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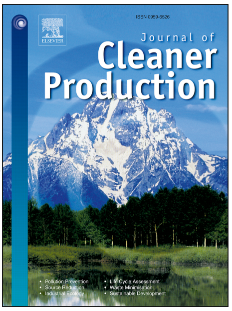

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Optimization of Reverse Logistics Network of End of Life Vehicles under Fuzzy Supply: A Case Study for Istanbul Metropolitan Area

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Abstract

Recycling aims at preventing rapid depletion of natural resources while transforming produced waste into value for economy. However, this process becomes a major challenge in automotive industry, which requires cooperative engagement of multiple players within a complex supply chain. In line with the essence of the topic, government agencies around the world issue directives drawing regulatory frameworks for designing recycling operations comprising various activities such as collection of end-of-life vehicles (ELVs), recovery of reusable components, shredding ELV's body, recycling valuable materials and disposal of the hazardous waste. In general, the amount of returned product in a reverse logistics network is highly uncertain, and the ELV market in Turkey is no exception to this. For that purpose, this study aims developing a fuzzy mixed integer location-allocation model for reverse logistic network of ELVs conforming to the existing directives in Turkey. Accordingly, this study uses a novel approach and assumes that ELV supply in the network is uncertain. The merit of the proposed mathematical model is proved on a real world scenario addressing the reverse logistics design problem for ELVs generated in metropolitan area of Istanbul. The network generated specifies that recycling process is not profitable under the existing circumstances with the given level of supplied ELV and the returned product records per capita in Istanbul are far beyond the EU averages. Consequently, sensitivity analyses question the reliability of the obtained results.

Keywords**:** End-of-Life Vehicles; Reverse Logistics; Location Allocation Problem; Fuzzy Linear Programming; Istanbul.

1. Introduction

An alternative approach relying on the principal of circular economy has recently gained importance for sustainable economy, which has led initializing new production models for recyclable products (Kazancoglu et al., 2018). Recycling aims to provide economic and environmental benefits with less material usage and resource consumption by transforming the produced waste into an input and value for the economy. In extant literature, several studies are made on recycling of the products, which are done in the concept of reverse logistics, such as (Giannetti et al., 2013), and a review on reverse logistics is done by Govindan and Soleimani (2017).

Each year, millions of tons of products complete their economic life and they are turned into nature as waste. Not surprisingly, End of Life Vehicles (ELVs) comprise a large portion of waste disposed into the nature and relevant figures demonstrate an exponentially growing positive trend in line with the economic development, which goes along with high urbanization rates, increased vehicle ownership rates, and adaptation of new technologies such as driverless and/or e-powered vehicles (Burchart-Korol et al., 2018). Solely, the number of ELVs arising in the EU-25 is around 6 million in 2015. This fact hammers home a serious action plan (European Parliament and Council of the European Union, 2000) to be taken in order to increase the recovery, reuse and recycle ratios of ELVs so that a major cause of excessive waste of material, labor hour, and natural resources can be avoided. In addition, seen through an ecological lens, deployment of new technologies is not gratis. For instance, extensive use of battery-powered electrical vehicles brings the danger of acidification and eutrophication as direct byproducts despite their benefit to reduction of direct CO_2 emissions (Burchart-Korol et al., 2018). Thus, there is a great need for reverse logistics networks that optimize the whole supply chain including recovery of used components, standards-conform regaining and/or disposal of chemicals, and efficient recycling of precious materials.

The urgency for recycling is more intense for developing countries like Turkey. As of January 2016, over 21 million motor vehicles are registered in Turkey whereas the same figure was just below 20 million in 2015. On the other hand, the number of deregistered vehicles from traffic was reported only as 118.658 in 2016. This corresponds to 0,563% of the total number of registered vehicles where the same ratio was realized as 2,051% in EU-28 in 2015 (Turkish Statistics Agency (TUİK), 2016).

Additionally, this figure, 118.658 deregistered vehicles, is an extremely optimistic estimate of the real number of ELVs in Turkey considering that not all deregistered vehicles flow to reverse logistics network for regaining purposes. A field study by EU underlines the gaps between the number of deregistered vehicles and ELVs in some European countries, as some deregistered vehicles are exported, improperly recycled or abandoned in the wild without going through the official ELV elimination procedures (Schneider, 2010).

Comparing Turkey's ELV market with one of EU country; Spain's, for example, where total number of registered vehicles is about 33 million (World Health Organization, 2015), and the reported number of ELVs in 2015 was 689.760 (EuroStats, 2018). Based on TUIK (2018) reports, about 20 millions of vehicles were registered in Turkey in 2015. The number of Turkey's registered cars is about two third of Spain's. Therefore, it is expected that the number of ELVs in Turkey be two third of Spain's. However, the number of ELVs in Turkey is way less than the expected amount (Figure 1). Thus, it is obvious that Turkey needs radical changes in its ELV action plans. There may be several reasons of this problem; used vehicles are sometimes exported, parts of ELVs are used in second hand market without proper reporting, or vehicles are deregistered and abandoned somewhere in environment due to their low economic value.

HERE COMES FIGURE 1

The above-drown framework underlines the following facts:

- Turkey, as an emerging economy that ambitiously introduce EU-guidelines on ELV, will be a major source of ELV.
- The extant official records reflect only a limited portion of real ELV numbers produced in the country. Thus, the given figures are partially reliable and possess certain degree of ambiguity.

Bearing in mind the issues discussed above, this study focuses on how to build a mathematical model for optimizing the open loop reverse logistic network for ELVs in Istanbul Metropolitan Area in accordance with the recent ELV directive (Ministry of Environment and Urbanization, 2009). The built model determines the optimum locations of facilities and the allocated amount of flows of raw materials between them under a fuzzy environment.

Deterministic mixed integer linear programming approach optimizes mathematical models, which considers deterministic parameters only. Therefore, first, a generic deterministic version of the proposed model is provided in the study. However, the problem considered includes stochastic (uncertain) parameters such as number of discarded vehicles. In the literature, several methodologies are provided to handle stochastic models. One of these methods is to develop a fuzzy version of the model and apply Zimmermann's (1991) fuzzy linear programming approach which best fits the problem studied. Hence, to handle the uncertainty related to the estimated number of discarded vehicles, a fuzzy mixed integer linear programming approach is used.

In reverse logistics networks, the amount of returned product is one of the most vital design parameters, yet it is subject to high uncertainty (Xu et al., 2017). This issue have been addressed in multiple studies dealing with logistics network design (Baykasoğlu and Subulan, 2015; Kim et al., 2018). However, in the domain reverse logistics network design for ELVs, the uncertainty became barely a focal point of the conducted studies (Phuc et al., 2017; Simic, 2015). The study conducted by Phuc et al. (2017) assumes a fuzzy environment prevailing over various parameters such as costs, prices and amounts of ELV components. Despite having employed a comprehensive fuzzy approach, the burden of the study is that the developed model was not applied on a real life case (Phuc et al., 2017). The latter study by Simic (2015) modelled the uncertainties related to transportation and processing costs and capacities of network entities as well as prices of scrap materials as a fuzzy risk explicit interval linear programming model. Additionally, a special attention was paid to fuzziness in decision maker's preferences (being defensive, neutral, or aggressive). Yet, the fuzziness of material on the flow was not prevailing as an explicit assumption (Simic, 2015). When we focus on the case studies done on Turkish ELV market, extant literature (Ene and Öztürk, 2017, 2015; Demirel et al., 2016; Özceylan et al., 2017) confirms that no single study has been conducted on Istanbul Metropolitan area so far despite its essential role in Turkish vehicle market and substantial weight in the Turkish economy.

This study will contribute to the domain of reverse logistics of ELVs in two aspects. First, it will be one of the rare ELV reverse logistics network design studies with a fuzzy demand assumption. Secondly, to the best of our knowledge, it will be the first study applied on a real-case study in metropolitan city of Istanbul where more than one fifth of motor vehicles and one third of the newly registered vehicles are hosted (Ene and Öztürk, 2017).

The remainder of this paper is organized as follows: in Section 2, extant literature is summarized and promising research directions are highlighted. Section 3 is devoted to the problem definition and mathematical model formulation where the details of the deterministic and fuzzy optimization model are presented. In Section 4, assumptions and model parameters specific to the case study are given and the computational results are summarized. Also, managerial insights based on the findings of the study are addressed in this section. Lastly, Section 5 concludes the study and indicates possible extension areas of the study.

2. Literature Review

In line with the environmental concerns at the end of the last century, ELV is a newly emerging research topic. Research attempts on reverse logistics network design of ELVs have started at the first decade of 2000s (Choi et al., 2005). Depending on the case study at hand, researchers proposed various approaches while modeling and solving reverse logistic network of ELVs.

Cin and Kusakci (2017) conducted a comprehensive review of network design studies on ELVs with cluster analysis using Kohonen's Self Organizing Maps (SOMs) (Kohonen, 1982) Here, we suffice ourselves with a short feedback on this work (Cin and Kusakci, 2017) and cornerstones of literature on reverse logistics design of ELVs. The main attributes used for clustering task of the extant literature are summarized in a tabulated form in Table 1 (Cin and Kusakci, 2017).

HERE COMES TABLE 1

The authors reported that the among the possible alternative cluster architectures 1x3 topology is the optimum one based on the Dunn's Index (Azar et al., 2013). The 23 articles related to topic were distributed among three clusters as 14, 2, and 7 articles, respectively (see Figure 2).

HERE COMES FIGURE 2

Furthermore, the authors tabulated average scores of the attributes in each cluster, which indicate the distinctive features of the group. A close look at Table 2, reveals that fuzzy approaches used for uncertainty handling is very rare (Simic, 2015; Phuc et al., 2017) and allocated them to the third cluster as one of its peculiar features.

HERE COMES TABLE 2

We briefly hit the high spots of the extant literature, which evolved during the last two decades. The very first initiatives in the field can be traced back to the empowerment of legal directives around the world, which focused on transfer of the conventional logistics network design approaches to the ELV domain. As one of the first examples of studies dealing with ELV network design, Choi et al. (2005) used a mixed integer linear programming (MILP) model applied on a real recycling problem. Similarly, Xiaolong et al. (2009) developed a mixed integer programming model and addressed the problem of location selection of the ELV reverse logistics network as a closed loop supply chain. Cruz-Rivera and Ertel (2009) dealt with a closed-loop supply chain network design for discarded vehicles where the model was developed as a facility location problem. Mahmoudzadeh et al. (2011) proposed a model that includes 3rd-Party Logistics parties for the recycling of ELVs in their work.

After recognizing the complex nature of the problem such as sustainability issues, high variety of recoverable and recyclable components and materials, we observe several extension directions in the domain. Among the pioneering works, Harraz and Galal (2011) presented a sustainable recycling network design for ELVs in Egypt, which proposed a mixed integer goal programming model to deal with multiple objectives. A spadework in recycling of ELVs was conducted by Simic and Dimitrijevic (2012) where the possible effects of recently adopted EU Directive on ELVs on vehicle recycling system in the region were studied. Another work by Simic and Dimitrijevic (2013) developed a risk explicit linear programming model for optimal planning of the long-term strategy in the EU vehicles recycling factories. The study by Srinivasan and Khan (2016) worked on a multi-period, multi-product and multi-purpose closed loop green supply chain (CLGSC) network. They built a mixed integer linear programming (MILP) model with the objective of minimizing the total cost and total emissions in the supply chain.

2.1. Uncertainty Handling in ELV Network Design

Another major branch of studies deviating from the conventional approaches addresses uncertainty-handling problem for optimal long-term planning. Within this track, most of the studies employed a scenario-based approach (Cruz-Rivera and Ertel, 2009; Demirel et al., 2016; Mansour et al., 2010; Özceylan et al., 2017) whereas fuzzy methods were exploited in only two cases (Phuc et al., 2017; Simic, 2015). Phuc et al. (2017) developed a reverse logistics network for ELV that minimizes the total cost of the entire network (including installation, handling and processing costs). Due to the ambiguities in the network, such as processing costs, selling prices, capacities and demand on ELV components, they employed fuzzy linear programming. Though proposing a highly comprehensive fuzzy approach, the major drawback of the study is that the model was not applied on a real case scenario.

On the other hand, Simic (2015) modelled the uncertainties related to costs of network activities, capacities of entities in the network, and selling prices of recovered and scrap components and metals by a fuzzy risk explicit interval linear programming model. The authors also focused on ambiguity in preferences of decision makers (being defensive, neutral, or aggressive). Yet, the fuzziness of material on the flow was not prevailing as an explicit assumption (Simic, 2015). Hence, the limited number of fuzzy approaches proves the novelty of this study.

2.2. ELV Studies in Turkey

When it comes to the case studies done on Turkish ELV market, following the newly adopted Turkish Directives on ELVs that was enforced in 2011 (Ministry of Environment and Urbanization, 2009), a very first study was a master thesis conducted by Niziplioğlu (2012). Ene and Öztürk (2015) used a deterministic method and maximized revenue using MILP model in the Turkish market. They used a scenario-based approach to deal with uncertainty related with returned vehicles from supply side. In a recent study, the main interest of the authors was directed to return flow of ELVs in Turkish market by using a grey forecasting method (Ene and Öztürk, 2017) without considering the network design stage of the problem. Another remarkable work presented a case study focusing on reverse logistics network design for ELVs in Ankara, the capital of Turkey. The authors also analyzed car ownership and ELV production in the long-term (Demirel et al., 2016). A very recent work by Özceylan et al. (2017) developed a closed loop supply chain for ELVs, which integrates the recovered and recycled parts and materials to the forward supply chain in the automobile industry in Turkey.

Based on the literature review, it can be concluded that one of the most untouched areas in the domain is the fuzziness in the ELV supply (Phuc et al., 2017; Simic, 2015). Even though, this issue is of vital importance in reverse logistics domain. Especially, when a new regulation comes into force and changes the usual way of thinking and conduct of business, an ambiguous climate dominates all decision-making processes. This was also the case in Turkey after the new Directive on ELVs was published in official gazette in 2009 (Ministry of Environment and Urbanization, 2009). Due to non-conforming current practices in the industry related to disposal of waste in ELV supply chain and lack of sound records, there is huge gaps of real number of ELVs and the number of vehicles recorded and processed in authorized treatment facilities in Turkey. Thus, main source of uncertainty in the network is the amount of returned ELV (Ene and Öztürk, 2017). Accordingly, this work focuses on the uncertainty in supply side while designing a reverse logistic network for ELVs in Istanbul, the economic capital of Turkey, which has not been addressed before.

3. Problem Definition and Model Formulation

According to the Turkish Directive on ELVs dated as 2009 (Ministry of Environment and Urbanization, 2009), journey of an ELV starts with its transport to authorized collection centers or dismantling centers. At this step, the owner is responsible for the transportation of the vehicle. A collection center is required to transfer the ELV within sixty days to an authorized dismantling center (ADC). Before the dismantling operation begins, the toxic and noxious fluids and chemicals, such as the hydraulic oil, the transmission oil, the coolant fluid, and the rest of the fuel, are drained from the vehicle (Zhang and Chen, 2018). Next, reusable parts from the EVL body are disassembled and barcoded by the ADC.

While the reusable parts are sold to second-hand markets after refurbishing operation, some components and materials are sent to recycling facilities. The rest, called *hulk*, goes to shredders where the ELV's body is torn into pieces by shredding cylinders and blades, and ferrous and non-ferrous metals are extracted. As the rest of the shredded hulk, called as auto-shredder residue (ASR) which is composed of textile, plastics, foam rubber, and insulators, has little economic value, and it is disposed of in the landfills sites or burnt out in cement factories.

The recycling facilities, on the other hand, separates the incoming components into two main categories: recyclable and hazardous materials. The recycled materials are sold to the suppliers while the hazardous ones are disposed (Özceylan et al., 2017).

Based on the described material flow, the reverse supply chain is composed of seven main clusters: (1) vehicle users, (2) collection centers, (3) dismantlers, (4) processing facility/shredders, (5) secondhand markets, (6) recyclers, and (7) disposal centers (see Figure 3).

HERE COMES FIGURE 3

Turkish Ministry for Environment and Urbanization has set the goals for reuse/recovery, and reuse/recycling as 85%, and 80% until 2020, respectively. Thenceforth, the same values are to be risen to 95% and 85% respectively (Ministry of Environment and Urbanization, 2009). Despite being less ambitious goals than of the EU (European Parliament and Council of the European Union, 2000), the given target values are highly demanding considering the fact that both recycling industry and recycling culture is in an early development phase in Turkey.

While designing the network, we made the following assumptions with regard to the mathematical model considering the currently enforced Turkish Directive on ELVs:

1. All deregistered vehicles arrive in a collection center or an ADC.
2. The last owner is responsible for the handover.
3. All ELV processing facilities and secondhand market are subject to limited and known annual capacities.
4. The potential locations of all facilities are determined based on existing authorized facilities.
5. All costs and prices are deterministic parameters.

6. The ratios of reverse flow of each subcomponents and materials gained from the ELV are predetermined.
7. All transported materials and subcomponents are measured in kg.
8. The weight of a vehicle is assumed as 1000 kg.
9. The current composition of dismantling and processing centers are potential candidates for final optimal locations of facilities.
10. The sources of ELVs are located at the centers of the districts.

3.1.Model Formulation

Having the above assumptions, the proposed deterministic MILP model is formulated as:

Set and Indices:

N, n: Set and index of components, n=1, 2, 3,…, N

I, i: Set and index of locations of last owners/districts, i= 1, 2, 3,…, I

J, j: Set and index of collection centers, j= 1, 2, 3,…, J

K, k: Set and index of ADCs, k=1, 2, 3,…, K

L, l: Set and index of processing/shredding centers, l= 1, 2, 3,…, L

P, p: Set and index of disposal centers, p= 1, 2, 3,…, P

R, r: Set and index of recycling centers, r= 1, 2, 3,…, R

M, m: Set and index of used product markets, m= 1, 2, 3,…, M

Parameters:

z_i: Amount of ELV produced by the last owner cluster *i* (tons)

$S1_n$: Unit price of component/material *n* sent from dismantling center to used product markets (₺/kg).

$S2_n$: Unit price of component/material *n* sent from recycling center to used product market (₺)

f_l: opening cost of processing/shredding facility *l* (₺)

f_k: opening cost of ADC *k* (₺)

cc_j: Collection cost of ELV in collection center *j* (₺/ton)

cc_k: Collection cost of ELV in ADC *k* (₺/ton)

dc_k: Dismantling cost in ADC *k* (₺/ton)

Sc_l: Processing/shredding cost in processing/shredding facility *l* (₺/ton)

lc_p: Disposal cost in disposal center *p* (₺/ton)

rc_r: Recycling cost in recycling facility *r* (₺/ton)

t: Average transportation cost of ELV and ELV components/materials (₺/ton/km)

d_{jk}: Distance between collection center *j* and ADC *k* (km)

d_{kl}: Distance between ADC *k* and processing/shredding facility *l* (km)

d_{kr}: Distance between ADC *k* and recycling facility *r* (km)

d_{lr}: Distance between processing/shredding facility *l* and recycling facility *r* (km)

d_{lp}: Distance between processing/shredding facility *l* and disposal center *p* (km)

d_{rp}: Distance between recycling facility *r* and disposal center *p* (km)

d_{km}: Distance between ADC *k* and used products market *m* (km)

d_{rm}: Distance between recycling facility *r* and used products market *m* (km)

cap_j: Annual capacity of collection center *j* (ton)

cap_k: Annual capacity of ADC *k* (ton)

cap_l: Annual capacity of processing/shredding facility *l* (ton)

cap_{nr}: Annual capacity of recycling center *r* for ELV subcomponent/material *n* (ton)

cap_p: Annual capacity of disposal center *p* (ton)

α_1: Ratio of hulk weight to whole ELV weight ($0 \le \alpha_1 \le 1$)

α_2: Ratio of weight of reusable subcomponents/materials to whole ELV weight ($0 \le \alpha_2 \le 1$)

α_3: Ratio of weight of non-reusable subcomponents to whole ELV weight ($\alpha_2 + \alpha_3 = 1$)

α_4: Ratio of weight of ASR within hulk ($0 \le \alpha_4 \le 1$)

α_5: Ratio of recyclable materials within hulk ($0 \le \alpha_5 \le 1$)

α_6: Ratio of disposed materials within recycled materials ($0 \le \alpha_6 \le 1$)

rat_n: Ratio of weight of component/material *n* to whole ELV weight

Decision Variables:

X_{ij}: Amount of ELV transferred from the last owner/district *i* to collection center *j* (ton)

Y_{ik} Amount of ELV transferred from the last owner/district *i* to ADC *k* (ton)

W_{jk}: Amount of ELV transferred from collection center *j* to ADC *k* (ton)

S_{nkm}: Amount of reusable subcomponent/material *n* of ELV sent from ADC *k* to used product market *m* (ton)

A_{nkr}: Amount of subcomponent/material *n* of ELV sent from ADC *k* to recycling center *r* (ton)

B_{kl}: Amount of hulk sent from ADC *k* to processing/shredding facility *l*. (ton)

G_{nlr}: Amount of subcomponent/material *n* sent from processing/shredding facility l to recycling center *r* (ton)

E_{lp}: Amount of ASR sent from processing/shredding facility *l* to disposal center *p* (ton)

F_{nrp}: Amount of material *n* sent from recycling center *r* to disposal center *p* (ton)

Fm_{nrm}: Amount of material *n* sent from recycling center *r* to market *m* (ton)

e_l: Binary decision variable indicating whether processing/shredding facility *l* is opened

$$e_l = \begin{cases} 1, \text{if facility } l \text{ is opened} \\ 0, else \end{cases}$$

e_k: Binary decision variable indicating whether ADC *k* is opened

$$e_k = \begin{cases} 1, \text{if } ADC\ k \text{ is opened} \\ 0, else \end{cases}$$

Mixed Integer Linear Programming Model:

The objective of the model is to minimize total cost which is the difference between fixed cost of facility establishment, collection, transport, shredding and disposal cost of ELV as well as total revenue generated by selling reused components and recycled material in the market.

$$\boldsymbol{Zmin = -\sum_n \sum_k \sum_m S_{nkm}.\, S1_n - \sum_n \sum_r \sum_m Fm_{nrm}.\, S2_n} \tag*{[1]}$$

$$+[\sum_l \boldsymbol{f_l.\, e_l} + \sum_k \boldsymbol{f_k.\, e_k} \tag*{[2]}$$

$$+\sum_j \sum_k W_{jk}\,.\,t.\,d_{jk} + \sum_n \sum_k \sum_r A_{nkr}\,.\,t.\,d_{kr} + \sum_k \sum_l B_{kl}\,.\,t.\,d_{kl} + \sum_n \sum_l \sum_r G_{nlr}\,.\,t.\,d_{lr}$$

$$+\sum_n \sum_k \sum_m S_{nkm}\,.\,t.\,d_{km} + \sum_l \sum_p E_{lp}\,.\,t.\,d_{lp} + \sum_n \sum_r \sum_p F_{nrp}\,.\,t.\,d_{rp} \tag*{[3]}$$

$$+\sum_n \sum_r \sum_m Fm_{nrm}\,.\,t.\,d_{rm}$$

$$+\sum_i \sum_j X_{ij}\,.\,cc_j + \sum_i \sum_k Y_{ik}\,.\,cc_k + \sum_j \sum_k W_{jk}\,.\,cc_k \tag*{[4]}$$

$$\boldsymbol{+\sum_j \sum_k W_{jk}\,.\,dc_k + \sum_i \sum_k Y_{ik}\,.\,dc_k + \sum_k \sum_l B_{kl}\,.\,sc_l + \sum_n \sum_k \sum_r A_{nkr}\,.\,rc_r}$$

$$\boldsymbol{+\sum_n \sum_l \sum_r G_{nlr}\,.\,rc_r} \tag*{[5]}$$

$$\boldsymbol{+\sum_l \sum_p E_{lp}\,.\,lc_p + \sum_n \sum_r \sum_p F_{nrp}\,.\,lc_p}] \tag*{[6]}$$

Subject to

Flow constraints:

$\sum_j X_{ij} + \sum_k Y_{ik} = Z_i$ $\quad \forall i$ [7]

$\sum_i X_{ij} = \sum_k W_{jk}$ $\quad \forall j$ [8]

$\sum_l B_{kl} = \alpha_1 (\sum_i Y_{ik} + \sum_j W_{jk})$ $\quad \forall k$ [9]

$\sum_m \sum_n S_{nkm} = \alpha_2 (\sum_i Y_{ik} + \sum_j W_{jk})$ $\quad \forall k$ [10]

$\sum_r A_{nkr} = \alpha_3 . rat_n . (\sum_i Y_{ik} + \sum_j W_{jk})$ $\quad \forall k$, n=3, 4, … 9 [11]

$\sum_p E_{lp} = \alpha_4 . rat_n . (\sum_k B_{kl})$ $\quad \forall l$, n=6, 7, 8, 9 [12]

$\sum_r G_{nlr} = \alpha_5 . rat_n . (\sum_k B_{kl})$ $\quad \forall l, n = 1{,}2$ [13]

$\sum_p F_{nrp} = \alpha_6 (\sum_k A_{nkr})$ $\quad \forall r$, n=3, 4, … 9 [14]

$\sum_p F_{nrp} = \alpha_6 (\sum_l G_{nlr})$ $\quad \forall r, n = 1{,}2$ [15]

$\sum_m Fm_{nrm} = (1 - \alpha_6) . (\sum_k A_{nkr})$ $\quad \forall r, \mathrm{n} = 3, 4, \ldots\ 9$ [16]

$\sum_m Fm_{nrm} = (1 - \alpha_6) . (\sum_l G_{nlr})$ $\quad \forall r, \mathrm{n} = 1{,}2$ [17]

Capacity constraints:

$$\sum_i X_{ij} \leq cap_j \qquad \forall j \qquad [18]$$

$$\sum_i Y_{ik} + \sum_j W_{jk} \;\leq\; cap_k \,.\, e_k \qquad \forall k \qquad [19]$$

$$\sum_k B_{kl} \leq\; cap_l \,.\, e_l \qquad \forall l \qquad [20]$$

$$\sum_k A_{nkr} + \; \sum_l G_{nlr} \leq\; cap_{nr} \qquad \forall n, r \qquad [21]$$

$$\sum_l E_{lp} + \; \sum_n \sum_r F_{nrp} \leq\; cap_p \qquad \forall p \qquad [22]$$

Natural constraints:

$$(\boldsymbol{X_{ij}}, \boldsymbol{Y_{ik}}, \boldsymbol{W_{jk}}, \boldsymbol{S_{nkm}}, \boldsymbol{A_{nkr}}, \boldsymbol{B_{kl}}, \boldsymbol{G_{nlr}}, \boldsymbol{E_{lp}}, \boldsymbol{F_{nrp}}, \boldsymbol{Fm_{nrm}}) > 0 \qquad \forall \boldsymbol{i, j, k, m, n, r, l, p} \qquad [23]$$

$$\boldsymbol{e_k} \,, \boldsymbol{e_l} \in \{\boldsymbol{0}, \boldsymbol{1}\} \qquad [24]$$

The model formulated above aims to minimize total cost that consist of six main components. The first part in the objective function add together the revenues generated by the reusable/recyclable subcomponents and materials sold to the used product markets and raw material vendors. Secondly, installation costs for ADCs and processing/shredding facilities on the selected sites are summed up in Equation 2. The third component pertains to the total transportation cost of ELVs, as well as subcomponents and materials extracted from ELVs throughout the entire network while Equation 4 formulates the collection cost of ELVs from last owners. The total disassembling, processing/shredding, recycling of ELV components and hulks are added with Equation 5. Lastly, Equation 6 sums up the total cost of disposal of ASR and other hazardous materials and liquids.

The constraints of the model are clustered into three main groups: flow constraints (Equations 7-17), capacity constraints (Equations 18-22) and non-negativity and binary constraints. The overall scrutiny of the model constraints is decoded below:

- Equation [7]: The total amount of ELV sent from last owners to the collection centers and ADCs must be equal.
- Equation [8]: The incoming flow of ELV to the collection centers should be equal to the outgoing flow from them to the ADCs.
- Equation [9]: Total amount of hulk derived from collected ELVs in ADCs must be equal to the transferred aggregate hulk to the processing/shredding facilities.
- Equation [10]: Total amount of reusable subcomponents/materials derived in ADCs and sold in used product markets (secondhand markets) must be identical.
- Equation [11]: Total amount of recycled subcomponent/materials n sent from k. ADC to r. recycling center and the unusable portion of total ELV must be equal.
- Equation [12]: Total input of ASR to processing/shredding facility *l* must be equal to its output sent to disposal center *p*.
- Equation [13]: total output of ferrous and nonferrous materials from processing/shredding facility l flowing into recycling center r should be to the total input flowing from k. ADC to processing/shredding facility l.
- Equation [14]: for each recycling center r, the total input of hazardous material flowing into *r* from each ADC should be equal to the total output sent to disposal center p.
- Equation [15]: for each recycling center r, the total input of hazardous material flowing into *r* from each processing/shredding facility *l* should be equal to the total output sent to disposal center p.

- Equation [16]: for each recycling center r, the total input of recyclable material flowing into *r* from each ADC should be equal to the total output sent to market m.
- Equation [17]: for each recycling center r, the total input of recyclable material flowing into *r* from each processing/shredding facility *l* should be equal to the total output sent to market m.
- Equation [18]: The capacity of each collection center *j* is given and cannot be exceeded.
- Equation [19]: Total inflow of ELV to ADC *k* is limited by its capacity.
- Equation [20]: Total hulk amount flowing from ADC *k* to processing/shredding facility l cannot exceed its capacity.
- Equation [21]: Total amount of reusable subcomponents/materials flowing from processing/shredding facility *l* to each recycling center *r* cannot exceed its capacity.
- Equation [22]: Total capacity of a disposal center *p* is given and cannot be exceed.
- Equation [23]: Non-negativity constraints.
- Equation [24]: Binary variable constraints.

3.2.Fuzzy MILP Model

According to Turkish Statistical Institute (TSI), total number of registered land vehicles in Turkey was recorded as 21090424 in 2016. By the end of the same year, Istanbul Metropolitan City hosted 3845349 vehicles, of which 434795 were newly registered in 2016 as given in Figure 4 (Turkish Statistics Agency (TUİK), 2016). Considering the fact that the average age of vehicles on Istanbul’s streets is 7 years and almost 45% of vehicles are younger than 3 years (Ene and Öztürk, 2017), ELV potential of Istanbul as the economic and industrial capital of Turkey is really high. However, number of deregistered vehicles, as depicted in Figure 5, was only 6677 in the same year (Turkish Statistics Agency (TUİK), 2016). A closer look at reported values in Figure 5 reveals that the data related to the number of EVLs shows highly volatile dynamics with a boom in year 2009, the year that ELV Directive in Turkey was issued, and a drastic decline thereafter. Thus, there is remarkable uncertainty for returned product in the reverse logistics network. The discussion above have led us to assume that the number of ELVs generated in Istanbul is a fuzzy parameter which may be handled with Zimmermann's (1991) fuzzy programming approach.

HERE COMES FIGURE 4

HERE COMES FIGURE 5

Accordingly, we revise the deterministic model by replacing the parameter, $\boldsymbol{Z_i}$ number of ELV collected from end users, with a fuzzy parameter $\boldsymbol{\widetilde{Z}_\iota}$. The newly established fuzzy model relies on the following assumptions additional to the original model:

- All assumptions of deterministic model are valid except the assumption related to amount of returned product.
- The amount of ELV generated by end-users is modelled as fuzzy number.

Given the above assumptions, the fuzzy model updates as:

<u>Newly added variable:</u>

λ: Membership degree of intersections of fuzzy sets

Fuzzy parameter:

$\widetilde{Z}_\iota$: Amount of ELV generated by user group *i* (ton)

The fuzzy objective function:

$$\begin{aligned}\widetilde{Zmax} = {} & \sum_n \sum_k \sum_m S_{nkm} . S_n + \sum_n \sum_r \sum_m Fm_{nrm} . H_n - \Big(\sum_l f_l . e_l + \sum_k f_k . e_k + \\ & \sum_j \sum_k W_{jk} . t . d_{jk} + \sum_n \sum_k \sum_r A_{nkr} . t . d_{kr} + \sum_k \sum_l B_{kl} . t . d_{kl} + \sum_n \sum_l \sum_r G_{nlr} . t . d_{lr} \\ & + \sum_n \sum_k \sum_m S_{nkm} . t . d_{km} + \sum_l \sum_p E_{lp} . t . d_{lp} + \sum_n \sum_r \sum_p F_{nrp} . t . d_{rp} + \\ & \sum_n \sum_r \sum_m Fm_{nrm} . t . d_{rm} + \\ & \sum_i \sum_j X_{ij} . cc_j + \sum_i \sum_k Y_{ik} . cc_k + \sum_j \sum_k W_{jk} . cc_k + \\ & \sum_j \sum_k W_{jk} . dc_k + \sum_i \sum_k Y_{ik} . dc_k + \sum_k \sum_l B_{kl} . sc_l + \sum_n \sum_k \sum_r A_{nkr} . rc_r + \\ & \sum_n \sum_l \sum_r G_{nlr} . rc_r + \sum_l \sum_p E_{lp} . lc_p + \sum_n \sum_r \sum_p F_{nrp} . lc_p \Big)\end{aligned} \qquad [25]$$

Fuzzy constraint:

$$\sum_j X_{ij} + \sum_k Y_{ik} \geq \widetilde{Z_\iota} \qquad \forall i \qquad [26]$$

Considering the symmetric nature of fuzziness in the model, we use Zimmermann's (Zimmermann, 1991) defuzzification approach. Given $\boldsymbol{cx} \gtrapprox \boldsymbol{b_0}$ and $(\boldsymbol{Ax})_{\boldsymbol{i}} \gtrapprox \boldsymbol{b_i}$ as symbolical reformulations of Equations 25 and 26, we can express the membership functions of the fuzzy sets with Equations 27 and 28 respectively:

$$\boldsymbol{\mu_o(x)} = \begin{cases} \boldsymbol{1}, & \boldsymbol{cx > b_0} \\ \boldsymbol{1 - \frac{b_0 - cx}{p_0}}, & \boldsymbol{b_0 - p_0 \leq cx \leq b_0} \\ \boldsymbol{0}, & \boldsymbol{cx < b_0 - p_0} \end{cases} \qquad [27]$$

$$\boldsymbol{\mu_i(x)} = \begin{cases} \boldsymbol{1}, & \boldsymbol{(Ax)_i < b_i} \\ \boldsymbol{1 - \frac{b_i - (Ax)_i}{p_i}}, & \boldsymbol{b_i - p_i \leq (Ax)_i \leq b_i} \\ \boldsymbol{0}, & \boldsymbol{(Ax)_i > b_i - p_i} \end{cases}, \qquad [28]$$

where c, A, b_0, and b_i denotes objective and constraints coefficients, as well as desired minimum aspiration levels of fuzzy objective function and constraints respectively. Furthermore, we assume p_0 and p_i represent predetermined tolerance values for objective function and constraints. Here, we assume that b_0 is equal to the objective function value of the deterministic model whereas b_{26}. is calculated as the average number of deregistered ELVs in the city over the last ten years. Related tolerance values, p_0 and p_1, are assumed to be 20% of the stated aspiration levels.

Accordingly, deterministic equivalent of the fuzzy optimization model can be written by replacing Equations 25 and 26 with Equations 29 and 31. Additionally, original fuzzy objective function becomes a deterministic constraint (Equation 30) with an aspiration level to be maximized.

Defuzzified objective function

$$Zmax = \lambda \qquad [29]$$

Defuzzified constraints

$$\begin{aligned} &\sum_n \sum_k \sum_m S_{nkm} . S_n + \sum_n \sum_r \sum_m Fm_{nrm} . H_n - (\sum_l f_l . e_l + \sum_k f_k . e_k + \\ &\sum_j \sum_k W_{jk} . t . d_{jk} + \sum_n \sum_k \sum_r A_{nkr} . t . d_{kr} + \sum_k \sum_l B_{kl} . t . d_{kl} + \\ &\sum_n \sum_l \sum_r G_{nlr} . t . d_{lr} + \sum_n \sum_k \sum_m S_{nkm} . t . d_{km} + \\ &\sum_l \sum_p E_{lp} . t . d_{lp} + \sum_n \sum_r \sum_p F_{nrp} . t . d_{rp} + \\ &\sum_n \sum_r \sum_m Fm_{nrm} . t . d_{rm} + \sum_i \sum_j X_{ij} . cc_j + \sum_i \sum_k Y_{ik} . cc_k + \sum_j \sum_k W_{jk} . cc_k + \\ &\sum_j \sum_k W_{jk} . dc_k + \sum_i \sum_k Y_{ik} . dc_k + \sum_k \sum_l B_{kl} . sc_l + \sum_n \sum_k \sum_r A_{nkr} . rc_r + \\ &\sum_n \sum_l \sum_r G_{nlr} . rc_r + \sum_l \sum_p E_{lp} . lc_p + \sum_n \sum_r \sum_p F_{nrp} . lc_p) \geq b_0 - p_0(1 - \\ &\lambda) \end{aligned} \qquad [30]$$

$$\sum_j X_{ij} + \sum_k Y_{ik} \geq b_i - p_i(1 - \lambda) \qquad \forall i \qquad [31]$$

4. Results and Discussions

4.1. Details of the Case Study

Here, we demonstrate the applicability of the proposed fuzzy programming approach on the economic capital of Turkey. By the end of 2016, the Ministry of Environment and Urbanization of Turkey issued license to 66 collection centers, 9 authorized dismantling centers (ADCs), 5 processing/shredding facilities and 3 disposal centers in Istanbul. However, currently, 52 collection centers, 5 ADCs, 4 processing/shredding facilities, and 2 disposal centers are actively operating. Furthermore, 3 recycling centers and 29 used product markets are identified within the municipal borders of the city. The constituent parties of the reverse logistics network for metropolitan region of the city are geo-located in Figure 6.

HERE COMES FIGURE 6

To elaborate proper estimates of model parameters, we employed the following hierarchical two-steps procedures: (i) collect data through field studies and interviews if possible, and (ii) use extant literature as reference and calculate the averages.

Accordingly, we assumed that opening cost of an ADC is 2500000 Turkish Lira (₺) (Demirel vd., 2016) and average opening cost of a processing/shredding facility is taken as 887500 ₺ (Ene ve Öztürk, 2015; Demirel vd., 2016). The capacities of each types of facilities are determined as given in Table 3. Additionally, interviews with the experts revealed that the cost of collecting one ELV is about 200 ₺ in collection centers and 100 ₺ in ADCs while the operating expenses each ADC, processing/shredding facility, recycling center and disposal field are assumed to be 490 ₺/ton, 135 ₺/ton, 500 ₺/ton (Özceylan et al., 2017), and 250 ₺/ton, respectively.

HERE COMES TABLE 3

A thousand kg of ELV can be decomposed into the following components with the given ratios: ferrous metals (67%), non-ferrous metals (8%), plastics and process polymers (13%), tires (4%), glass (4%), accumulators (1,3%), fluids (2%), air bags (0,1%) and other (textiles, rubber sealing) (%0,6). The hulk to ELV ratio after disassembling the reusable components is 81% whereas ASR obtained from the hulk is approximated as 18,5% of the hulk. The market prices of reusable components and recycled precious materials extracted in ADCs ($S1_n$) and in recycling centers ($S2_n$) are listed Table 4.

HERE COMES TABLE 4

4.2.Computational Results

The fuzzy model described above resulted in a problem with 4971 continuous and 9 binary variables, and 321 constraints. It is solved by using CPLEX solver on GAMS software on an

Intel Core i7 processor within two CPU seconds. At the optimum, the objective function attains a value of $\boldsymbol{\lambda} = 0.63$. This indicates the membership function of the optimum solution to the defined fuzzy set. Using that value, the total cost attains the value of 14270778 ₺. Decomposition of the total cost function into its main components is depicted in Figure 7. A closer look at the figure reveals that total revenue generated by recovered and recycled products covers around 57% of the total cost incurred in the network due to processing, collection, transportation of ELVs and ELV components, as well as due to facility opening decisions. If we further decompose the total cost, we observe that solely 57.6% is associated with processing activities, while the rest is allocated to opening cost of processing/shredding facilities (14.5%), opening of ADCs (13.3%), collection (13.5%) and transportation (0.7%) of ELVs, respectively. On the revenue side, the recovered products sold in the used-product markets are responsible for a substantial proportion (83.0%) of the generated revenue whereas contribution of recycling activities is comparatively less (17%).

HERE COMES FIGURE 7

According to the optimum solution of the fuzzy model, all of the five ADCs and two of the four processing/shredding facilities must be opened. In total 13203 tons of ELV were collected by the collection centers and the rest (11032 tons) was directly sent to ADCs. For the given flow of ELVs in the network, the average capacity utilization of ADCs is 94% while processing/shredding resources are exploited by 95% on average (see Figure 8). Obviously, this indicates that these two stages may be potential bottleneck operations for the whole network in the end due to high utilization rates. Thus, policy makers must pay a special attention to this issue.

HERE COMES FIGURE 8

Figure 9 shows the locations of the established ADCs and flow of material to the shredding facilities. As given in

Table5, amount of ELV shredded annually in two facilities are 8000 tons (utilization rate 100%) in the first one, and 7278 tons in the second one (utilization rate 91%), respectively.

HERE COMES FIGURE 9

HERE COMES TABLE 5

Our model assumes a direct flow of reusable/recovered products (such as tires, windshields, mirrors, and doors) from ADCs to used product markets. Figure 10 shows that three out of 29 candidate second hand markets are used for this purpose. Not surprisingly, the model assigns each ADC to the nearest second hand market.

HERE COMES FIGURE 10

HERE COMES FIGURE 11

HERE COMES TABLE 6

Figure 11 depicts the flow of material from ADCs to recycling centers. The optimum solution shows that two of the existing three recycling centers are connected with ADCs. Table 6 gives the details of the material flow into the recycling centers. The recycling centers, R_1 and R_2, collect 130.8 and 906.6 tons of materials and components from five ADCs. As illustrated in Figure 12, another major source of material inflow into the recycling centers is the shredded ferrous and non-ferrous metals originated from processing/shredding facilities.

Table 7 gives the details of the stream in this channel and indicates 12451.7 tons of ferrous and non-ferrous materials will be annually extracted from ELVs in the network. Considering annual capacities of the recycling centers (11000 tons/year), the network utilizes 100% and 33% of capacities of R_1 and R_2, respectively. The rest of the hulk coming into shredding/processing facilities are disposed as ASR. According to Table 8, total ASR amounts to 2826.454 tons, which results from shredding/processing operations of hulk.

HERE COMES FIGURE 12

HERE COMES TABLE 7

HERE COMES TABLE 8

Besides the direct disposal of materials coming into recycling centers, a major proportion is processed and returned to seven second-hand or used product markets. Total product following this channel amounts to 11465.761 tons. The details of the flow are shown in Figure and Table 9. On the other hand, recycling centers produces 2023.369 tons of hazardous materials disposed in two landfills.

HERE COMES FIGURE 13

HERE COMES TABLE 9

4.3.Sensitivity Analysis

Recall that in $\sum_j X_{ij} + \sum_k Y_{ik} \geq b_i - p_i(1 - \lambda)$ (Equation 31), λ controls the aspiration level of fuzzy demand. In this section, we assume λ is an external parameter and, accordingly, we vary the aspiration level and solve the optimization model for different λ values. Table 10 summarizes the results where objective function value, total cost and revenue, as well as number of ADCs and processing/shredding facilities needed for meeting varying degree of

ELV supply are reported. According to the table, total profit generated by the network is -12067052 ₺ for an aspiration level of zero whereas for $\lambda = 0.7$, the same variable attains the value of -14401956 ₺. When this parameter increases further, the problem becomes infeasible due to the available capacity of ADCs registered in Istanbul. Another remarkable result is the number of facilities to be opened for different aspiration levels. If $\lambda = 0.3$, one more ADC is needed additional to the existing four ADCs whereas the total capacity of two processing/shredding facilities is enough to meet the demand level at any aspiration level. Thus, current capacity of ADCs must be improved to be able to cover a possible increase in ELVs when the current Directive on ELVs fully implemented.

HERE COMES TABLE 10

4.4. Managerial Insights

This section provides some insights, which managers need to bear in mind while evaluating the findings of the study. The proposed framework provides managers a robust mathematical model, which can be applied to any reverse logistics network within the concept of ELVs by applying small modifications. Since both deterministic and stochastic versions of the model are developed, managers are free to apply any of two whether having uncertain parameters or not.

Obviously, based on the results, one can argue that the network is not profitable under the current circumstances with the given level of supplied ELV. However, we note that the returned product records per capita in Istanbul are far beyond the EU averages (see Figure 1). Thus, there is still space for cost improvement if more ELVs enter into the network and the famous economies-of-scale rule applies.

Another major issue affecting the profitability of the network is the estimated prices of the reusable and recyclable components, which are highly volatile and are depended on several different factors, such as brand, model, price in the Original Equipment Manufacturer (OEM) market, and current condition (whether slightly damaged or in good condition). Although we have devoted great effort to determine the right price parameters while solving the model, this issue requires further analyses in which the prices prevailing in the second hand markets for different types of subcomponents for various vehicle models and brands are examined.

Furthermore, based on our company visits, we should note that Turkish ELV industry is experiencing a tremendous transformation. More precisely, before the adoption of Turkish ELV directives, most of them, with a few exceptions, were used to operate as waste collectors with limited operational capacity and hands-on expertise on recycling and disposal of hazardous materials. Thus, we may describe the prevailing business environment as “a transitional grey market” which partially conforms to the regulations. Definitely, with the current ELV Directives, fundamental changes must have been undertaken on traditional ways they operate. To facilitate this, the policy makers, including the Ministry of Environment and Urbanization, and the Metropolitan Municipality of Istanbul, need to put pressure to realize fully enforcement of the newly established standards in the industry.

ELV is a major issue requiring active involvement of various players, including the ministry, local municipalities, automobile manufacturers and/or importers, OEM manufacturers, ELV operators, end users, and insurance companies (Ministry of Environment and Urbanization, 2009). Without any doubt, a neat and smooth implementation of the current directive is only possible if all players work in harmony in line with the introduced standards. However, one should keep in mind that each party comes with its own habits that have been gained with regard to treatment of ELVs in the past, which may not always conform the environmental standards. Changing habits is not a trivial task and requires continuous supervision and corrective feedbacks and incentives from regulatory agencies. To this end, implementation of two policies may be effective. First, the extended producer responsibility principle should be strengthened where the producer/importer is required to collect a certain proportion of the produced ELV and pay deposit for its products on the market similar to the extended responsibility of producers/importers of electronic equipment. The second policy adjustment is about motivating end users to return their ELV to the authorized places by granting some incentives for this action. Indeed, Turkish government has recently materialized the latter suggestion where the consumer receives a considerable discount while purchasing a new vehicle if s/he returns the ELV. Yet, its effect to be seen in the next year’s figures.

Lastly, after the introduction of the Turkish Directives on ELVs in 2011, Niziplioğlu (2012) proposes a deterministic model in which ELV management in Turkey is studied. As difference, the model proposed decides on the number of facilities to be opened and their locations as a strategic managerial decision. Furthermore, the model proposed in this study applies a more intuitive uncertainty handling approach, fuzzy linear programming, instead of generating scenario based analysis as done in Ene and Öztürk (2015), which helps managers to make decisions considering uncertain parameters. Above all, the studied network, to the best of our knowledge, is the first model that develops a network for the managers of Istanbul, which is the economical capital of Turkey. Being proposed for Istanbul does not decrease the ability of the model to be applied to other networks in the world, the very opposite it is applicable to any networks that include uncertain parameters.

5. Conclusions

Recycling of ELVs has recently become a hot research topic due to latest environmental challenges, public interest, regulations of governing bodies and extended producer responsibility practices of major manufacturers. Although ELVs are usually considered as a major source of environmental pollution, they also provide a great economic value considering recoverable components and precious recyclable materials regained when they are properly treated. Reverse logistic network design for ELV draws the necessary framework of proper treatment of ELVs and, thus, it is a significant part of sustainable economic and environmental policies. Following similar initiative in the EU, Turkish Ministry of Environment and Urbanization has adopted Turkish Directives on ELVs with ambitious goals in terms of recovery, reuse and recycling of ELVs (Ministry of Environment and Urbanization, 2009).

In line with the current directives, this study proposed a reverse logistics network with seven main clusters for Istanbul Metropolitan area and optimized it. In the reverse logistics networks, one of the main challenges that the policymakers face with, is the precise estimation of returned product. Due to the practices related to disposal of ELVs in the industry, which are non-conforming with the current regulations, the number of ELVs reported in Turkey was of arguable reliability. Thus, we considered the amount of returned product as an uncertain parameter in the model. Accordingly, this model assumes that ELV supply was a fuzzy parameter. It comprises all reverse logistics operations and determines the location of ELV treatment facilities (ADCs and processing/shredding facilities) and the material flows between the clusters of the network for multiple subcomponents and recycled materials obtained from disassembled vehicles. The resulted model was classified as fuzzy location-allocation mixed-integer linear programming problem that maximizes the aspiration level of the fuzzy constraints. We validated the merit of the model with a case study conducted for metropolitan area of Istanbul. To gain more insights, we applied a sensitivity analysis on the number of required processing facilities and the total profit by changing the amount of returned product. Additionally, reverse logistics networks should also be evaluated from other aspects such as social and environmental benefits. Accordingly, further research efforts can be devoted to possible environmental and social consequences of the network.

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TABLES

Table 1: Summary of literature survey on reverse logistics network design of ELVs (Cin and Kusakci, 2017)

		Network Structure		Modeling Technique										Solution Approach		
				Model				Objective F.		Methods to handle uncertainty						
References	**Year**	**OLSC**	**CLSC**	**LP**	**NLP**	**MILP**	**MINLP**	**Single**	**Multi**	**SA**	**SC**	**ST**	**FO**	**E**	**H**	**M-H**
Choi et al. (2005)	2005	+				+		+		+	+			+		
Schultmann et al. (2006)	2006		+				+	+			+				+	
Mansour and Zarei (2008)	2008	+				+		+			+				+	
Xiaolong et al. (2009)	2009		+			+		+			+			+		
Cruz-Rivera and Ertel (2009)	2009		+			+		+			+			+		
Mahmoudzadeh et al. (2009)	2009	+				+		+		+				+		
Mansour et al. (2010)	2010	+				+		+			+					+
Harraz and Galal (2011)	2011	+				+			+					+		
Mahdi Mahmoudzadeh et al. (2011)	2011	+				+		+		+				+		
Merkisz-Guranowska (2011)	2011	+				+		+							+	
Merkisz-Guranowska (2011)	2011	+				+		+							+	
Niziplioğlu (2012)	2012	+				+		+			+			+		
Simic and Dimitrijević (2012)	2012	+		+				+		+	+			+		
Gołębiewski et al. 2013)	2013		+				+	+		+						+
Simic and Dimitrijević (2013)	2013	+				+			+	+	+			+		
Ene and Öztürk (2014)	2014	+				+		+								+
Simic and Dimitrijević (2015)	2015	+		+				+			+			+		
Ene and Öztürk (2015)	2015	+				+		+		+	+			+		
Simic (2015)	2015	+		+				+			+		+	+		+
Demirel et al. (2016)	2016	+				+		+			+			+		
Phuc et al. (2017)	2016	+				+		+					+	+		
Srinivasan and Khan (2016)	2016		+			+			+	+	+			+		
Özceylan et al. (2017)	2017		+	+					+		+			+		
This Study		+				+			+				+	+		

OLSC: Open-loop supply chain, **CLSC**: Closed-loop supply chain, **LP**: Linear Programming, **NLP**: Nonlinear Programming, **MILP**: Mixed Integer Linear Programming, **MINLP**: Mixed Integer Nonlinear Programming, **SA**: Sensitivity Analysis, **SC**: Scenario Analysis, **ST**: Stochastic Optimization, **FO**: Fuzzy Optimization, **E:** Exact, **H:** Heuristics, **M-H:** Meta-heuristics

Table 2: Average scores of attributes in each cluster (Cin and Kusakci, 2017)

	Network Structure		**Model**				**Objective Function**		**Methods to handle uncertainty**				**Solution Method**		
NODE	OLSC	CLSC	LP	NLP	MILP	MINLP	Single	Multi	SA	SC	ST	Fuzzy	E	H	M-H
NODE (1.1)	0.71	0.28	0	0	0.71	0.29	1	0	0.14	0.43	0	0	0	0.57	0.43
NODE (1.2)	0	1	0.5	0	0.5	0	0	1	0.5	1	0	0	1	0	0
NODE (1.3)	0.86	0.14	0.2	0	0.78	0	0.86	0.14	0.36	0.64	0	0.14	1	0	0.07

Table 3: Assumed capacities of facilities

Facility	Capacity (ton/year)	Reference
Collection Center	1000	Field Study and (Mahdi Mahmoudzadeh et al., 2011; Özceylan et al., 2017; Phuc et al., 2017)
ADC	4000	Field Study and (Ene and Öztürk, 2015; Mahdi Mahmoudzadeh et al., 2011; Özceylan et al., 2017; Srinivasan and Khan, 2016)
Processing/shredding Facility	8000	Field Study and (Özceylan et al., 2017))
Disposal Center	25000	(Ene and Öztürk, 2015; Özceylan et al., 2017; Srinivasan and Khan, 2016)
Recycling Center	11000	(Ene and Öztürk, 2015; Özceylan et al., 2017)

Table 4: Market prices of reusable components and recycled materials

	$\mathbf{S1_n}$								$\mathbf{S2_n}$				
	$\mathbf{S1_1}$	$\mathbf{S1_2}$	$\mathbf{S1_3}$	$\mathbf{S1_5}$	$\mathbf{S1_6}$	$\mathbf{S1_7}$	$\mathbf{S1_8}$	$\mathbf{S1_9}$	$\mathbf{S2_1}$	$\mathbf{S2_2}$	$\mathbf{S2_4}$	$\mathbf{S2_6}$	$\mathbf{S2_7}$
₺/ton	1200	6000	6000	6000	3100	6250	200	600	250	750	150	250	300

Table5: Flow of materials and components between ADCs and processing/shredding facilities

		Processing/shredding facility	
	ADC	L1	L3
B_{kl} /(ton)	K1	-	3240
	K2	-	3240
	K3	1525.69	798.19
	K4	3234.31	-
	K5	3240	-

Table 6: Flow of materials and components between ADCs and recycling centers

	ADC	Recycling Center	Recycled components and materials						
			Plastics and Polymers	Tires	Glass	Accumulators	Fluids	Airbags	Other
A_{nkr} /(ton)	K1	R1	-	-	-	-	-	-	-
	K2		-	-	-	11.44	17.6	0.88	5.28
	K3		-	-	-	8.205	12.62	0.63	3.79
	K4		-	-	-	11.42	17.57	0.88	5.27
	K5		-	-	-	11.44	17.6	0.88	5.28
	K1	R2	114.4	35.2	35.2	11.44	17.6	0.88	5.28
	K2		114.4	35.2	35.2	-	-	-	-
	K3		82.05	25.25	25.25	-	-	-	-
	K4		114.2	35.14	35.14	-	-	-	-
	K5		114.4	35.2	35.2	-	-	-	-

Table 7: Flow of ferrous and non-ferrous metals between processing/shredding facilities and recycling centers

	Recycled material	**Processing/shredding facility**	**Recycling center**	
			R1	**R2**
G_{nlr} /(ton)	Ferrous metals	L1	4242.02	1582.51
		L3	5299.01	-
	Non-ferrous metals	L1	695.47	-
		L3	632.72	-

Table 8: Amount of ASR disposed from processing/shredding facilities

	Shredding facility	Disposal center	Amount of ASR			
			Accumulators	Fluids	Airbags	Other
E_{lp} /(ton)	L1	P1	-	-	-	222
		P2	481	740	37	-
	L3	P1	437.6	-	33.66	-
		P2	-	673.23	-	201.97

Table 9: Recycled materials sold in used product markets

	Product group	Recycling Center	Used Product Market						
			M1	M4	M6	M16	M20	M24	M28
Fm_{nrm} /(ton)	Ferrous metals	R1	-	-	-	-	-	8109.88	-
	Non-ferrous metals		-	-	-	-	1128.96	-	-
	Accumulators		36.13	-	-	-	-	-	-
	Fluids		55.58	-	-	-	-	-	-
	Airbags		2.78	-	-	-	-	-	-
	Other		16.68	-	-	-	-	-	-
	Ferrous metals	R2	-	-	-	-	-	1345.13	-
	Plastics and Polymers		-	-	-	-	-	458.53	-
	Tires		-	-	-	-	-	-	141.09
	Glass		-	-	141.09	-	-	-	-
	Accumulators		-	-	-	-	-	9.72	-
	Fluids		14.96	-	-	-	-	-	-
	Airbags		-	0.75	-	-	-	-	-
	Other		-	-	-	4.49	-	-	-

Table 10: Sensitivity of the model to aspiration level of fuzzy demand

Lambda	Total Profit (₺)	Total Cost (₺)	Total Revenue (₺)	Number of ADCs	Number of Processing/ Shredding Facilities
0.0	-12067052	-26049473	13982421	4	2
0.1	-12273701	-27077306	14803606	4	2
0.2	-12480239	-28105039	15624800	4	2
0.3	-13574485	-30020480	16445994	5	2
0.4	-13781180	-31048358	17267179	5	2
0.5	-13987889	-32076263	18088373	5	2
0.6	-14194962	-33104520	18909558	5	2
0.7	-14401956	-34132708	19730752	5	2
0.8			Infeasible		
0.9			Infeasible		
1.0			Infeasible		

FIGURES

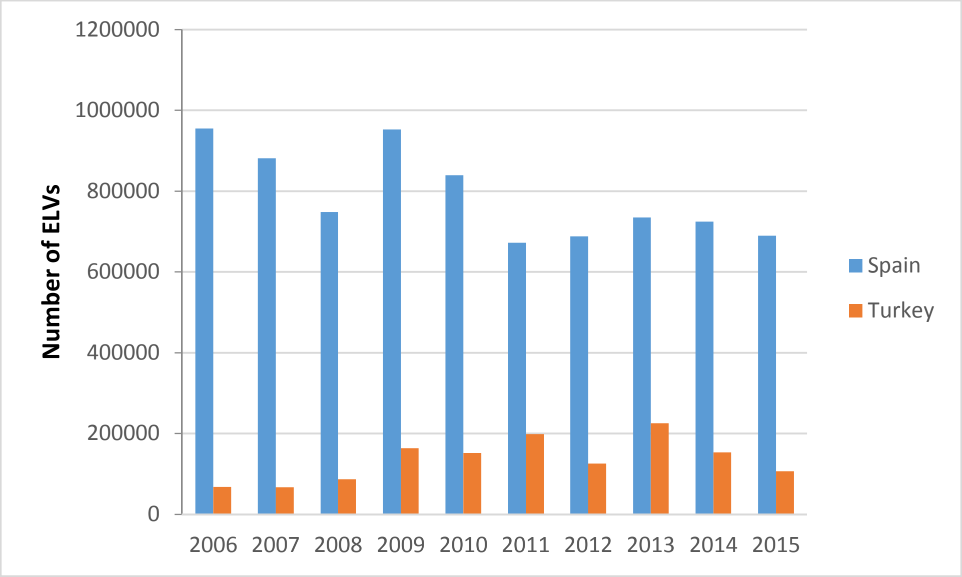


Figure 1: Number of deregistered vehicles from traffic in Spain and Turkey (EuroStats, 2018; Turkish Statistics Agency (TUİK), 2016)

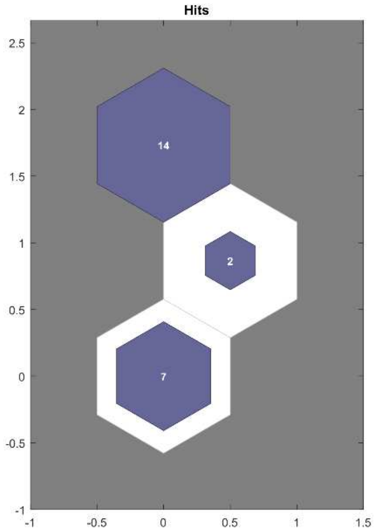


Figure 2: Topology of the SOM and number of papers in each clusters (Cin and Kusakci, 2017)

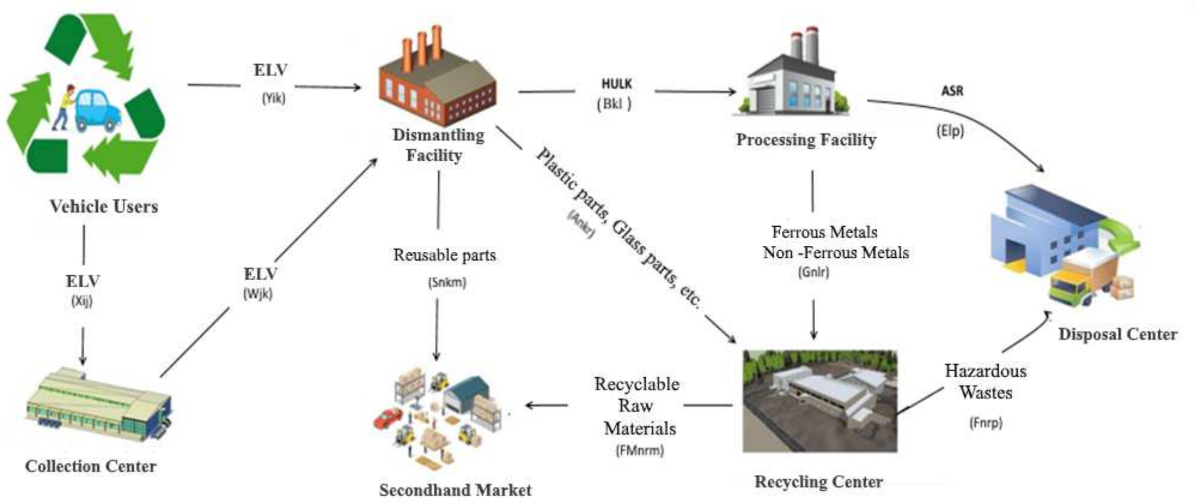


Figure 3: Structure of Reverse Logistics Network for ELVs

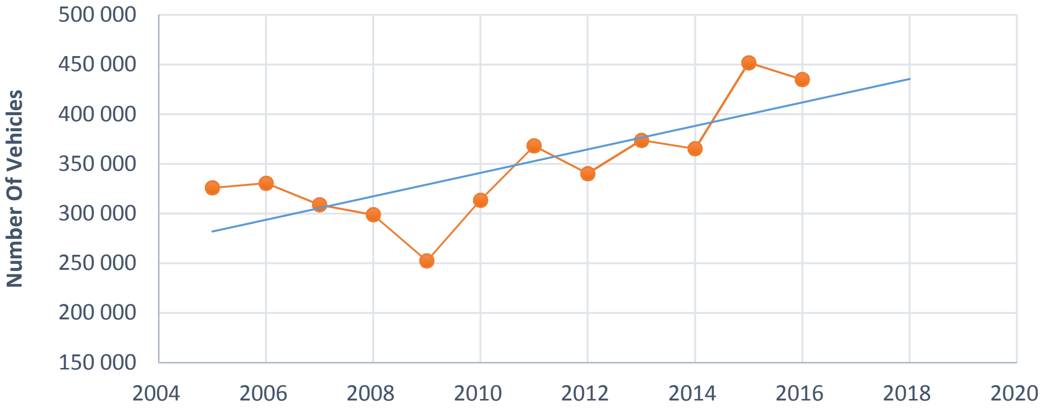


Figure 4: Number of newly registered vehicles in Istanbul

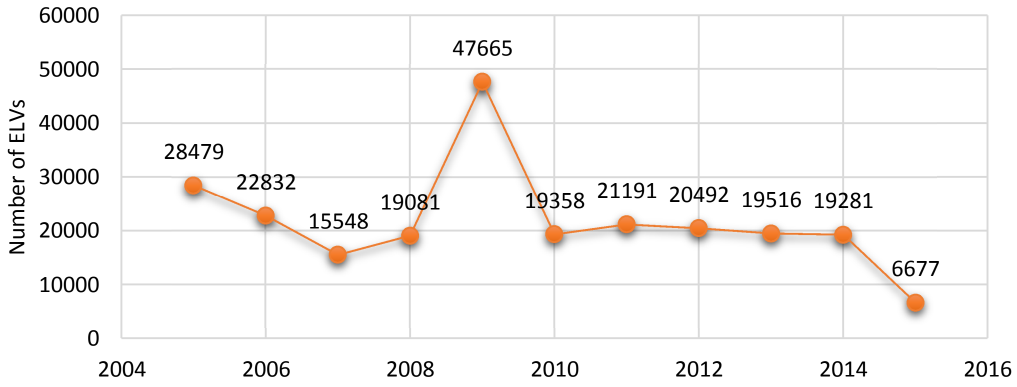


Figure 5: Number of degistered vehicles in Istanbul Metropolitan Area

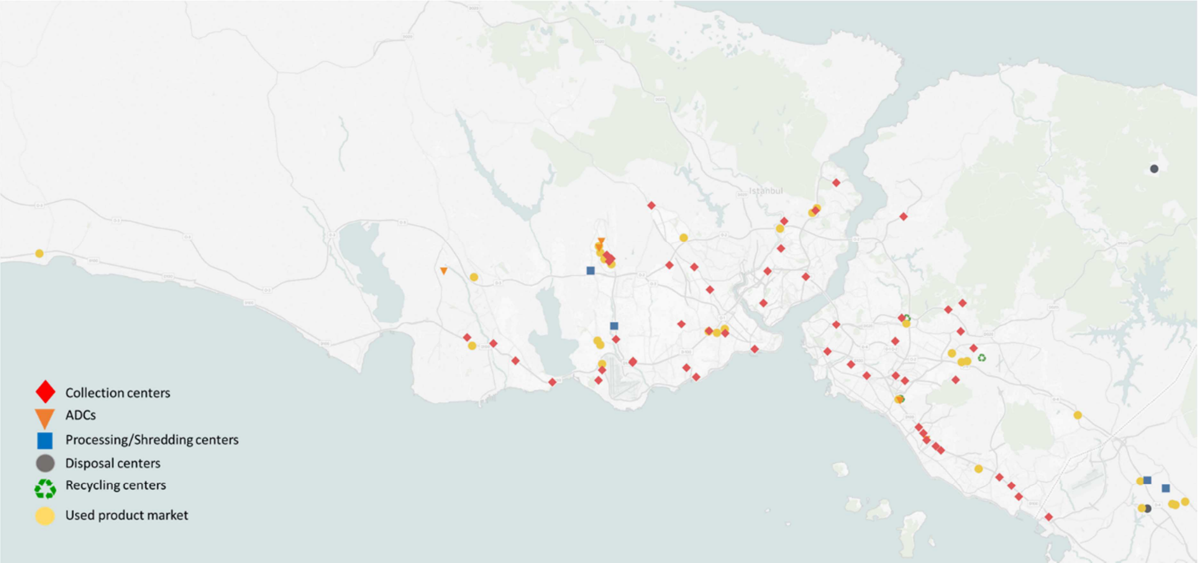


Figure 6: Locations and types of multi-tier members in the supply chain

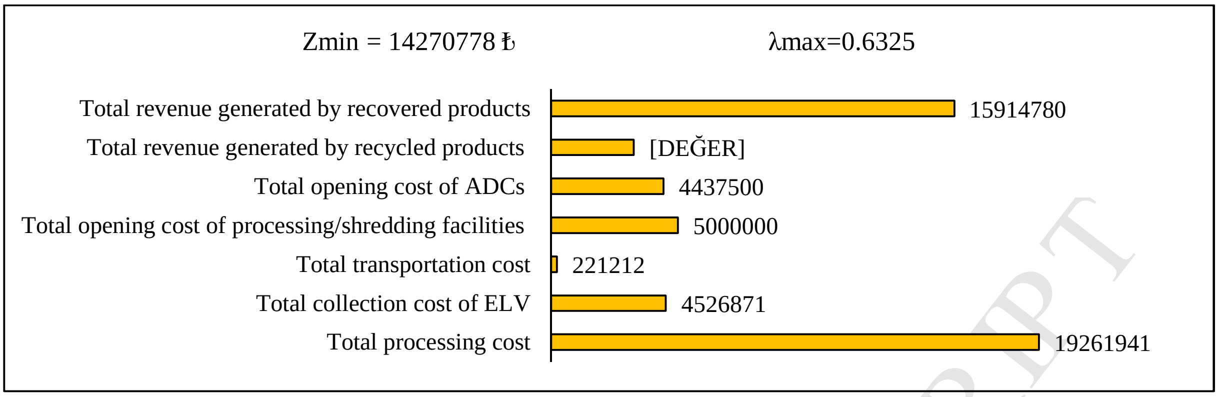
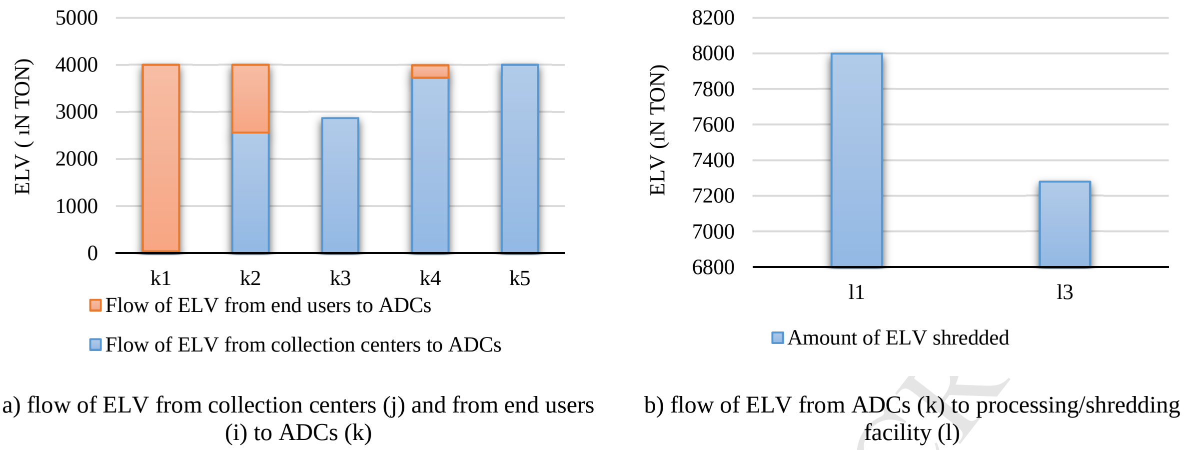


Figure 7: Decomposition of the cost function into its main components



a) flow of ELV from collection centers (j) and from end users (i) to ADCs (k)

b) flow of ELV from ADCs (k) to processing/shredding facility (l)

Figure 8: Capacity utilizations of (a) ADCs and (b) processing/shredding facilities

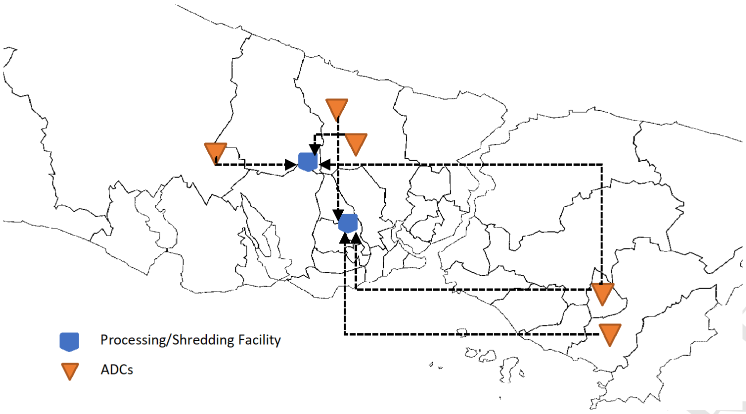


Figure9: Flow of ELVs from ADCs to processing/shredding facilities

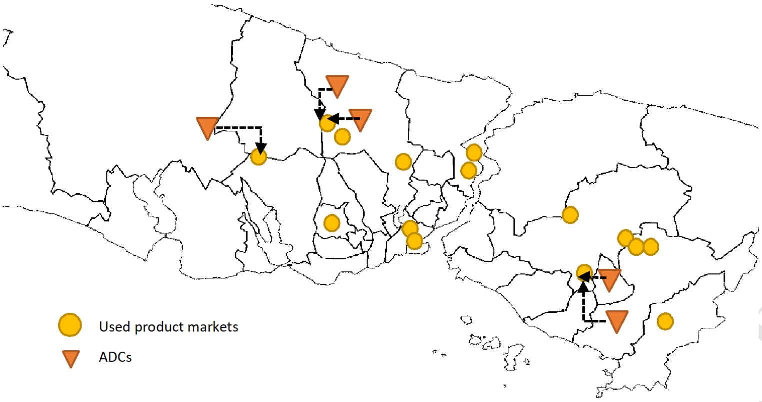


Figure 10: Flow of materials and components from ADCs to used product markets

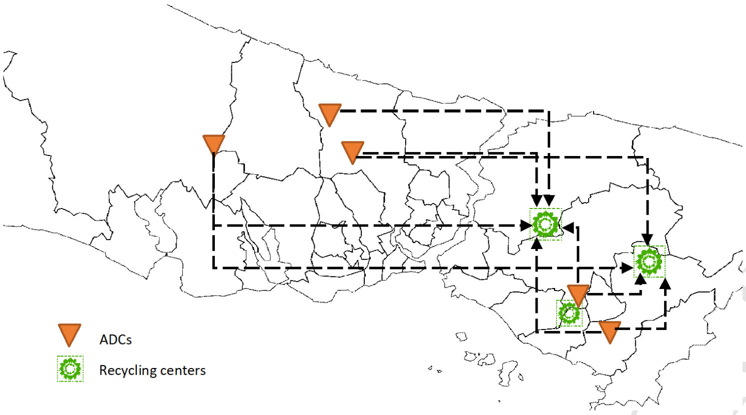


Figure 11: Flow of raw materials from ADCs to recycling centers

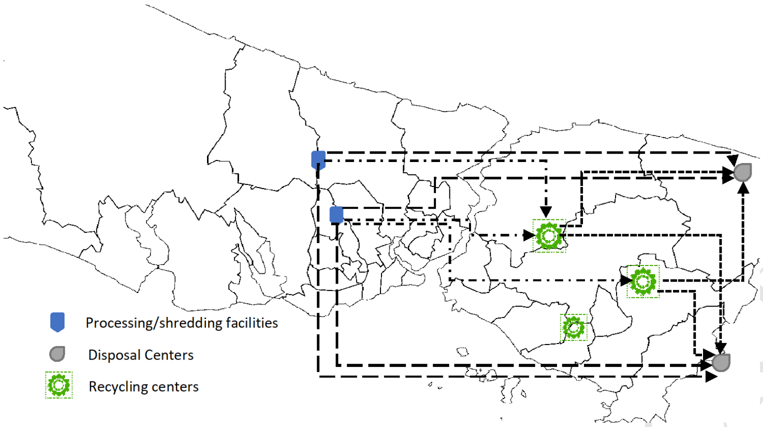


Figure 12: Flow of materials from processing/shredding facilities to recycling and disposal centers

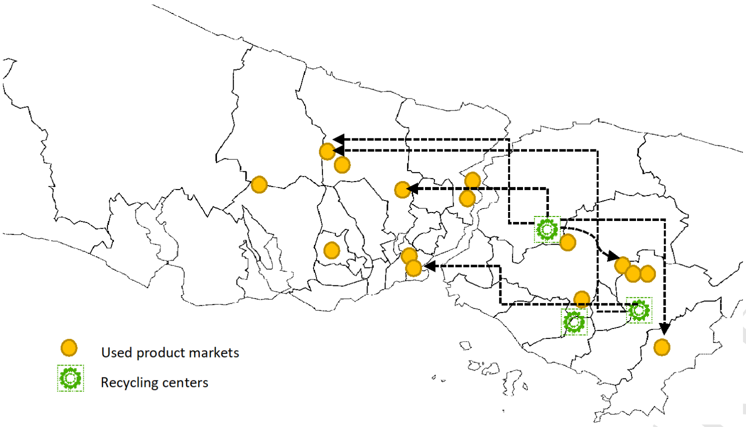


Figure 13: Flow of recycled materials from recycling centers to used product markets