Çorum	536.483		

Table A. 1 Population Information of Turkey

B. The results of optimum solution

SW(jku)			
Storage Sites	**WR**	**Product Category**	**Value**
Ankara type 3	Ankara Manual 2	small household	605237
Ankara type 4	Ankara Automatic 1	TV's	566562
Ankara type 4	Ankara Automatic 2	cooling and freezing	211230
Ankara type 4	Ankara Automatic 2	large household	41958
Ankara type 4	Ankara Automatic 2	large household	347711
Ankara type 4	Ankara Automatic 2	TV's	350366
Ankara type 4	Ankara Manual 2	small household	3777298
Bursa type 3	Bursa Manual 2	cooling and freezing	83676
Bursa type 3	Bursa Manual 2	large household	125617
Bursa type 3	Bursa Manual 2	small household	1835567
Bursa type 3	Bursa Manual 2	TV's	56827
Bursa type 3	İstanbul Automatic 2	TV's	50107
Diyarbakır type 2	Ankara Automatic 1	TV's	61713
Diyarbakır type 2	Ankara Manual 2	small household	417465
Diyarbakır type 2	Diyarbakır Manual 1	cooling and freezing	102790
Diyarbakır type 2	Kayseri Automatic 1	large household	74953
Eskişehir type 3	Ankara Automatic 1	TV's	42372
Eskişehir type 3	Bursa Manual 2	small household	362983
Eskişehir type 3	Eskişehir Manual 1	cooling and freezing	94443
Eskişehir type 3	Eskişehir Manual 1	large household	85998
Eskişehir type 3	Eskişehir Manual 1	small household	518037
Eskişehir type 3	Kocaeli Manual 1	large household	60495
Mersin type 2	Ankara Automatic 1	TV's	31165
Mersin type 2	Ankara Automatic 2	large household	16983
Mersin type 2	Mersin Manual 1	cooling and freezing	109847
Mersin type 2	Mersin Manual 1	large household	22932
Mersin type 2	Mersin Manual 1	small household	787292
İstanbul type 3	İstanbul Automatic 2	cooling and freezing	266666
İstanbul type 3	İstanbul Automatic 2	cooling and freezing	37085
İstanbul type 3	İstanbul Automatic 2	large household	283637
İstanbul type 3	İstanbul Automatic 2	TV's	470029
İstanbul type 3	İstanbul Manual 2	large household	91155
İstanbul type 3	İstanbul Manual 2	small household	3706140
İzmir type 2	İzmir Manual 1	cooling and freezing	7268
İzmir type 2	İzmir Manual 1	large household	21284
İzmir type 2	İzmir Manual 2	cooling and freezing	103958
İzmir type 2	İzmir Manual 2	TV's	197991
İzmir type 3	İzmir Manual 1	large household	173265
İzmir type 3	İzmir Manual 2	cooling and freezing	52520
İzmir type 3	İzmir Manual 2	small household	2203752
Kayseri type 3	Kayseri Automatic 1	cooling and freezing	172220
Kayseri type 3	Kayseri Automatic 1	large household	157411
Kocaeli type 3	Kocaeli Manual 1	large household	40398
Kocaeli type 3	Kocaeli Manual 1	TV's	43486
Kocaeli type 3	Kocaeli Manual 2	cooling and freezing	73507
Kocaeli type 3	Kocaeli Manual 2	large household	78652
Kocaeli type 3	Kocaeli Manual 2	small household	2305745
Samsun type 2	Ankara Automatic 1	TV's	98186
Samsun type 2	Ankara Automatic 2	cooling and freezing	66408
Samsun type 2	Ankara Automatic 2	large household	9936
Samsun type 2	Kocaeli Manual 1	large household	77364

Table A. 2 The optimal flows of WEEE units from storage sites to WRs for optimum scenario (Collection rate 100%, HR 90%, TR 90%)

WS(klf)			
WR	**Secondary Market**	**Useful Material**	**Value**
Diyarbakır Manual 1	Hatay	Ferrous	2107863.14
Mersin Manual 1	Hatay	Ferrous	4393071.87
Kayseri Automatic 1	Hatay	Ferrous	6937833.53
Bursa Manual 2	Zonguldak	Ferrous	9761014.96
Eskişehir Manual 1	Zonguldak	Ferrous	5549024.92
İstanbul Automatic 2	Zonguldak	Ferrous	10614272.3
İstanbul Manual 2	Zonguldak	Ferrous	9554236.98
İzmir Manual 1	Zonguldak	Ferrous	6195740.89
İzmir Manual 2	Zonguldak	Ferrous	7741143.4
Kocaeli Manual 1	Zonguldak	Ferrous	5658020.68
Kocaeli Manual 2	Zonguldak	Ferrous	9745353.32
Ankara Automatic 1	Karabük	Ferrous	1396816.56
Ankara Manual 2	Karabük	Ferrous	8704800
Diyarbakır Manual 1	Karabük	Ferrous	12638312.4
Ankara Automatic 1	Konya	Aluminum	43200.396
Ankara Manual 2	Konya	Aluminum	1116000
Bursa Manual 2	Konya	Aluminum	652571.542
Diyarbakır Manual 1	Konya	Aluminum	311338.602
Diyarbakır Manual 1	Konya	Aluminum	47319.3765
Eskişehir Manual 1	Konya	Aluminum	231102.075
Mersin Manual 1	Konya	Aluminum	251527.935
İstanbul Automatic 2	Konya	Aluminum	261254.439
İstanbul Manual 2	Konya	Aluminum	932887.836
İzmir Manual 1	Konya	Aluminum	155327.503
İzmir Manual 2	Konya	Aluminum	600978.834
Kayseri Automatic 1	Konya	Aluminum	168260.796
Kocaeli Manual 1	Konya	Aluminum	142894.147
Kocaeli Manual 2	Konya	Aluminum	838029.412
Diyarbakır Manual 1	Diyarbakır	Copper	146259.891
Mersin Manual 1	Diyarbakır	Copper	522891.561
Ankara Automatic 1	Samsun	Copper	216000.504
Ankara Manual 2	Samsun	Copper	2008800
Bursa Manual 2	Samsun	Copper	1266211.28
Diyarbakır Manual 1	Samsun	Copper	784388.376
Eskişehir Manual 1	Samsun	Copper	490343.393
İstanbul Automatic 2	Samsun	Copper	715397.166
İstanbul Manual 2	Samsun	Copper	1698526.61
İzmir Manual 1	Samsun	Copper	325160.829
İzmir Manual 2	Samsun	Copper	1227781.99
Kayseri Automatic 1	Samsun	Copper	400685.976
Kocaeli Manual 1	Samsun	Copper	306654.368
Kocaeli Manual 2	Samsun	Copper	1568813.32
Bursa Manual 2	Bursa	Plastic	8497598.06
Eskişehir Manual 1	Bursa	Plastic	4388277.46
İstanbul Automatic 2	İstanbul	Plastic	8601700.47
İstanbul Manual 2	İstanbul	Plastic	9003089.22
İzmir Manual 1	İzmir	Plastic	3898678.26
İzmir Manual 2	İzmir	Plastic	8028829.09
Ankara Automatic 1	kocaeli	Plastic	2318406.7
Ankara Manual 2	kocaeli	Plastic	9374400
Diyarbakır Manual 1	kocaeli	Plastic	9465243.82
Diyarbakır Manual 1	kocaeli	Plastic	1862662.73
Mersin Manual 1	kocaeli	Plastic	3972147.4
Kayseri Automatic 1	kocaeli	Plastic	4916115.11
Kocaeli Manual 1	kocaeli	Plastic	3646853.75
Kocaeli Manual 2	kocaeli	Plastic	9094010.43
Bursa Manual 2	Bursa	Glass	989335.339
İstanbul Automatic 2	İstanbul	Glass	5842167.55
İzmir Manual 2	İzmir	Glass	3446944.11
Ankara Automatic 1	kocaeli	Glass	8985577.54

WR	Secondary Market	Useful Material	Value
Diyarbakır Manual 1	kocaeli	Glass	3935310.91
Kocaeli Manual 1	kocaeli	Glass	757073.866
Bursa Manual 2	Bursa	Others	778951.232
Eskişehir Manual 1	Bursa	Others	361706.272
İstanbul Automatic 2	İstanbul	Others	738128.745
İstanbul Manual 2	İstanbul	Others	882627.102
İzmir Manual 1	İzmir	Others	418909.181
İzmir Manual 2	İzmir	Others	652373.591
Ankara Automatic 1	kocaeli	Others	273600.684
Ankara Manual 2	kocaeli	Others	892800
Diyarbakır Manual 1	kocaeli	Others	847138.302
Diyarbakır Manual 1	kocaeli	Others	90336.9915
Mersin Manual 1	kocaeli	Others	291600.361
Kayseri Automatic 1	kocaeli	Others	415522.692
Kocaeli Manual 1	kocaeli	Others	401028.071
Kocaeli Manual 2	kocaeli	Others	825573.346

Table A. 3 The optimal flows of useful materials from WRs to secondary markets for optimum scenario (Collection rate 100%, HR 90%, TR 90%)

WH(khg)			
WR	**HR**	**Hazardous material**	**Value**
Bursa Manual 2	Burdur type 1	Circuit boards	361072.4
Bursa Automatic 1	Burdur type 1	Circuit boards	103300.1
İzmir Manual 1	Burdur type 1	Circuit boards	175094.1
İzmir Manual 2	Burdur type 1	Circuit boards	591305.7
Bursa Manual 2	Çankırı type 4	Circuit boards	240000
Bursa Automatic 1	Çankırı type 4	Circuit boards	1943996
Bursa Automatic 2	Çankırı type 4	Circuit boards	1226319
Mersin Manual 1	Çankırı type 4	Circuit boards	60003.4
İstanbul Manual 2	Çankırı type 4	Circuit boards	267346.5
İstanbul Automatic 2	Çankırı type 4	Circuit boards	1519204
Kayseri Automatic 1	Çankırı type 4	Circuit boards	209127.6
İstanbul Automatic 1	Çankırı type 4	Circuit boards	266102.3
İstanbul Automatic 2	Çankırı type4	Circuit boards	230517.4
Bursa Manual 2	Burdur type 1	CFC	41419.62
İstanbul Automatic 2	Burdur type 1	CFC	46749.29
İzmir Manual 1	Burdur type 1	CFC	3597.66
İzmir Manual 2	Burdur type 1	CFC	77456.61
İstanbul Automatic 1	Çankırı type 4	CFC	137430.8
İzmir Automatic 2	Çankırı type 4	CFC	881.05
Mersin Manual 1	Çankırı type 4	CFC	54374.27
İstanbul Automatic 2	Çankırı type 4	CFC	150356.7
Kayseri Automatic 1	Çankırı type 4	CFC	85248.9
Kocaeli Automatic 1	Çankırı type 4	CFC	36385.97

Table A. 4 The optimal flows of hazardous materials from WRs to HRs for optimum scenario (Collection rate 100%, HR 90%, TR 90%)

WT(klf)			
WR	**TR**	**Hazardous material**	**Value**
Diyarbakır Manual 1	Bingöl	CFC	50000

Table A. 5 The optimal flows of hazardous materials from WRs to TRs for optimum scenario (Collection rate 100%, HR 90%, TR 90%)

HD(hm)		
HRs	**Disposals**	**Value**
Burdur type1	İzmir	140000
Çankırı type4	kocaeli	643403.883

Table A. 6 The optimal flows of wastes from HRs to Disposals for optimum scenario (Collection rate 100%, HR 90%, TR 90%)

HS(hl)		
HRs	**Secondary markets**	**Value**
Burdur type1	Konya	1260000
Çankırı type 4	Karabük	5790634.947

Table A. 7 The optimal flows of useful materials from HRs to secondary markets for optimum scenario (Collection rate 100%, HR 90%, TR 90%)

TD(Bingöl, Kocaeli) = 750

TH(Bingöl, Çankırı) = 6750

C. CPLEX code

```
//index:
 int I=...; //collection points locations
 int J=...; //storage sites locations
 int K=...; //WEEE recycling facility locations
 int H=...; //hazardous material recycling facility locations
 int T=...; //treatment facility locations
 int L=...; //secondary market locations
 int M=...; //disposal locations
 int U=...; //product types
 int Q=...; //treatment technology type
 int F=...; //useful material type
 int G=...; //hazardous material type

 range CollectionPoints=1..I;
 range StorageSites=1..J;
 range WEEERec=1..K;
 range HazMatRec=1..H;
 range Treatment=1..T;
 range SecondaryMarket=1..L;
 range Disposal=1..M;
 range ProductCategory=1..U;
 range Technology=1..Q;
 range UsefulMat=1..F;
 range HazMat=1..G;

 //parameters0...
 int a[CollectionPoints][ProductCategory]=...; //number of u type product at collection point i
 float weight[ProductCategory]=...; //weight of product u
 float PercUseful[ProductCategory][UsefulMat]=...; //weight percentage of useful material f at product type u
 float RecRate[WEEERec]=...; //recycling rate of the recycling facility K -> will be used instead of the next two parameters, because I didn't
 float MinRacRateOfU[ProductCategory]=...; //minimum recycling rate for the product category u
 float PercHazar[ProductCategory][HazMat]=...; //weight percentage of g type hazardous material at product type u
 float WeightRed[HazMat][Technology]=...; // weight reduction of treatable hazardous material type n by treatment technology q
 float PercRecHazWaste[HazMat][Technology]=...; //weight percentage of recyclable waste obtained from NR-hazmat type n treated by technology q
 float PercUsefulHR=...;      //weight percentage of useful material that is generated in haz-mat recycling facility h
 float volume[ProductCategory]=...; //volume of product type u
 float MinCapSt[StorageSites]=...;
 float MaxCapSt[StorageSites]=...;
 float MinCapWEEE[WEEERec]=...;
```

```
 float MaxCapWEEE[WEEERec]=...;
 float MinCapHR[HazMatRec]=...;
 float MaxCapHR[HazMatRec]=...;
 float MinCapT[Technology]=...;
 float MaxCapT[Technology]=...;
 float UTypeTransCost[ProductCategory]=...;
 float FTypeTransCost[UsefulMat]=...;
 float ZTypeTransCost=...;
 float NTypeTransCost=...;
 float RwasteTransCost=...; //transportation cost of recyclable waste transported from
treatment facility to hazmat recycling facility
 float UsefulTransCost=...; //transportation cost of useful material transported from
haz-mat recycling facility to secondary market
 float NRwasteTransCost=...;//transportation cost of non-recyclable waste transported
from treatment facility to disposal
 float HandlingCostOfU[StorageSites][ProductCategory]=...; //per unit
 float ProcessingCostofUWEEE[WEEERec]=...;//per kg
 float TreatmentCostOf[HazMat][Technology]=...; //per kg
 float RecyclingCostAtHazmatR=...;
 float FixedCostStorage[StorageSites]=...;
 float FixedCostWEEE[WEEERec]=...;
 float FixedCostHazmatR[HazMatRec]=...;
 float FixedCostTreatment[Technology]=...;
 float PricePerKGUseful[UsefulMat]=...;
 float PricePerKG=...;
 float distanceCS[CollectionPoints][StorageSites]=...;
 float distanceSW[StorageSites][WEEERec]=...;
 float distanceWS[WEEERec][SecondaryMarket]=...;
 float distanceWH[WEEERec][HazMatRec]=...;
 float distanceWT[WEEERec][Treatment]=...;
 float distanceTH[Treatment][HazMatRec]=...;
 float distanceHS[HazMatRec][SecondaryMarket]=...;
 float distanceTD[Treatment][Disposal]=...;
 float distanceHD[HazMatRec][Disposal]=...;
 float com[HazMat][Technology]=...; // shows that N can be treated by technology q or
not
 float Market[SecondaryMarket][UsefulMat]=...; // shows that f can be sold in secondary
market l or not
 float treat [HazMat]=...;
 float recycle [HazMat]=...;

 ////decision variables:
 dvar int+ CS[CollectionPoints][StorageSites][ProductCategory];
 dvar int+ SW[StorageSites][WEEERec][ProductCategory];
 dvar float+ WS[WEEERec][SecondaryMarket][UsefulMat];
 dvar float+ WH[WEEERec][HazMatRec][HazMat];
 dvar float+ WT[WEEERec][Treatment][HazMat];
 dvar float+ TH[Treatment][HazMatRec];
 dvar float+ HS[HazMatRec][SecondaryMarket];
 dvar float+ TD[Treatment][Disposal];
 dvar float+ HD[HazMatRec][Disposal];
 dvar int+ b[StorageSites][ProductCategory];
 dvar int+ c[WEEERec][ProductCategory];
 dvar float+ usefulWR[WEEERec][UsefulMat];
 dvar float+ usefulHR[HazMatRec];
 dvar float+ soldWR[SecondaryMarket][UsefulMat];
 dvar float+ soldHR[SecondaryMarket];
 dvar float+ GtypeHazarWaste[WEEERec][HazMat];
 dvar float+ NRhazmatT[Treatment][HazMat][Technology];
 dvar float+ RhazmatHR[HazMatRec][HazMat];
 dvar float+ RwasteHR[HazMatRec];
```

```
 dvar float+ RwasteT[Treatment];
 dvar float+ NRwasteT[Treatment];
 dvar float+ WasteHR[HazMatRec];
 dvar float+ TotalHR[HazMatRec];
 dvar boolean  St[StorageSites];
 dvar boolean W[WEEERec];
 dvar boolean HR[HazMatRec];
 dvar boolean Tr[Treatment][Technology];
 dvar float obj;
 dvar float+ hazmatcost;
 dvar float+ papercost;
 dvar float+ revenueWEEE;
 dvar float+ revenuehazmat;
 dvar float+ TransportaionCost;

 //objective:
 minimize obj ;

 subject to{

objective:

obj==hazmatcost+papercost-revenueWEEE-revenuehazmat;

hazmatcost== sum (t in Treatment, h in HazMatRec )(TH [t] [h]*distanceTH [t]
[h]*RwasteTransCost)+
sum( h in HazMatRec, l in SecondaryMarket )(HS [h] [l]*distanceHS [h]
[l]*UsefulTransCost)+
sum( t in Treatment, m in Disposal )(TD [t] [m]*distanceTD [t] [m]*NRwasteTransCost)+
sum( h in HazMatRec, m in Disposal )(HD [h] [m]*distanceHD [h] [m]*NRwasteTransCost)+
sum( t in Treatment, g in HazMat, q in Technology )(NRhazmatT[t] [g] [q]*
TreatmentCostOf[g][q]) +
sum( h in HazMatRec)(TotalHR [h]*RecyclingCostAtHazmatR)+
sum( h in HazMatRec)(HR[h]*FixedCostHazmatR[h])+sum( t in Treatment, q in Technology
)(Tr[t] [q]*FixedCostTreatment [q])+
sum( k in  WEEERec, h in HazMatRec,  g in HazMat )(WH [k] [h] [g]*distanceWH [k]
[h]*ZTypeTransCost)+
sum( k in  WEEERec, t in Treatment,  g in HazMat )(WT [k] [t] [g]*distanceWT [k]
[t]*NTypeTransCost);

papercost== sum( i in CollectionPoints,  j in StorageSites, u in ProductCategory)(CS [i]
[j] [u]*distanceCS [i] [j]*UTypeTransCost [u])+
sum( i in CollectionPoints,  j in StorageSites, u in ProductCategory )(CS [i] [j]
[u]*HandlingCostOfU [j] [u])+
sum( j in StorageSites, k in  WEEERec, u in ProductCategory )(SW [j] [k] [u]*weight
[u]*ProcessingCostofUWEEE [k])+
sum( j in StorageSites)(St [j]*FixedCostStorage [j])+sum( k in  WEEERec)(W
[k]*FixedCostWEEE [k])+
sum( j in StorageSites, k in  WEEERec, u in ProductCategory )(SW [j] [k] [u]*distanceSW
[j] [k]*UTypeTransCost [u])+
sum( k in  WEEERec, l in  SecondaryMarket,  f in UsefulMat )(WS [k] [l] [f]*distanceWS
[k] [l]*FTypeTransCost [f]);

revenueWEEE==sum( l in  SecondaryMarket,  f in UsefulMat)(soldWR [l] [f]*PricePerKGUseful
[f]);
revenuehazmat== sum( l in SecondaryMarket)(soldHR [l]*PricePerKG);


TransportaionCost==sum (t in Treatment, h in HazMatRec )(TH [t] [h]*distanceTH [t]
[h]*RwasteTransCost)+
```

```
sum(   h   in   HazMatRec,   l   in   SecondaryMarket   )(HS   [h]   [l]*distanceHS   [h]
[l]*UsefulTransCost)+
sum( t in Treatment, m in Disposal )(TD [t] [m]*distanceTD [t] [m]*NRwasteTransCost)+
sum( h in HazMatRec, m in Disposal )(HD [h] [m]*distanceHD [h] [m]*NRwasteTransCost)+
sum(  i  in  CollectionPoints,   j  in  StorageSites,  u  in  ProductCategory)(CS  [i]  [j]
[u]*distanceCS [i] [j]*UTypeTransCost [u])+
sum( j in StorageSites, k in  WEEERec, u in ProductCategory )(SW [j] [k] [u]*distanceSW
[j] [k]*UTypeTransCost [u])+
sum( k in  WEEERec, l in  SecondaryMarket,  f in UsefulMat )(WS [k] [l] [f]*distanceWS
[k] [l]*FTypeTransCost [f])+
sum(  k  in   WEEERec,  h  in  HazMatRec,   g  in  HazMat)(WH  [k]  [h]  [g]*distanceWH  [k]
[h]*ZTypeTransCost)+
sum(  k  in   WEEERec,  t  in  Treatment,   g  in  HazMat  )(WT  [k]  [t]  [g]*distanceWT  [k]
[t]*NTypeTransCost);

 ///1) constraints corresponding to flow between "collection points --> storage sites"
 cons01:
 forall( i in CollectionPoints,  u in ProductCategory)
 sum( j in StorageSites) CS [i] [j] [u]==a [i] [u];

 cons02:
 forall( j in StorageSites, u in ProductCategory )
 sum( i in CollectionPoints ) CS [i] [j] [u]==b [j] [u];

 ///2)  constraints  corresponding  to  flow  between  "storage  sites  -->  WEEE-recycling
facilities"
 cons03:
 forall( j in StorageSites, u in ProductCategory )
 sum( k in  WEEERec) SW [j] [k] [u]==b [j] [u];

 cons04:
 forall( k in  WEEERec, u in ProductCategory )
 sum( j in StorageSites) SW [j] [k] [u]==c [k] [u];

 ///3) constraints corresponding to flow between "WEEE-recycling facilities --> secondary
markets"
 cons05:
 forall( k in  WEEERec, f in UsefulMat )
 sum(   u   in   ProductCategory   )   (c   [k]   [u]*weight   [u]*PercUseful   [u]   [f]*RecRate
[k])==usefulWR[k] [f];

 cons06:
 forall( k in  WEEERec, f in UsefulMat )
 sum( l in SecondaryMarket) (WS[k][l][f]*Market[l][f])==usefulWR[k][f];

 cons07:
 forall( l in  SecondaryMarket,  f in UsefulMat )
 sum( k in  WEEERec) (WS [k] [l] [f]*Market[l][f])==soldWR [l] [f];

cons08:
 forall( k in  WEEERec, g in HazMat )
 sum( u in ProductCategory) (c [k] [u]*weight [u]*PercHazar[u][g])==GtypeHazarWaste [k]
[g];

 forall( k in  WEEERec, g in HazMat )
 sum( h in HazMatRec) WH [k] [h] [g]*recycle[g] + sum( t in Treatment ) WT [k] [t] [g]*
treat [g]==GtypeHazarWaste [k] [g];

 forall( t in Treatment, g in HazMat)
 sum( k in  WEEERec) WT [k] [t] [g]* treat [g]==sum( q in Technology ) NRhazmatT [t] [g]
[q]*com [g] [q];
```

```
forall( h in HazMatRec,  g in HazMat )
sum( k in  WEEERec) WH [k] [h] [g]*recycle[g]==RhazmatHR [h] [g];

///4) constraints corresponding to flow between "Treatment --> haz-mat recycling"
cons14:
forall( t in Treatment )
sum(  g in HazMat , q in Technology )(NRhazmatT [t] [g] [q]*com [g] [q]*(1-WeightRed
[g] [q])*PercRecHazWaste [g] [q])==RwasteT [t];

cons15:
forall( t in Treatment )
sum( h in HazMatRec )TH [t] [h]==RwasteT [t];

cons16:
forall( h in HazMatRec )
sum( t in Treatment )TH [t] [h]==RwasteHR [h];

///5) constraints corresponding to flow between "Treatment --> disposal"

cons17:
forall( t in Treatment)
(sum(   g  in  HazMat  ,  q  in  Technology)(NRhazmatT[t][g][q]*(1-WeightRed[g][q])*(1-
PercRecHazWaste[g][q])))== NRwasteT[t];

 cons19:
forall(t in Treatment)
sum( m in Disposal)TD[t][m]==NRwasteT[t];


///6) constraints corresponding to flow between "Haz-mat recycling --> Disposal" and
toward "Haz-mat recycling"

cons20:
forall( h in HazMatRec )
RwasteHR [h]+sum(  g in HazMat )RhazmatHR [h] [g]==TotalHR [h];

cons21:
forall( h in HazMatRec )
TotalHR [h]*(1-PercUsefulHR)==WasteHR [h];

cons22:
forall( h in HazMatRec )
sum( m in Disposal )HD [h] [m]==WasteHR [h];


///7) constraints corresponding to flow between "Haz-mat recycling --> Secondary market"

cons24:
forall( h in HazMatRec )
TotalHR [h]*(PercUsefulHR)==usefulHR [h];

cons25:
forall(h in HazMatRec)
sum(l in SecondaryMarket)HS [h] [l]==usefulHR [h];

cons26:
forall( l in SecondaryMarket )
sum( h in HazMatRec )HS [h] [l]==soldHR [l];
```

```
/////////////////////// capacity constraints/////////////////////:
//storage site capacity:
cons30:
forall( j in StorageSites)
sum(u in ProductCategory)(b [j] [u]*volume [u])>=MinCapSt [j]*St [j];

cons31:
forall( j in StorageSites)
sum( u in ProductCategory )(b [j] [u]*volume [u])<=MaxCapSt [j]*St [j];

//WEEE recycling capacity:
con32:
forall( k in  WEEERec)
sum( u in ProductCategory )(c [k] [u]*weight[u])>=MinCapWEEE [k]*W [k];

cons33:
forall( k in  WEEERec)
sum( u in ProductCategory )(c [k] [u]*weight[u])<=MaxCapWEEE [k]*W [k];

//Haz-Mat recycling capacity:
cons34:
forall( h in HazMatRec )
TotalHR[h]>=MinCapHR[h]*HR[h];

cons35:
forall( h in HazMatRec)
TotalHR[h]<=MaxCapHR[h]*HR[h];

//Treatment capacity:

cons36:
forall( t in Treatment, q in Technology )
 sum ( g in HazMat)NRhazmatT [t] [g] [q]>=MinCapT[q]*Tr[t][q];

cons37:
forall( t in Treatment, q in Technology )
sum ( g in HazMat )NRhazmatT [t] [g] [q]<=MaxCapT [q]*Tr [t] [q];

cons38:
forall( g in HazMat, q in Technology, t in Treatment )
NRhazmatT [t] [g] [q]<=MaxCapT [q]*com [g] [q];

 cons41:
forall(u in ProductCategory)
(sum(k        in        WEEERec)(c[k][u]*weight[u]*RecRate[k]))/sum        (i        in
CollectionPoints)(a[i][u]*weight[u])>=MinRacRateOfU[u];

}
```

CURRICULUM VITAE

PERSONAL INFORMATION

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EDUCATION

Degree	Institution	Year of Graduation
BS	Tabriz University	2012
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WORK EXPERIENCE

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2012-2016	Mohammadi MDF Company	Sales Manager

FOREIGN LANGUAGES

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HOBBIES

Movies, Traveling, Ping Pong, Badminton, Music, Drawing, Fashion designing, Architecture, Coding.