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Reverse logistics system design for the waste of electrical and electronic equipment (WEEE) in Turkey

Huseyin Selcuk Kilic[a,*], Ufuk Cebeci[b], Mustafa Batuhan Ayhan[a]

[a] Marmara University, Department of Industrial Engineering, 34722 Göztepe, İstanbul, Turkey
[b] Istanbul Technical University, Department of Industrial Engineering, 34367 Maçka, İstanbul, Turkey

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ABSTRACT

Depending on the high consumption in the world, the amount of waste increases. One of the critical waste types to be handled is the electrical and electronic waste (WEEE). The recovery of WEEE is very important both from environmental and economic aspects and has become mandatory in most of the countries in the world. Reverse logistics which is mainly the backward flows of used products from consumers to producers is an important stage while constructing a recovery system. The network structure of reverse logistics system plays an important role in the total cost of the recovery system. These structures mainly include the locations of facilities and the flows between the related points. With this study, a reverse logistics system is designed for WEEE in Turkey which is one of the fast developing countries in the world. Ten scenarios are taken into account regarding different collection rates via a mixed integer linear programming model. Different types of storage sites and recycling facilities are considered within the model differing from the existing studies. The optimum locations of storage sites and recycling facilities are obtained for each scenario satisfying the minimum recycling rates stated by the European Union directive for each product category.

1. Introduction

Due to the increasing population in the world and consumption levels, the economic usage and the recovery of natural resources for the industrialized society become vital for the sustainability of life. While the natural sources decline, the amount of the used products increases. To overcome these two problems, reverse logistics, which is simply the recovery of the used products, becomes more important. The first known definition of reverse logistics was published by the Council of Logistics Management as "*the term often used to refer to the role of logistics in recycling, waste disposals, and management of hazardous materials*" (Zhou and Wang, 2008). However, a formal definition was set by members of European Research Network on Reverse Logistics (REVLOG) in 1998 (REVLOG, 1998) as; "*It is the process of planning, implementing, and controlling backward flows of raw materials, in process inventory, packaging, and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal*" (De Brito and Dekker, 2004).

One of the important materials considered within reverse logistics is the waste of electrical and electronic equipment (WEEE). The amount of WEEE has been increasing depending on the population and the technological developments. In the world, the yearly amount of disposed WEEE was about 30–50 million tons in 2013 and it is expected to be 40–70 million tons by 2015 (Menikpura et al., 2014). Whereas, in Europe, the amount of WEEE was approximately 5 million tons in 2005 and expected to grow to 12.3 million tons by 2020 (Cebeci et al., 2005; UNU, 2008). On the other hand, in Turkey, the amount of disposed WEEE in 2011 was about 565k tons and expected to reach 894k tons in 2020 (REC Turkey, 2011).

Due to this huge amount of WEEE, the potential hazard to the environment increases. Moreover, product disposal costs increase depending on the depletion of landfill and incineration capacities. In order to prevent the hazardous effects to the environment and provide economic gains, recycling and recovery options for WEEE are considered. Therefore, environmental regulations have been issued in most of the countries in the world like Taiwan, China and Japan (Shih, 2001; Yu et al., 2010; Menikpura et al., 2014). A similar environmental regulation has been implemented in Europe via WEEE Directive (2002/96/EC) (EC, 2003). It was approved by the European Parliament on 27 January 2003 including the recovery policies of the products which were classified as shown in Table 1

* Corresponding author. Tel.: +90 0216 348 02 92; fax: +90 0216 347 28 59.
E-mail addresses: huseyin.kilic@marmara.edu.tr (H.S. Kilic), cebeciu@itu.edu.tr (U. Cebeci), batuhan.ayhan@marmara.edu.tr (M.B. Ayhan).

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Table 1
The ten WEEE product categories (Grunow and Gobbi, 2009).

No	Category
1	Large household appliances
2	Small household appliances
3	IT and telecommunications equipment
4	Consumer equipment
5	Lighting equipment
6	Electrical and electronic tools
7	Toys, leisure and sports equipment
8	Medical devices
9	Monitoring and control instruments
10	Automatic dispensers

Table 2
Limits for recovery and recycling rates for producers (EC, 2003).

WEEE category	Recovery rate	Recycling rate
1, 10	80%	75%
3, 4	75%	65%
2, 5, 6, 7, 9	70%	50%
8	No data	No data

(Grunow and Gobbi, 2009). The detail list of products which fall under the categories can be found in the directive (EC, 2003).

This directive also sets standard limits for the recovery and recycling rates as shown in Table 2 (EC, 2003). Since the 8th category represents the medical devices, there are no limits defined for them.

In order to achieve these recovery and recycling rates and minimize the cost of product disposals, the manufacturers should solve the reverse logistics problem which should designate the optimal sites and determine the capacities of collection centers, inspection centers, remanufacturing facilities and/or recycling plants (Alumur et al., 2012). For handling this problem, various studies have been performed as seen in the review studies (Pokharel and Mutha, 2009; Aras et al., 2010; Ongondo et al., 2011; Wang and Xu, 2014).

As can be seen in the review study of Ongondo et al. (2011), there are different WEEE management practices in various countries such as Germany, United Kingdom, Switzerland, China, India, Japan. They presented the existing situation of countries regarding the global trends in the quantities and composition of WEEE. The findings of Ongondo et al. (2011) also revealed that there are still open research areas in most of the countries. Conforming to the inferences of Ongondo et al. (2011), reverse logistics network modeling is also an immature research area for Turkey.

Since Turkey is on the edge of European Union, it should have a recycling network system satisfying the requirements of WEEE Directive. Constructing such a recycling network system can be regarded as a strategic decision making process including various crucial decisions such as the locations and types of storage points and recycling facilities. Since such determinations highly affect the total cost, this critical decision making process should be handled systematically. At this point, there are a limited number of studies providing a comprehensive network design. With this study, it is strategically aimed to fulfill this gap. For this aim, a reverse logistics network design is performed for Turkey case including different scenarios each of which is based on different quantities of WEEE to be collected. For each scenario, the suitable locations, numbers and types of storage points and recycling facilities are determined so as to minimize the total cost of the system. The system is modeled via a mixed integer linear programming (MILP) model which is developed by benefiting from the generic models in the literature. However, the model mainly differs from the existing literature by considering the recycling rate constraint which provides the minimum rates indicated in the WEEE Directive. Since the recycling capability and operating cost of manual and automatic facilities are different, it is important to determine suitable facility types and the quantities of WEEE to be allocated to them. While the manual facilities can provide recycling rates over the indicated value in the WEEE Directive, the operating cost is high. On the other hand, the operating cost is low in the automatic facilities but the recycling capabilities of them are under the required levels. Hence, this tradeoff is handled in the proposed model via the recycling rate constraint.

In order to clarify and provide an easy flow, the mapping of the remaining parts is as follows. Literature review is given in Section 2. Section 3 introduces the challenges in applying WEEE Directive in Turkey. The structure of the reverse logistics system and the mathematical model are provided in Section 4. Section 5 reveals the application of the mathematical model and conclusion is given in Section 6 with the references following.

2. Literature review

There are numerous studies related with reverse logistics. However, this study mainly focuses on the network design in reverse logistics. Hence, the literature is mainly reviewed regarding this perspective. Network design is also an extensively studied subject including different research areas in reverse logistics. For performing a better analysis, network design is reviewed under four topics focusing on: different sectors, location models, multi-products and applications for different countries.

Studies dealing with the network designs for different sectors include; steel industry, recycling of sand, carpets, batteries, tires and paper. Spengler et al. (1997) proposed a modified MILP model for the recycling network in steel industry. Barros et al. (1998) presented a tailored multi-level capacitated facility location model for recycling of sand in construction industry. Jayaraman et al. (1999) analyzed the logistics network of a revised electronics equipment producer. Louwers et al. (1999) and Realff et al. (2004) dealt with carpets sector's network design, Schultmann et al. (2003) and Bigum et al. (2013) examined the network design for battery recycling options, De Figueiredo and Mayerle (2008) focused on tires, Pati et al. (2008) handled paper recycling. The studies of Krikke (2011) and Srivastava (2008) are the examples of remanufacturing options focusing on copiers and personal computers, respectively. Regarding the studies for different sectors, there are good representations of reverse logistics networks. On the other hand, since they are concerning specific application areas, they are not readily applicable to a wide range of industries.

Another focus of the previous works is on facility location models. Franke et al. (2006) presented a model to determine the facility location for remanufacturing plant. Walther et al. (2008) dealt with the facility location problem for treatment of large household appliances. Queiruga et al. (2008) applied Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) as a ranking method for the alternative locations of recycling plants. Similarly, Gamberini et al. (2010) addressed WEEE collection network design and considered multi criteria decision methods in order to determine the most suitable facility location. Golebiewski et al. (2013) presented a mathematical model to specify the optimum locations of the dismantling facilities for end-of-life vehicles. However, reverse logistic design is much more than selecting a facility location. In order to design a better recycling network, a holistic view including all the other elements of the network is required.

In addition, some papers deal with multi-product reverse logistics models. The paper of Jayaraman et al. (1999) can be nominated as the first study dealing with this issue. Listeş and Dekker (2005) proposed a stochastic approach dealing with three categories of sand waste, Pati et al. (2008) presented a goal programming approach considering different types of paper. Srivastava (2008) introduced a generic mathematical model enabling the incorporation of multiple types of products. Similarly, Fonseca et al. (2010) developed a two-stage stochastic bi-objective mixed-integer programming formulation dealing with multi-types of commodities. In a recent study by Alumur et al. (2012), a multi period reverse logistics network design was proposed, which was also focusing on the multi-product items. In the first phase, the locations of the facilities were determined and in the second phase the other decisions about capacity and multi products were made. As seen in the analyzed studies, the consideration of the multi-product case in the network design models provides flexibility and more practical solutions to the real life cases. Moreover, it is inferred that there is a gap incorporating multi-product case in WEEE network design problems.

Finally, there are various applications of reverse logistics for different countries in the literature including Taiwan, Mexico, Denmark, Greece, China, Portugal, Brazil, Sri-Lanka and Finland. Shih (2001) performed a reverse logistics system design for recycling electrical appliances and computers in Taiwan. He proposed a mixed integer model and aimed to minimize total cost including; transportation cost, final disposal cost, landfill cost, operating and fixed cost of new facilities as well as the revenue of reclaimed materials. The results of various scenarios depending on the three different take-back rates (30%–50%–70%), which were presumed to demonstrate the dynamic of the reverse logistics system, were revealed. However, different types of recycling facilities with different recycling rates were not considered in the study. An uncapacitated facility location problem was handled for the collection of vehicles in Mexico (Cruz-Rivera and Ertel, 2009). However, the capacity for the recycling facilities is one of the most important constraints of the model that cannot be assumed infinite. According to the Denmark application of reverse logistics network, static and dynamic models were developed and the results were compared with those of an institutional agency called WEEE-System. For each WEEE class, their model revealed solutions with less than 0.5% deviation from the target waste volumes (Grunow and Gobbi, 2009). In Greece application, a decision support tool employing a MILP model to optimize recovery of WEEE was proposed for the region of Central Macedonia (Achillas et al., 2010). They suggested the consideration of some other costs related with the development of the required storage areas, management of WEEE in storage areas, container usage, and contracting with third party logistics companies. Achillas et al. (2012) also focused on the effect of different types of containers. They presented a multiple objective linear programming model for the minimization of total reverse logistics costs, consumption of fossil fuel and production of emissions considering the use of different container types. The existing structure of e-waste management in China was reviewed by Yu et al. (2010). They focused on the unofficial collection of e-waste by informal recyclers. They proposed two policies to overcome this problem. In the first policy, financial responsibility was shared among manufacturers, consumers, and government. In the second one, an e-waste channel was proposed where informal dealers collected/reused and the formal sector dismantled/recycled. Gomes et al. (2011) proposed a MILP model for the recovery network of WEEE for Portugal case and they suggested a tactical network planning by determining both the number of sorting and recycling centers and their locations. Since collected WEEE was sent to recycling without any kind of sorting activity regarding the recovery of components in Portugal, they pointed out the importance of sorting of the collected WEEE. Due to its importance, a maximum distance of 50 km was imposed between sources of WEEE and sorting centers in their model. Brazilian case was compared with the world situation after presenting different systems used for WEEE recycling in various countries (De Oliveira et al., 2012). In this study, the collection process was noted as the main difficulty for e-waste recycling system. The reasons of this difficulty were mainly the existence of informal sector, the problems related with the education and cooperation. Mallawarachchi and Karunasena (2012) handled the WEEE management problem in Sri Lanka in three cases; household appliances, IT & telecommunication equipments, and lightning equipments. According to their study, they provided suggestions for national policy enhancements in the areas of waste collection, storage, treatment, disposal, monitoring, evaluation, and reporting. In addition, the implementation process of WEEE Directive in Finland was analyzed by Ylä-Mella et al. (2014). According to their analysis, Finland was successful in the implementation of WEEE Directive and reached to the collection rate of 9.5 kg per capita which was over the requirements indicated in the WEEE Directive. As seen from the studies, since each country has its own special conditions and characteristics, there are various applications of network designs for different countries. Therefore, there is still a need of application in the countries in which the reverse logistics networks have not been designed yet.

In order to summarize the literature review, various network designs are performed for different sectors, many studies deal with facility location problems, a significant number of papers consider multi-product network design. In addition, there are various applications of network designs for different countries. However, there is still need of studies about reverse logistics network models which can adapt to the changes in real applications. The recycling rate constraint of WEEE is handled in this study and a mathematical model generating a solution to this problem is proposed. Moreover, to the best knowledge of the authors, reverse logistics network modeling is an immature research area especially for Turkey. Hence, this study aims to fulfill this gap by both designing a reverse logistics network for the related country and incorporating recycling rate constraint into generic models.

3. Challenges in applying WEEE Directive in Turkey

Since Turkey wants to be a member of European Union (EU), it is required to transpose and implement WEEE Directive. With the aim of assisting the government and senior officials of the Ministry of Environment and Urban Planning (MoEUP) to assess the impacts of the adoption of the WEEE Directive, a Regulatory Impact Analysis (RIA) report was prepared in 2011 (REC Turkey, 2011).

According to the RIA report, Turkey deals with 539,000 tons of WEEE yearly in 2010 and expecting 894,000 tons in 2020 with an increasing average growth rate as 5% per year. In addition to this growth in WEEE amount, Turkey also aims to increase the collected WEEE amount from 0.27 kg per capita to 4.87 kg per capita by 2020 (REC Turkey, 2011). Hence, there is a need for Turkey to construct a WEEE recycling system not only by regarding WEEE Directive and political reasons but also considering these increasing rates.

However, the situation of WEEE in Turkey is challenging with the following problems to implement the Directive:

- Turkey has less WEEE amount compared to EU countries.
- The amount of WEEE varies across the country.
- Turkey does not have separate collection infrastructure.
- Turkey does not possess proper treatment facilities for cooling and freezing equipment.
- The WEEE recycling sector is highly dominated by informal scrap dealers.
- Turkey does not still have the awareness for proper collection and treatment of WEEE.
- Moreover, there is inadequate intellectual knowledge for technical and financial sides.

Turkey has less quantities of WEEE with respect to arising and collection rates when compared to EU countries. While the arising and collection rates for Turkey are 7.5 kg per capita and 0.27 kg per capita respectively, EU values are 20 kg per capita and 6.5 kg per capita. When the geographical distribution of WEEE is investigated, the amount of WEEE arising is greatly different across the country because of the difference in economic structures. For instance, while the amount of WEEE arising rate is 10.91 kg per capita in Istanbul which is located in the west of Turkey, this rate is at about 2.48 kg per capita in the eastern cities such as Bitlis, Hakkari, Muş and Van (REC Turkey, 2011).

Moreover, most of the WEEE arising is actually collected by different operators and does not end up in municipal waste dumps. In general, small distributors and second-hand sellers informally purchase or collect significant portions of the WEEE with free of charge and sell them to the scrap dealers. Scrap dealers and various informal operators collect and treat WEEE causing significant hazards to environment, health problems and labor safety risks for themselves and the community (REC Turkey, 2011). As a result, constructing a WEEE recycling network design is a necessity for Turkey considering the above mentioned challenges.

4. The structure of the reverse logistics system and the mathematical model

The reverse logistics network structure includes five main elements as shown in Fig. 1. These are sources of WEEE, municipality collection points, storage sites, recycling facilities and secondary material market/final disposal facilities. In the first stage, municipalities collect WEEE from different sources such as houses and retailers. Then, the responsibility of the producers starts. They are in charge of both the collection and recycling. Hence, the reverse logistics network design mainly focuses on the responsibility area of the producers from the municipality collection points to the secondary material market/final disposal facilities.

There are three flows which are under the producers' responsibility and taken into account in this study. These are the flows from the central municipality collection points to producer storage sites, the flows from producer storage sites to recycling facilities and the flows from recycling facilities to secondary material market or final disposal facilities.

The producers or the consortium of producers are responsible to collect the required amount of WEEE with respect to their market share from the municipality collection points to their storage sites. The WEEE is classified and stored in four categories such as large household appliances, cooling & freezing appliances, TV's (Monitors) and small household appliances as indicated in the WEEE Directive. There will be handling and storage costs varying for each category. The WEEE of different categories will be transported to the suitable recycling facilities providing the minimum required recycling rate. After the recycling process in the recycling facilities, the useful materials such as iron, aluminum, and copper are sent to the secondary material market and the hazardous materials such as circuit boards, chlorofluorocarbon (CFC) which require additional treatment are sent to the final disposal facilities.

There are generic models about reverse logistics in the literature mainly including flow constraints, capacity constraints and constraints about the maximum number of storage sites and facilities (Shih, 2001; Fleischmann, 2003; Dekker et al., 2004). In this study, while constructing the MILP model, it is benefited from them. However, the model used in the study differs from the existing studies by taking into account the recycling rates which are compulsory to be achieved by laws and vary with respect to the product categories. Moreover, various recycling facility types with different recycling rate capabilities and capacities are considered in the model. Besides recycling facilities, there are also different types of storage sites having various sizes. Hence, it is aimed to find the suitable answers to the following questions via the mathematical model:

- The types, numbers and locations of storage sites.
- The types, numbers and locations of recycling facilities.
- The quantity of product categories to be allocated to storage sites.
- The quantity of product categories to be allocated to recycling facilities.
- The network flow of product categories through storage sites, recycling facilities and secondary market.
- The total cost of the reverse logistics system.

The proposed model, whose framework is indicated in Fig. 2, can easily provide the best answers to these questions after accurately determining the related variables, parameters and constraints.

The proposed MILP model is as follows:

Assumptions

All the parameters are deterministic

The products will stay one month in the storage points

Objective function

$$\begin{aligned}\min z = &\sum_i\sum_j\sum_u (m1_{iju} * d1_{ij} * tm_u) + \sum_j\sum_k\sum_u (m2_{jku} * d2_{jk} * tm_u) + \sum_k\sum_l\sum_f (m3_{klf} * d3_{kl} * tm2_f) \\ &+ \sum_k\sum_m\sum_z (m4_{kmz} * d4_{km} * tm3_z)(\text{transportation costs}) + \sum_i\sum_j\sum_u (m1_{iju} * em_{ju})(\text{handling costs at storage sites}) \\ &+ \sum_j\sum_k\sum_u (m2_{jku} * im_{ku} * au_u)(\text{operation costs at the recycling facilities}) \\ &+ \sum_j (\text{desm}_j * dv_j) + \sum_k (\text{tesm}_k * tv_k)(\text{fixed costs of storage sites and recycling facilities}) \\ &+ \sum_k\sum_z (\text{ham2}_{kz} * \text{gid}_z)(\text{hazardous materials disposal cost}) - \sum_k\sum_f (\text{ham1}_{kf} * \text{get}_f)(\text{revenue from secondary materials})\end{aligned} \quad (1)$$

Constraints

Flow constraints

$$\sum_j m1_{iju} = a_{iu} \quad \forall u, \forall i \quad (2)$$

$$\sum_i m1_{iju} = b_{ju} \quad \forall u, \forall j \quad (3)$$

$$\sum_k m2_{jku} = b_{ju} \quad \forall u, \forall j \quad (4)$$

$$\sum_j m2_{jku} = c_{ku} \quad \forall u, \forall k \quad (5)$$

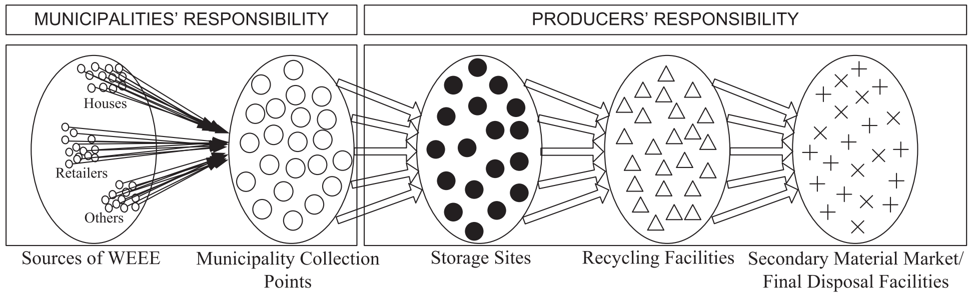

Fig. 1. Reverse logistics network structure.

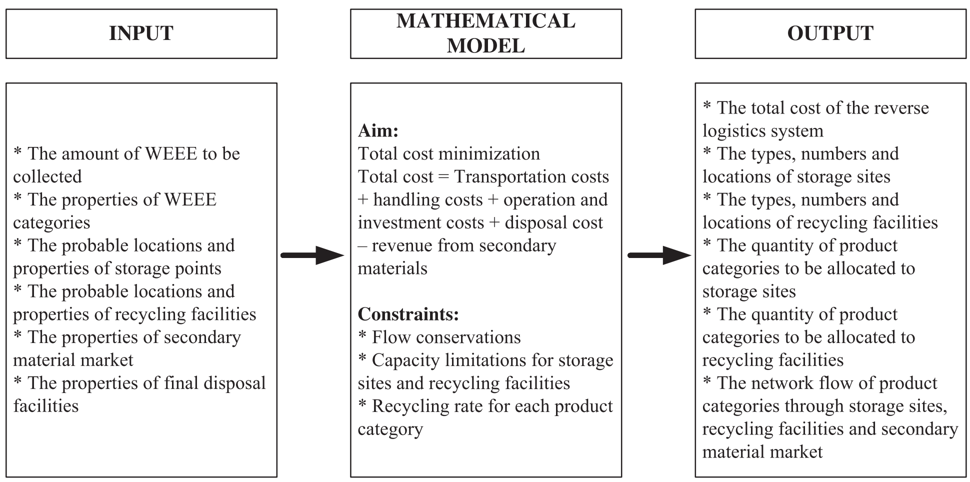

Fig. 2. The structure of the proposed model.

$$\sum_u (c_{ku} * au_u * \text{malz1}_{uf} * v_{kf}) = \text{ham1}_{kf} \quad \forall k, \forall f \tag{6}$$

$$\sum_l m3_{klf} = \text{ham1}_{kf} \quad \forall k, \forall f \tag{7}$$

$$\sum_u (c_{ku} * au_u * \text{malz1}_{uz}) = \text{ham2}_{kz} \quad \forall k, \forall z \tag{8}$$

$$\sum_m m4_{kmz} = \text{ham2}_{kz} \quad \forall k, \forall z \tag{9}$$

$$\sum_k m3_{klf} = nham1_{lf} \quad \forall l, \forall f \tag{10}$$

$$\sum_k m4_{kmz} = nham2_{mz} \quad \forall m, \forall z \tag{11}$$

Capacity constraints

$$\sum_u (b_{ju} * hu_u) \geq \min deka_j * dv_j \quad \forall j \tag{12}$$

$$\sum_u (b_{ju} * hu_u) \leq \max deka_j * dv_j \quad \forall j \tag{13}$$

$$\sum_u (c_{ku} * au_u) \geq \min teka_k * tv_k \quad \forall k \tag{14}$$

$$\sum_u (c_{ku} * au_u) \leq \max teka_k * tv_k \quad \forall k \tag{15}$$

$$nham1_{lf} \leq \max paka_{lf} \quad \forall l, \forall f \tag{16}$$

$$nham2_{mz} \leq \max zateka_{mz} \quad \forall m, \forall z \tag{17}$$

Maximum number limit of storage sites and facilities

$$\sum_j dv_j \leq x \tag{18}$$

$$\sum_k tv_k \leq y \tag{19}$$

Recycling ratio constraint

$$\frac{\left(\sum_k (c_{ku} * au_u * r_{ku})\right)}{\left(\sum_i (a_{iu} * au_u)\right)} \geq \text{rec}_u \quad \forall u \tag{20}$$

0/1 *integer variables*

$$dv, tv \in \{0, 1\} \tag{21}$$

Non negative decision variables

$$\text{others} \geq 0 \tag{22}$$

The description of model constraints and the nomenclature of the mathematical model are provided in Tables 3 and 4 respectively.

5. Application of the mathematical model

Since the ultimate aim is to achieve the European Union standards (4 kg of WEEE per capita) gradually, 10 scenarios are created for Turkey application. Scenario 1 (S1) represents the 10% of total target value of collection rate and Scenario 10 (S10) represents the upper limit and considers the collection rate as 100% of 4 kg per capita. These scenarios will also help any individual firm or a consortium in the sector by analyzing the system design for the scenario which is close to its market share. For instance, if a firm

Table 3
Description of model constraints.

No	Description
1	Objective function, which includes all costs and revenue
2	Flow conservation at the collection points
3, 4	Flow conservation at the storage sites
5	Flow conservation at the recycling facilities
6, 7	Useful material conservation at the recycling facilities
8, 9	Hazardous materials conservation at the recycling facilities
10	Flow conservation at the secondary material market
11	Flow conservation at the final treatment facility
12, 13	Capacity constraints for the storage sites
14, 15	Capacity constraints for the recycling facilities
16	Capacity constraints for the secondary material market
17	Capacity constraints for the final treatment facilities
18	Maximum number limit for the storage sites
19	Maximum number limit for the recycling facilities
20	Minimum recycling rate constraint for the product categories
21	Integer constraint
22	Positive constraint for the variables

has 30% of market share then it is responsible to collect 30% of total target of 4 kg per capita and it can benefit from Scenario 3.

5.1. Determining the parameters

To obtain accurate results, it is important to determine the right values of the parameters. Within the scope of the mathematical model, the values of the following main parameters will be determined:

- The amount of WEEE to be collected.
- The properties of WEEE categories.
- The probable locations and properties of storage sites.
- The probable locations and properties of recycling facilities.
- The properties of secondary material market.
- The properties of final disposal facilities.

Table 4
Nomenclature of the mathematical model.

Type	Description
Subscript	
u	Product categories
i	Collection points
j	Storage sites
k	Recycling facilities
l	Secondary material market
m	Final treatment facilities for the hazardous materials
f	Useful materials which bring revenue
z	Hazardous materials which cause cost
Variables	
$m1_{iju}$	Quantity of product category "u" transported from the collection point "i" to the storage site "j" (units)
$m2_{jku}$	Quantity of product category "u" transported from the storage site "j" to the recycling facility "k" (units)
$m3_{klf}$	Quantity of useful material "f" transported from the recycling facility "k" to the secondary material market "l" (kg)
$m4_{kmz}$	Quantity of hazardous material "z" transported from the recycling facility "k" to the final treatment facility "m" (kg)
b_{ju}	Quantity of product category "u" at the storage site "j" (units)
c_{ku}	Quantity of product category "u" at the recycling facility "k" (units)
dv_j	Selection of the storage site "j" (1/0)
tv_k	Selection of the recycling facility "k" (1/0)
$\mathrm{ham}1_{kf}$	Quantity of useful materials "f" at the recycling facility "k" (kg)
$\mathrm{ham}2_{kz}$	Quantity of hazardous materials "z" at the recycling facility "k" (kg)
$n\mathrm{ham}1_{lf}$	Quantity of the useful material "f" at the secondary material market "l" (kg)
$n\mathrm{ham}2_{mz}$	Quantity of the hazardous material "z" at the final treatment facility "m" (kg)
Parameters	
a_{iu}	Quantity of product category "u" at the collection point "i" (units)
$d1_{ij}$	Distance from the collection point "i" to the storage site "j" (km)
$d2_{jk}$	Distance from the storage site "j" to the recycling facility "k" (km)
tm_u	"u" product category per km transportation cost
$tm2_f$	"f" useful material kg*km transportation cost
$tm3_z$	"z" hazardous material kg*km transportation cost
em_{ju}	Handling cost of the product category "u" at the storage site "j"
im_{ku}	Kg operation cost of the product category "u" at the recycling facility "k"
au_u	Weight of the product category "u" (kg)
hu_u	Volume of the product category "u" (m3)
$\mathrm{malz}1_{uf}$	Weight percentage of the useful material "f" in the product category "u"
$\mathrm{malz}2_{uz}$	Weight percentage of the hazardous material "z" in the product category "u"
get_f	Revenue of the useful material "f" (money/kg)
gid_z	Cost of the hazardous material "z" (money/kg)
$desm_j$	Annual fixed cost of the storage site "j"
$tesm_k$	Annual fixed cost of the recycling facility "k"
$\mathrm{min}deka_j$	Minimum capacity of the storage site "j"
$\mathrm{max}deka_j$	Maximum capacity of the storage site "j"
$\mathrm{min}teka_k$	Minimum capacity of the recycling facility "k"
$\mathrm{max}teka_k$	Maximum capacity of the recycling facility "k"
v_{kf}	The recycling rate of the material "f" at the recycling facility "k"
r_{ku}	The recycling rate of the product category "u" at the recycling facility "k"
$\mathrm{max}paka_{lf}$	Capacity of the secondary material market "l" for the material "f"
$\mathrm{max}zateka_{mz}$	Capacity of the final treatment facility "m" for the hazardous material "z"
rec_u	Minimum recycling rate for the product category "u"
x	Maximum number of the storage sites
y	Maximum number of the recycling facilities

5.1.1. The amount of WEEE to be collected

One of the most important parameters is the amount of WEEE to be collected. The number of storage sites, recycling facilities, transportation costs, handling costs, processing costs are affected by the quantity of WEEE to be collected. Hence, each amount of collected WEEE requires a new network design. Depending on this crucial effect, the scenarios are constructed according to various amounts of WEEE to be collected.

There are two important factors affecting the amount of WEEE that can be collected. These are population and economic structure of cities which are regarded as the collection points. Based on these factors, a study was performed (REC Turkey, 2011) and the amount of WEEE that can be collected per capita is determined for each city in Turkey. The report states that less amount of WEEE is expected to be collected from the east cities of Turkey than west cities due to the social and economic differences of the regions.

Based on the information provided in the report, 10 scenarios are created in this study. While S10 (Scenario 10) represents 100% of the amount of WEEE (also the target value, 4 kg per capita) to be collected, S1 (Scenario 1) indicates 10% of WEEE to be collected. The following scenarios increase by 10% and the data for 10 of the 81 cities in Turkey are shown in Table 5.

5.1.2. The properties of WEEE categories

There are four categories of WEEE in the model. The categories have similar properties and are already in use in European WEEE systems (Cebeci et al., 2005). The categories are:

Large household appliances: Washing machines, dishwashers, ovens and dryers are in this group.

Cooling and freezing appliances: Refrigerators, freezers and air conditioners are in this group. This group differentiates from the other categories via including hazardous gases such as CFC, HCFC and HF.

TV's (Monitors): All Tv's and monitors including CRT are in this group.

Small household appliances: Vacuum cleaners, irons, sandwich toasters, shavers, mobile phones and the similar equipment are all in this group.

Quantifiable properties of related WEEE categories are presented in the succeeding sections. Moreover, there can be further impacts of different WEEE categories beyond those of quantifiable in terms of cost but only the accessible and numerical parameters are considered. The minimum recycling rates of product categories (EC, 2003) are given in Appendix Table A1.

The expected amount of WEEE is calculated with respect to the product categories. The percentage of product categories is obtained from the RIA report (REC Turkey, 2011). The average weight of each category is determined and the ratio indicating the breakdowns in weights and units are provided in Fig. 3. The average weight for each category is mainly determined by direct measurements and expert views as 60 kg, 45 kg, 30 kg and 5 kg.

Since the volume of the product categories is important in the storage areas, the average volume of each product category is determined by taking some representative products' dimensions. The related values are shown in Appendix Table A1.

For calculating the transportation costs, it is benefited from the average volume of the product categories. Hence, for each category, the transportation cost for one product per km is determined as in Appendix Table A1. While calculating the cost, a truck having a volume of 40 m^3 and a weight capacity of 14.5 tons is considered in Turkey market conditions and accepted as working with full capacity. It is also benefited from the study of Gül and Elevli (2006) while calculating the costs.

The material composition of the product categories is important so as to determine the revenue that will be obtained from the useful materials. Ongondo et al. (2011) indicate that there are mainly five

Table 5
The amount of WEEE to be collected in 10 cities including 10 different scenarios.

No	City	Amount of WEEE to occur in 10 different scenarios (kg)									
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	Adana	779,399.5	1,558,799	2,338,198.5	3,117,598	3,896,997.5	4,676,397	5,455,796.5	6,235,196	7,014,595.5	7,793,995
2	Adıyaman	123,351.31	246,702.61	370,053.92	493,405.23	616,756.54	740,107.84	863,459.15	986,810.46	1,110,161.8	1,233,513.1
3	Afyon	230,347.43	460,694.86	691,042.29	921,389.72	1,151,737.1	1,382,084.6	1,612,432	1,842,779.4	2,073,126.9	2,303,474.3
4	Ağrı	86,850.184	173,700.37	260,550.55	347,400.74	434,250.92	521,101.11	607,951.29	694,801.48	781,651.66	868,501.84
5	Amasya	88,985.917	177,971.83	266,957.75	355,943.67	444,929.59	533,915.5	622,901.42	711,887.34	800,873.26	889,859.17
6	Ankara	2,631,737.3	5,263,474.5	7,895,211.8	10,526,949	13,158,686	15,790,424	18,422,161	21,053,898	23,685,635	26,317,373
7	Antalya	945,129.21	1,890,258.4	2,835,387.6	3,780,516.8	4,725,646.1	5,670,775.3	6,615,904.5	7,561,033.7	8,506,162.9	9,451,292.1
8	Artvin	47,525.547	95,051.093	142,576.64	190,102.19	237,627.73	285,153.28	332,678.83	380,204.37	427,729.92	475,255.47
9	Aydın	403,734.78	807,469.56	1,211,204.3	1,614,939.1	2,018,673.9	2,422,408.7	2,826,143.5	3,229,878.2	3,633,613	4,037,347.8
10	Balıkesir	388,844.89	777,689.77	1,166,534.7	1,555,379.5	1,944,224.4	2,333,069.3	2,721,914.2	3,110,759.1	3,499,604	3,888,448.9

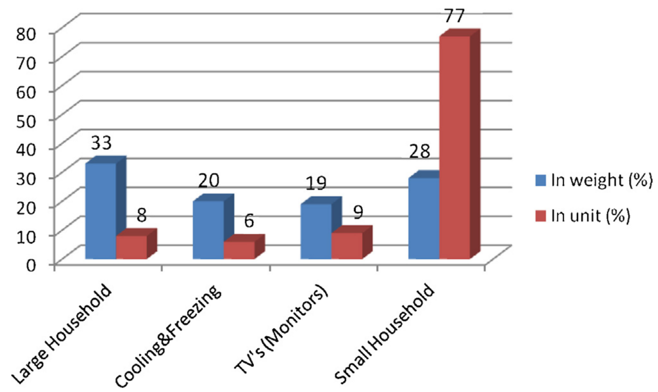

Fig. 3. The occurrence rates of product categories in weight and unit (REC Turkey, 2011).

categories of materials such as ferrous metals, non-ferrous metals, glass, plastics and other materials. The most common materials are iron and steel constituting of nearly half of the total weight. The plastics (21%) and non-ferrous metals (13%) are the other highly used materials. Within this study, it is benefited from various studies to determine the material composition (Jofre and Morioka, 2005; EHS, 2005; WRAP, 2009). The material composition for each product category is shown in Fig. 4.

The revenue that can be obtained from the useful materials and the cost caused by hazardous materials are shown in Appendix Table A2 (URL 1; URL 2; URL 3; Shih, 2001).

The average transportation cost per ton for useful and hazardous materials in Turkey market conditions are depicted in Appendix Table A2. Due to the density of the materials, the unit cost for some materials can change. Moreover, the truck type and fuel consumption rates per km affect the cost. While these values are being computed, an average truck having a capacity of 14.5 tons is regarded and it is benefited from the study of Gül and Elevli (2006).

5.1.3. The probable locations and properties of storage sites

The producers will take the required amount of WEEE from the central municipality collection points to the storage sites. It is important to determine the suitable storage sites so as to minimize the transportation and storage costs. Regarding the cities' economical and geopolitical situations, a set of probable 78 storage sites in 21 different cities are formed. The related cities are Adana, Ankara, Antalya, Bursa, Çanakkale, Denizli, Diyarbakır, Elazığ, Erzurum, Eskişehir, Hatay, İçel, İstanbul, İzmir, Kayseri, Kocaeli, Konya, Samsun, Trabzon, Van and Zonguldak as shown in Fig. 5.

5.1.4. The capacity of the storage sites

Since the product categories differ from each other, the capacity of the storage sites is not given in units but in volume. It is considered that there will be 6 types of storage sites. The capacities in volume are 4000 m^3, 8000 m^3, 12,000 m^3, 16,000 m^3, 20,000 m^3 and 24,000 m^3 respectively. Moreover, the minimum capacity is determined as 80%. So, the annual minimum and maximum capacities and the location points of the storage types are provided in Appendix Table A3 depending on the assumption that the products will stay one month in the storage sites.

There are two types of cost for storage sites. These are fixed and variable costs. While determining the fixed costs; the depreciation cost, annual fixed energy cost, annual fixed office cost and annual management cost are taken into account. The variable cost is the handling cost which changes according to the product category based on its volume. Since the locations of the storage sites affect the cost parameters especially the land cost, three types of costs are provided representing west, middle and east parts of Turkey. Depending on the market research and expert views gathered through personal interviews, annual fixed costs of these three regional locations are shown in Appendix Table A4.

Different from annual fixed costs, the variable handling cost does not change with respect to the storage site location. However, it varies for each product category and tabulated in Appendix Table A4.

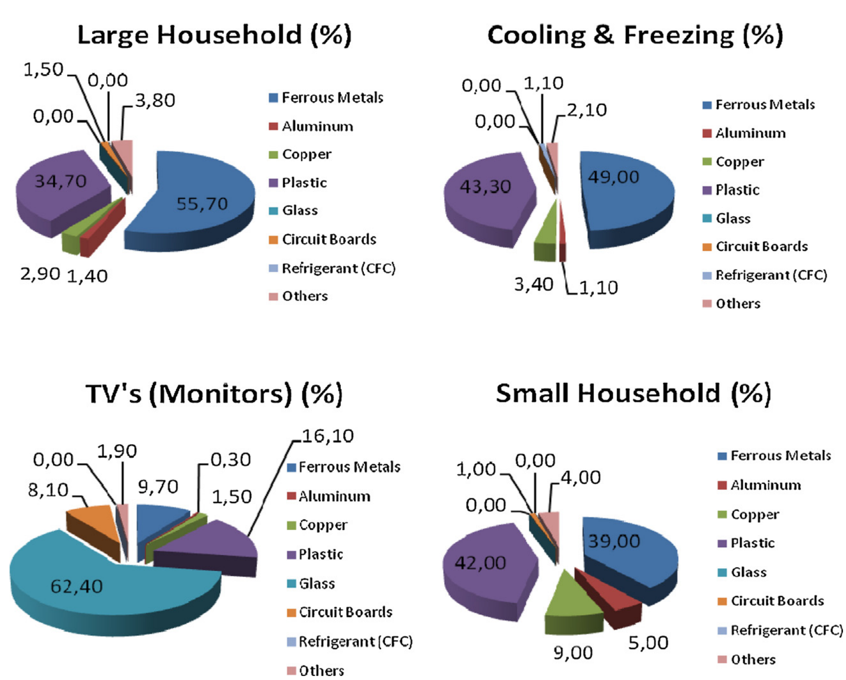

Fig. 4. Material composition for each product category (Jofre and Morioka, 2005; EHS, 2005; WRAP, 2009).

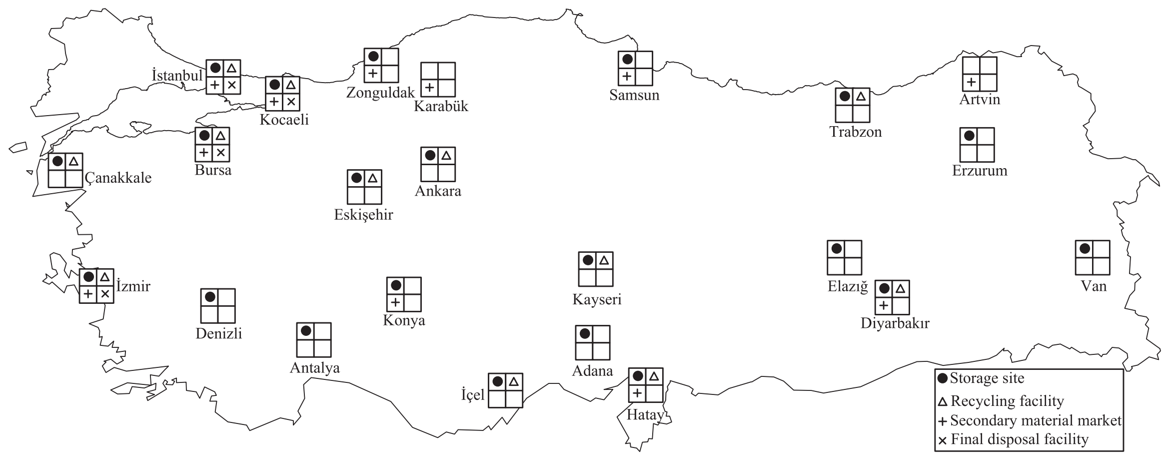

Fig. 5. The location of the probable storage sites, recycling facilities, secondary material market and final disposal facilities.

5.1.5. The probable locations and properties of recycling facilities

Recycling operation can be performed by three systems. These are automatic disassembly with robots, recycling with shredders and manual disassembly. Since automatic disassembly with robotics is still not suitable for WEEE due to the balancing and product design, it has not been accepted as a recycling option yet (Yuksel and Baylakoglu, 2007). So the WEEE in the storage sites can go to two types of recycling facilities. One of them is the manual disassembly recycling facility and the other one is the automatic recycling facility with shredders. There are advantages and disadvantages of these two types of recycling facilities. In short, the manual disassembly recycling facilities have expensive processing cost per kg but yields high recycling rates whereas automatic recycling facilities have cheap processing cost but low recycling rates. On the other hand, the investment cost is higher in recycling facilities with shredders than in manual disassembly plants. Besides, according to a recent study performed to present a decision support tool for WEEE recovery network systems, the manual disassembly is proven more profitable depending on the level of disassembly (Achillas et al., 2013).

5.1.6. The probable locations and capacities of recycling facilities

The probable locations for each type of the recycling facilities are determined regarding economical and geopolitical situation of cities. There are two types for manual and automatic systems with different capacities. The minimum and maximum capacities are defined in kg for the recycling facilities as shown in Appendix Table A5. Minimum capacity is taken as 80% capacity of one shift and maximum capacity is accepted as the full capacity of the three shifts.

The locations of the different types of recycling facilities are depicted in Appendix Table A5 and the locations of the probable recycling facilities are shown on Turkey map as in Fig. 5.

5.1.7. The fixed and variable cost of recycling facilities

The fixed cost of manual disassembly facilities is low and the recycling cost per kg is high due to manual recycling processes. Opposite to this situation, the fixed cost of automatic systems is high due to expensive investment but the recycling cost per kg is low. There are two types of both automatic and manual recycling facilities having different capacities. Since there is not certain information about the costs, the fixed and variable costs for the recycling facilities are assumed as shown in Appendix Table A6 (REC Turkey, 2011; Yuksel and Baylakoglu, 2007).

Table 6
The market locations for each useful material.

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

Table 7
The final disposal facilities locations for each hazardous material.

Materials	Locations
Circuit boards Refrigerant (CFC)	Bursa, İstanbul, İzmir, Kocaeli

5.1.8. The recycling rates of recycling facilities

Achieving the required recycling rates for each of four product categories is important. The recycling rates are higher in manual systems than in automatic systems. The recycling rates are determined as 93% for manual systems and 60% for automatic systems with shredders (Yuksel and Baylakoglu, 2007).

5.1.9. The properties of secondary material market

The useful materials are sent to the secondary material market after the recycling facilities. The market locations for the useful materials are considered according to the existence of the plants or industry operating with the related material. That is, since there are iron and steel plants in Hatay, Zonguldak, and Karabük, these cities are considered as the market locations for ferrous metals. The other market locations for each useful material are indicated in Table 6 and shown on Turkey map as in Fig. 5.

5.1.10. The properties of final disposal facilities

Some of the hazardous materials need extra treatment after the process in recycling facilities. These materials are sent to related final disposal facilities whose locations are indicated in Table 7 and shown on Turkey map as in Fig. 5.

5.2. Results of the mathematical model

When the mathematical model is run for 10 scenarios, the optimum solutions are obtained via GAMs optimization program as shown in Table 8 including the locations and types of both storage sites and recycling facilities. Depending on the high monetary

Table 8
The results of the scenarios.

Scenario no	Collection rate (%)	Cost (€)	Cost (€/ton)	Storage sites (Type)	Recycling facilities (Type)
1	10	(−) 841,564	(−) 27.81	Ankara (Type1)	Ankara (Manual 1)
				Kocaeli (Type 3)	Kocaeli (Manual 1, Automatic 1)
2	20	(−) 2,422,593	(−) 40.04	Ankara (Type 2)	Ankara (Manual 1)
				İçel (Type 1)	İçel (Manual 1)
				İstanbul (Type 2)	İstanbul (Manual 1)
				İzmir (Type 1)	İzmir (Manual 1)
				Kocaeli (Type 3)	Kocaeli (Automatic 1)
3	30	(−) 4,106,879	(−) 45.25	Ankara (Type 4)	Ankara (Automatic 1)
				İstanbul (Type 4)	İstanbul (Manual 2)
				İzmir (Type 2)	İzmir (Manual 1)
				Kocaeli (Type 3)	Kocaeli (Manual 1, Automatic1)
4	40	(−) 5,640,855	(−) 46.61	Ankara (Type 3)	Ankara (Automatic 1)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 5)	İstanbul (Manual 1, Automatic 2)
				İzmir (Type 3)	İzmir (Manual 2)
				Kocaeli (Type 3)	Kocaeli (Manual 2)
5	50	(−) 7,564,255	(−) 50.01	Ankara (Type 5)	Ankara (Manual 1, Automatic 1)
				Bursa (Type 2)	Bursa (Manual 1)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 6)	İstanbul (Manual 1, Automatic 2)
				İzmir (Type 3)	İzmir (Manual 2)
				Kocaeli (Type 2)	Kocaeli (Manual 1)
6	60	(−) 9,034,593	(−) 49.78	Ankara (Type 5)	Ankara (Manual 1, Automatic 1)
				Bursa (Type 3)	Bursa (Manual 2)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 2, Type 6)	İstanbul (Manual 2, Automatic 2)
				İzmir (Type 3)	İzmir (Manual 2)
				Kayseri (Type 2)	Kayseri (Automatic 1)
				Kocaeli (Type 2)	Kocaeli (Manual 1)
7	70	(−) 10,976,224	(−) 51.83	Ankara (Type 5)	Ankara (Manual 1, Automatic 1)
				Bursa (Type 3)	Bursa (Manual 2)
				Diyarbakır (Type 2)	Diyarbakır (Manual 1)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 3-6)	İstanbul (Manual 2, Automatic 2)
				İzmir (Type 5)	İzmir (Manual 1, Automatic 1)
				Kocaeli (Type 3)	Kocaeli (Manual 2)
8	80	(−) 12,516,215	(−) 51.72	Ankara (Type 6)	Ankara (Manual 2, Automatic 1)
				Bursa (Type 3)	Bursa (Manual 2)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 4-6)	İstanbul (Manual 2, Automatic 2)
				İzmir (Type 5)	İzmir (Manual 2, Automatic 1)
				Kayseri (Type 3)	Kayseri (Automatic 1)
				Kocaeli (Type 3)	Kocaeli (Manual 2)
9	90	(−) 14,315,566	(−) 52.58	Ankara (Type 6)	Ankara (Manual 2, Automatic 1)
				Bursa (Type 3)	Bursa (Manual 2)
				Diyarbakır (Type 2)	Diyarbakır (Manual 1)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 5-6)	İstanbul (Manual 1–2, Automatic 2)
				İzmir (Type 6)	İzmir (Manual 2, Automatic 1)
				Kayseri (Type 3)	Kayseri (Automatic 1)
				Kocaeli (Type 3)	Kocaeli (Manual 2)
10	100	(−) 15,955,676	(−) 52.74	Ankara (Type 6)	Ankara (Manual 1, Automatic 2)
				Bursa (Type 3)	Bursa (Manual 2)
				Diyarbakır (Type 2)	Diyarbakır (Manual 1)
				Eskişehir (Type 2)	Eskişehir (Manual 1)
				İçel (Type 2)	İçel (Manual 1)
				İstanbul (Type 5-6)	İstanbul (Manual 1–2, Automatic 2)
				İzmir (Type 6)	İzmir (Manual 2, Automatic 1)
				Kayseri (Type 3)	Kayseri (Automatic 1)
				Kocaeli (Type 5)	Kocaeli (Manual 1–2)

value of the metal scrap especially the copper, all of the scenarios yield profits. That is why the values in the cost column are shown in negative sign representing the profits for each scenario.

Table 8 also reveals an important inference. Forming consortiums to collect WEEE is more meaningful and profitable. For example, if there are two firms of each sharing 10% of market share, they must collect 10% of WEEE individually and they will make € 841,564 profit (27.81 €/ton) separately. However, if they form a consortium for this aim, the total profit will increase to € 2,422,593 (40.04 €/ton), which is more than the summation of separate profits.

In addition to the optimum points and types of storage sites and recycling facilities, the related flows within the network are also obtained. The results are given for only the Scenario 1. The flows of product categories from collection points to storage sites for the first 10 collection points are provided in Appendix Table B1. The numbers of products transported from storage sites to recycling facilities are as in Appendix Table B2. The useful material flows from the recycling facilities to the secondary material market are depicted in Appendix Table B3. Finally, the hazardous material flows from the recycling facilities to the final disposal facilities are shown in Appendix Table B4.

6. Conclusion

The recovery of used materials is an essential field. Depending on the importance of the subject, numerous studies have been performed in the recent years. Reverse logistics dealing with the backward flows in a recovery system has become very important. Due to the importance of the subject, the construction of recycling systems has become mandatory by environmental laws in most of the countries in the world. Turkey being one of the biggest economies in the world has also relevant laws and legislations about this field. Although the laws have not been fully applied in Turkey, they will be in force in the following years.

With this study, to provide guidance to the firms in Turkey, a reverse logistics design is performed for 10 different scenarios considering various collection rates. A mixed integer linear programming model is used to provide solutions for the scenarios. Although it is benefited from the generic models in the literature, the proposed mathematical model mainly differs from the existing models by considering recycling rates for each product category. The optimum locations and flows are determined for each scenario via the mathematical model. Hence, the proposed algorithm can be used to optimize recycling network structure of WEEE by potential stakeholders.

This study also releases some managerial insights dealing with WEEE reverse logistics cost. Regarding the optimal solution for each scenario, there is a profit range between 27.81 €/ton and 52.74 €/ton values. The occurrence of profit in this study depends on the high market values of secondary materials. Moreover, increasing values of marginal profit depend on the savings provided by economies of scale. The positive effect of economies of scale also presents a reasonable basis for firms which are considering forming consortiums rather than acting individually. The proposed model in the study can be extended by incorporating some options such as reuse and remanufacturing in the further studies. The parameter values can be updated with the new applications. Moreover, the model can be used for various cases including other waste types different from WEEE. Last but not least, stochastic and fuzzy programming can be used for the related problem.

Appendix A. Input parameter values

See Tables A1–A6.

Appendix B. Output flow values

See Tables B1–B4.

Table A2
Cost parameters for materials (URL 1; URL 2; URL 3; Shih, 2001; Gül and Elevli, 2006).

Materials	Revenue (cost)	€/(ton × km)
Ferrous metals	0.20	0.048
Aluminum	1.00	0.083
Copper	4.00	0.083
Plastic	0.20	0.167
Glass	0.10	0.048
Others	0.10	0.094
Circuit boards	(0.28)	0.094
Refrigerant (CFC)	(3.00)	0.094

Table A3
Locations and capacity limits of storage types.

No	Storage site	Storage type					
		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
1	Adana	x	x	x			
2	Ankara	x	x	x	x	x	x
3	Antalya	x	x	x			
4	Bursa	x	x	x	x	x	x
5	Çanakkale	x	x	x			
6	Denizli	x	x	x			
7	Diyarbakır	x	x	x			
8	Elazığ	x	x	x			
9	Erzurum	x	x	x			
10	Eskişehir	x	x	x			
11	Hatay	x	x	x			
12	İçel	x	x	x			
13	İstanbul	x	x	x	x	x	x
14	İzmir	x	x	x	x	x	x
15	Kayseri	x	x	x			
16	Kocaeli	x	x	x	x	x	x
17	Konya	x	x	x			
18	Samsun	x	x	x			
19	Trabzon	x	x	x			
20	Van	x	x	x			
21	Zonguldak	x	x	x			
Min. capacity (m^3)		38,400	76,800	115,200	153,600	192,000	230,400
Max. capacity (m^3)		48,000	96,000	144,000	192,000	240,000	288,000

Table A4
Fixed and variable costs for storage types.

Storage type	Annual fixed costs (€)			Variable cost (€/unit)			
	West	Middle	East	C1	C2	C3	C4
1	49,750	42,250	35,650	0.0972	0.1620	0.0240	0.0081
2	65,000	56,500	49,500	0.0486	0.0810	0.0120	0.0041
3	80,250	70,750	63,350	0.0432	0.0720	0.0107	0.0036
4	103,000	92,500	84,700	0.0405	0.0675	0.0100	0.0034
5	118,250	106,750	98,550	0.0324	0.0540	0.0080	0.0027
6	133,500	121,000	112,400	0.0324	0.0540	0.0080	0.0027

Table A1
Properties of WEEE product categories (EC, 2003; Gül and Elevli, 2006).

Product categories	Minimum recycling rate (EC, 2003)	Dimension (m × m × m)	Volume (m^3)	Transportation cost (€/(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	0.540	0.0092
TV's (Monitors)	65%	0.4 × 0.4 × 0.5	0.080	0.0014
Small household appliances	50%	0.3 × 0.3 × 0.3	0.027	0.0005

Table A5
Locations and capacity limits of recycling facilities.

No	Location	Recycling facility type			
		Manual 1	Manual 2	Automatic 1	Automatic 2
1	Ankara	x	x	x	x
2	Bursa	x	x	x	x
3	Çanakkale	x		x	x
4	Diyarbakır	x			
5	Eskişehir	x		x	
6	Hatay	x			
7	İçel	x			
8	İstanbul	x	x	x	x
9	İzmir	x	x	x	x
10	Kayseri	x		x	x
11	Kocaeli	x	x	x	x
12	Trabzon	x			
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 A6
Annual fixed and processing costs of the recycling facilities (REC Turkey, 2011; Yuksel and Baylakoglu, 2007).

Recycling facility type	Annual fixed cost (€)	Processing cost (€/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

Table B1
The flows of product categories from collection points to storage sites for the first 10 collection points in Scenario 1.

No	From (collection point)	To (storage site): Ankara				To (storage site): Kocaeli			
		Large household	Cooling and freezing	TV's	Small household	Large household	Cooling and freezing	TV's	Small household
1	Adana	4287	3464	–	43,646	–	–	4936	–
2	Adıyaman	678	548	–	6908	–	–	781	–
3	Afyon	–	–	–	–	1267	1024	1459	12,899
4	Ağrı	–	386	–	–	478	–	550	4864
5	Amasya	–	395	–	–	489	–	564	4983
6	Ankara	14,475	11,697	–	147,377	–	–	16,668	–
7	Antalya	–	–	–	–	5198	4201	5986	52,927
8	Artvin	–	–	–	–	261	211	301	2661
9	Aydın	–	–	–	–	2221	1794	2557	22,609
10	Balıkesir	–	–	–	–	2139	1728	2463	21,775

Table B2
The flows from storage sites to recycling facilities.

No	From (storage site)	To (recycling facility)	Large household	Cooling and freezing	TV's	Small household
1	Ankara	Ankara (Manual 1)	41,345	43,034	–	420,947
2	Kocaeli	Kocaeli (Manual 1)	34,293	18,085	29,032	1,273,298
3	Kocaeli	Kocaeli (Automatic 1)	90,766	73,343	162,584	–

Table B3
The flows from recycling facilities to secondary material market.

No	From (recycling facility)	To (secondary material market)	Ferrous metals (kg)	Aluminum (kg)	Copper (kg)	Plastic (kg)	Glass (kg)	Others (kg)
1	Ankara (Manual 1)	Kocaeli				2,402,487		203,784
2	Ankara (Manual 1)	Konya		149,979				
3	Ankara (Manual 1)	Samsun			304,304			
4	Ankara (Manual 1)	Karabük	2,930,902					
5	Kocaeli (Manual 1)	Kocaeli				3,608,897	505,450	340,833
6	Kocaeli (Manual 1)	Konya		333,587				
7	Kocaeli (Manual 1)	Samsun			626,252			
8	Kocaeli (Manual 1)	Zonguldak	3,824,424					
9	Kocaeli (Automatic 1)	Kocaeli				2,462,480	1,826,144	221,357
10	Kocaeli (Automatic 1)	Konya		76,308				
11	Kocaeli (Automatic 1)	Samsun			205,987			
12	Kocaeli (Automatic 1)	Zonguldak	3,074,252					

Table B4
The flows of hazardous material from recycling facilities to final disposal facilities.

No	From (recycling facility)	To (final disposal facility)	Circuit board (kg)	Refrigerant (kg)
1	Ankara (Manual 1)	Kocaeli	58,257	21,302
2	Kocaeli (Manual 1)	Kocaeli	165,079	8952
3	Kocaeli (Automatic 1)	Kocaeli	476,769	36,305

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