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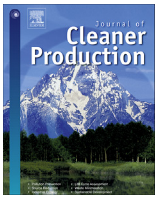

A mixed integer linear programming model to optimize reverse logistics activities of end-of-life vehicles in Turkey

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A B S T R A C T

There are legislations encumbering manufacturers to incorporate environmental factors into their decisions in several industries. Automotive is one of these sectors and in many countries, particularly in those who are a member of the European Union, there are regulations to guarantee the recycling of end-of-life vehicles (ELVs). In Turkey, recovery of ELVs is regulated with Regulation About Controlling of ELVs which was issued by the Turkish Republic Ministry of Environment and Forestry in Official Gazette in 2009. Manufacturers are responsible for free take-back of ELVs from end-users, depolluting, dismantling, shredding and recycling of ELVs. In this paper, in order to comply with related regulations and manage the recovery of ELVs efficiently, we presented a mixed integer linear programming (MILP) model for network design including the different actors taking part in ELV recovery system. The proposed framework is justified by a real case performed in Ankara, the capital and second largest city of Turkey. We also presented a modeling approach for the projection of car ownership and number of ELVs and generated scenario analyzes based on the long-term average developments in the number of ELVs. The case study and analyzes provided important insights on how logistics network behave over time. The results demonstrated that the number of facilities to be located and the system cost increase while the number of ELVs are getting higher in the future.

1. Introduction

Management of end-of-life products becomes vitally important not only because of environmental effects of increasing waste quantities due to worldwide increasing trend of consumption but also economical factors. The automotive industry is one of the industries where the responsibility of the manufacturers is regulated by governments. ELVs are classified as hazardous waste and have the potential for polluting the environment if they are not managed properly whereas they are potential sources of recyclable materials.

The volume of in-use vehicles in world, which is increasing dramatically, is expected to triple in the next years (Levizzari et al., 2002) which accounts for a large amount of ELVs. In 2009, it was estimated that 30 million vehicles reached the end of their service life throughout the world (Ahmed et al., 2009). This number is rising rapidly due to the increasing number of vehicles on the roads. Approximately 14 million ELVs of classes M1 (passenger vehicles with less than eight seats) and N1 (vans not exceeding 3.5 tons) retire each year in Europe (Johnson and Wang, 2002). In order to cope with the problems created by the generation of ELV waste arisings, the European Union adopted the ELVs Directive (2000/52/EC) in October 2000. This directive attempts to reduce the amount of hazardous waste and sets clear targets for reuse, recycling, and recovery (Moakley et al., 2010). The directive also called for developing an infrastructure for the manufacturers to establish ELV collection and recycling network (Kanari et al., 2003).

From the perspective of Turkey, according to data from Turkish Statistical Institute (TURKSTAT), the population increased 5.5% in the last decade, whereas the number of vehicles on the roads increased by 87%, reaching 17 million by the end of 2012. There was a vehicle for eight inhabitants and an automobile for fifteen inhabitants in 2003. These numbers became a vehicle for four inhabitants and an automobile for nine inhabitants in 2012 with the increase in the number of vehicles. Turkish ELV directive came into force on the 1st of January 2011 and currently states that 85% of an ELV must be reused and recovered similar to EU directive on ELVs, and the ratio must reach 95% by 2020. The European Union expects

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a 95% ELV recovery and reuse rate, an increase from the current target of 85% by 2015. Since manufacturers are responsible for free take-back of ELVs from end-users as well as depolluting, dismantling, shredding and recycling of them, it is necessary to manage the ELV recycling process effectively to minimize the costs. We designed a network configuration for fulfilling the requirements of the relevant directive as well as effective management of recycling process of ELV of class M1 which contains vehicles for passenger transport with a maximum of eight seats. Proposed model aims to gain the economic value from the ELV wastes constituting an important source of recycled materials and to minimize the harmful effect of ELVs on the environment by reducing the landfilled quantities. The proposed general framework is justified by a case study focusing on reverse logistics network design for ELVs in Ankara, the capital and second largest city of Turkey. We also presented a model in order to quantify the long-term average developments in the number of ELVs and generated scenario analysis based on the projections of ELVs till 2022.

2. Overview of the literature

Due to the increasing environmental concern, resource reduction and depleting landfill capacities in many countries, reverse logistics has received growing attention in the last decades (Demirel and Gökçen, 2008). The design of product recovery networks is one of the important and challenging issues in reverse logistics environment. Enacted obligations by governments on waste minimization and end-of-life (EOL) products make reverse logistics processes more important in certain industries such as packaging, electrical and electronic equipment and battery. Automotive is also one of these industries since huge amount of vehicle quantities on roads means a huge amount of ELVs and high metal content in the vehicle makes it an attractive source of raw material recovery (Harraz and gallal, 2011). For example, in 2001, the 217 million vehicles on the U.S. roads contained 5.3% of all steel and 13.8% of all aluminum in use in the United States (Jody et al., 2010). Different end-of-life strategies, as well as their main features, are addressed in the literature. Reuse, repair, refurbishing, recycling, cannibalization and remanufacturing are among the most used (Saavedra et al., 2013).

This section gives a brief overview of relevant recent studies and advancements in the design of recovery networks for different EOL products and strategies. In addition to the studies provided by this section, readers are referred to Ilgin and Gupta (2010) for a comprehensive survey on reverse logistics network design models.

Caruso et al. (1993) developed a location-allocation model to determine the number and locations of the waste disposal plants in the region of Lombardy (Italy) while Bautista and Pereira (2006) focused on selecting the locations of municipal waste collection points in Barcelona. Wang et al. (1995) dealt with determining the optimal site locations of processing stations for paper and cardboard which formed the largest fraction of post-consumer and municipal solid waste in the state of Iowa. A model for optimizing the collection and recycling processes of EOL computers and home appliances was developed by Shih (2001). Spengler et al. (1997) focused on the development of MILP model for recycling byproducts in steel industry. Sand recycling was addressed by Barros et al. (1998). Flapper et al. (1998), Realff et al. (1999), Ammons et al. (1997) and Louwers et al. (1999) considered designing recycling network for carpet waste. Krikke et al. (1999) presented a MILP model to determine an optimal reverse logistics network for copiers. Krikke et al. (2003) developed a model to support product design and logistics network design together. In order to illustrate the applicability, the model was applied to a closed loop supply chain (CLSC) design problem for refrigerators. Schultmann et al. (2003) and Kannan et al. (2010) addressed recycling network design for spent batteries. Sasikumar et al. (2010) developed a mixed integer nonlinear programming (MINLP) model to maximize the profit of reverse logistics network and presented a case of truck tire remanufacturing. Gomes et al. (2011) developed a MILP model for network design for electric and electronic waste recovery including waste sources, sorting centres and recycling facilities in Portuquese. Mutha and Pokharel (2009) proposed a mathematical model for the design of a reverse logistics network that consists of retailers, warehouses, reprocessing centers, remanufacturing factories, distribution and recycling centers, spare markets, disposal sites and suppliers. They considered modular product structure with different disposal and recycling fractions for each module of each product in the model. Demirel and Gökçen (2008) proposed a MILP model for a remanufacturing system including both forward and reverse flows. Baenas et al. (2011) analyzed the reverse logistics chain adopted by car battery industries in the midwest of the state of São Paulo, Brazil. Santibanez-Gonzales and Diabat (2013) proposed a mathematical model for a three echelon reverse logistics network including sourcing facilities, collection sites and reclamation facilities. They used Bender's decomposition algorithm to solve the problem and computational experiments for randomly generated networks are presented. Özkır and Başlıgil (2013) proposed a mathematical model for CLSC regarding three recovery options; material recovery, component recovery and product recovery with the objectives of maximizing satisfaction level of trade, maximizing satisfaction degrees of customers, and maximizing total profit of the chain. Özceylan and Paksoy (2013a) proposed an integrated, multi-echelon, multi-period, and multi-part MILP model to optimise the production and distribution planning for a CLSC network. They presented computational results for a number of scenarios. In another study of authors, they extended their previous mathematical model by including fuzziness (Özceylan and Paksoy, 2013b). They used GAMS software to solve the proposed problems in both studies. Fahimnia et al. (2013) proposed a MILP model to evaluate the effects of carbon pricing on a CLSC. They implemented the model on a textile firm servicing in Australia.

Besides given studies, several authors proposed inventory models and policies for integrated production systems including manufacturing and recovery (Teunter, 2001). Teunter proposed an EOQ (Economic order quantity) model of an inventory system for recoverable products. He addressed repairing, refurbishing and remanufacturing options for product recovery in the model (Teunter, 2001). Jonrinaldi and Zhang proposed an integrated production and inventory control model for a CLSC including multiple products. They considered third party logistics (3PL) providers for collection of used products from end customers and disassembly of used products (Jonrinaldi and Zhang, 2013).

It has been recognized that although there are many papers in the published literature on the optimization of the reverse logistics networks for different EOL products recovery, only few of them concern ELV recycling (Guranowska, 2011). Zarei et al. (2010) proposed a mathematical model in which new vehicle distributors were responsible for ELV collection and they used joint potential facilities for distribution and collection. A number of test problem instances were generated in order to measure the effectiveness of the proposed model and solution methodology based on genetic algorithm. Mansour and Zarei (2008) proposed a network design and its mathematical formulation from the perspective of manufacturers in order to obtain maximum economic benefits from ELV recovery and fulfill the relevant legislations. The proposed model focused on establishing the optimized locations for collection centers and dismantlers and material flows between the facilities. For the collection of ELVs in Mexico, a strategic network design was studied by Cruz-Rivera and Ertel (2009). The authors aimed to

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Table 1
Recovery targets based on the EU and Turkish directive.

Vehicle type	Date		Reuse/recovery target	Reuse/recycling target
	EU	Turkish		
All ELVs	2006	2011	85%	80%
ELVs produced before 1980	2006	2011	75%	70%
All ELVs	2015	2020	95%	85%

determine optimal number and locations of collection sites in which take-back, depollution and dismantling operations were performed. Three scenarios composed of 100%, 90%, and 75% of ELV collection coverage were presented. Another recycling network design for ELVs and its mathematical model were presented by Guranowska (2011). Minimization of the total cost of the system including the costs of setting up the network and transportation was aimed in the model. The model was presented on Polish ELV recycling case study. Farel et al. (2013) proposed a mathematical model for ELV glazing recycling network including car manufacturers, dismantlers, shredders, collection and transportation facilities, and the glass treatment facilities. Vehicle routing problem was studied by Schultmann et al. (2006). The proposed model seeked to minimize the total length of tours between the dismantlers and reprocessing facilities in which ELV shredding and cleaning processes were done in Germany.

Besides the lack of optimization of ELV recycling networks for real-life applications, another gap is owing to its complexity, considering the incomes coming about ELV recycling processes. To the best of our knowledge, no published work has studied a generic network design for ELV recycling and its mathematical model considering the incomes of selling remanufacturable/reusable parts obtained by dismantling process and ferrous/non-ferrous materials obtained by shredding process as well as an approach determining the network behaviors in the future. In this paper, in order to comply with related regulations and manage the recovery of ELVs efficiently, we presented a MILP model for reverse logistics network design including the different actors taking part in ELV recovery system. The proposed general framework is justified by a real case performed in Ankara (Turkey). A systematic approach is also presented in order to generate real scenario analysis based on car ownership and number of ELVs in the future. Behavior of the network and its mathematical model is analyzed by means of developments in the number of ELVs. Estimations of demographic and economic developments, number of vehicles per capita and other statistical data are combined in the projection part of the study.

3. Recycling network design for ELVs

In order to improve the management of ELVs, the European Union adopted the Directive on ELVs (Directive 2000/53/EC) in 2000. The directive aims at limiting the use of hazardous substances in vehicles as well as setting specific targets on the reuse, recycling and recovery of waste from vehicles for the years 2006 and 2015 (Andersen and Larsen, 2008). Regulation About Controlling of ELVs in Turkey has only a few differences from the Directive 2000/52/EC. The prominent difference is in the years during which the targets are aimed to be achieved on the reuse, recycling and recovery of wastes from the vehicles (Table 1).

Since the directive seeks to make producers responsible for the cost to take back and treat their vehicles and ensures the certain recovered quantities of materials from ELVs, an efficient network for ELV recovery is vitally important. In this section, we introduced a MILP model for reverse logistics network including the ELV sources such as last owners, insurance companies and abandoned vehicles; collection centers; dismantlers; shredders; recycling facilities; secondary markets and disposal areas for recycling the ELVs (Fig. 1). The objective of the model is to minimize the transportation, recovery, disposal and fixed opening costs in a multistage reverse logistics network. Revenues obtained from selling the reused/remanufactured parts and scrap metals are also considered in the proposed model.

ELVs must only be treated at permitted treatment facilities which are known as Authorised Treatment Facilities (ATFs) and have to meet strict environmental standards in Turkey. ATFs are licensed and regulated by the Turkish Republic Ministry of Environment and Forestry. ELVs undergo a process of depollution, involving the removal of fuel, oil and other fluids, as well as the battery, airbags and heavy metals in dismantlers. Valuable parts are sold to secondary markets in this stage. Remaining ELV body which is called as ‘hulk’ is sent to the shredders. Shredding involves a capital intensive mechanical process and results in the recovery of

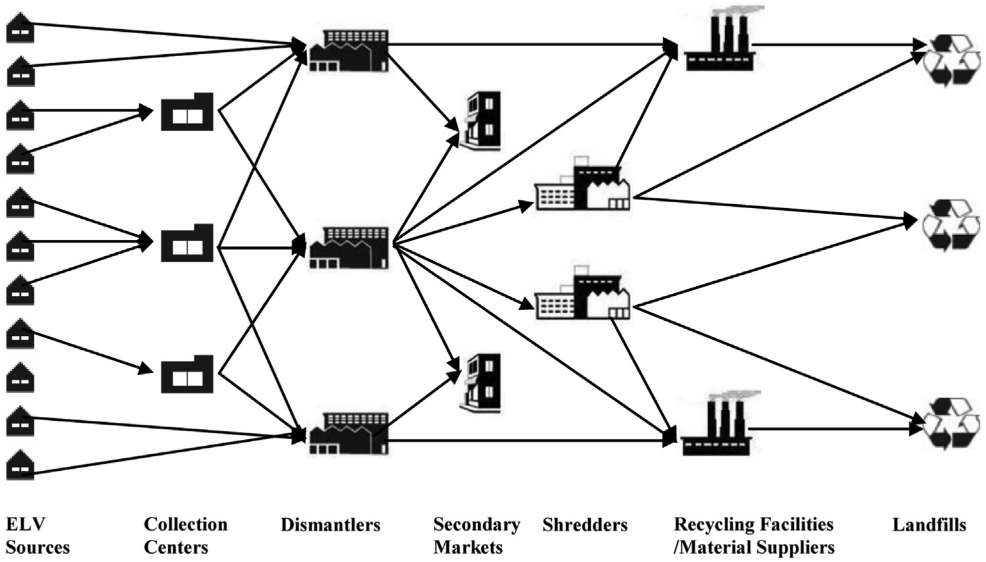

Fig. 1. ELV recycling network.

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metals from the vehicle, leaving auto-shredder residue (ASR), a combination of materials such as plastics, textiles and glass (GHK, 2006). ASR has been disposed of in landfill sites in Turkey although it is being treated to separate useable fractions via using advanced technologies such as mechanical seperation and thermal treatment in order to enhance rates of recycling in some developed countries.

The following assumptions have been considered in developing the mathematical model regarding the regulation and current application in Turkey:

- Last owners must return their vehicle to one of the collection centers or dismantlers.
- Manufacturers have to take back ELVs free of charge from the vehicle's last owner.
- All the ELVs must be collected.
- ELV recycling network consists of ELV sources, licensed collection centers, dismantlers, shredders, recycling facilities and landfills; secondary markets and flows between the facilities.
- 25 districts of Ankara province are accepted as ELV sources.
- Current licensed dismantlers and shredders are considered as candidate sites for facility location. The selection of the final location is done from among the potential locations.
- The geographical position of every locality (ELV sources, collection centers, dismantlers, shredders, recycling facilities and landfills) is defined by cartographic coordinates (longitude and latitude in kilometers).

The proposed model can be formulated as following:

3.1. Indexes

i ELV sources, $i = 1, 2,\ldots,I$
j collection centers $j = 1, 2,\ldots J$
k dismantlers $k = 1, 2,\ldots,K$
l shredders $l = 1,2,\ldots,L$
m secondary markets $m = 1, 2,\ldots,M$
n ferrous and non-ferrous material recycling facilities $n = 1, 2,\ldots,N$
p fluid recycling facilities $p = 1, 2,\ldots,P$
r tyre recycling facilities $r = 1, 2,\ldots,R$
s battery recycling facilities $s = 1, 2,\ldots,S$
u landfills $u = 1, 2,\ldots,U$
t periods $t = 1, 2,\ldots,T$

3.2. Parameters

R_{it}: amount of ELV returned from ELV source i in period t (ton)
f_{kt}: the fixed opening cost for dismantler k in period t (TL)
f_{lt}: the fixed opening cost for shredder l in period t (TL)
dc_{kt}: unit cost of dismantling at dismantler k in period t (TL/ton)
sc_{lt}: unit cost of shredding at shredder l in period t (TL/ton)
lc_{ut}: unit cost of disposal at landfill u in period t (TL/ton)
rc_{pt}: unit cost of fluid recycling at recycling facility p in period t (TL/ton)
rc_{rt}: unit cost of tyre recycling at recycling facility r in period t (TL/ton)
rc_{st}: unit cost of battery recycling at recycling facility s in period t (TL/ton)
s_{1t}: unit price of selling of dismantler for ferrorus material for reusing or remanufacturing in period t (TL/ton)
s_{2t}: unit price of selling of dismantler for non-ferrorus material for reusing or remanufacturing in period t (TL/ton)
s_{3t}: unit price of selling of dismantler for fluid for reusing or remanufacturing in period t (TL/ton)
s_{4t}: unit price of selling of dismantler for battery for reusing or remanufacturing in period t (TL/ton)
s_{5t}: unit price of selling of dismantler for other material (i.e. plastics, glass, textile, rubber) for reusing or remanufacturing in period t (TL/ton)
z_{1t}: unit price of selling of shredder for ferrous material for recycling in period t (TL/ton)
z_{2t}: unit price of selling of shredder for non-ferrous material for recycling in period t (TL/ton)
t_{ijt}: unit cost of transportation between ELV source i and collection center j for ELV in period t (TL/ton*km)
t_{ikt}: unit cost of transportation between ELV source i and dismantler k for ELV in period t (TL/ton*km)
t_{jkt}: unit cost of transportation between collection center j and dismantler k for ELV in period t (TL/ton*km)
t_{klt}: unit cost of transportation between dismantler k and shredder l for hulk in period t (TL/ton*km)
t_{lut}: unit cost of transportation between shredder l and landfill u for ASR in period t (TL/ton*km)
t_{kpt}: unit cost of transportation between dismantler k and recycling facility p for fluid in period t (TL/ton*km)
t_{krt}: unit cost of transportation between dismantler k and recycling facility r for tyre in period t (TL/ton*km)
t_{kst}: unit cost of transportation between dismantler k and recycling facility s for battery in period t (TL/ton*km)
d_{ij}: distance between ELV source i and collection center j (km)
d_{ik}: distance between ELV source i and dismantler k (km)
d_{jk}: distance between collection center j and dismantler k (km)
d_{kl}: distance between dismantler k and shredder l (km)
d_{kp}: distance between dismantler k and recycling facility p (km)
d_{kr}: distance between dismantler k and recycling facility r (km)
d_{ks}: distance between dismantler k and recycling facility s (km)
d_{lu}: distance between shredder l and landfill u (km)
cap_{jt}: capacity of collection center j in period t (ton)
cap_{kt}: capacity of dismantler k in period t (ton)
cap_{lt}: capacity of shredder l in period t (ton)
cap_{pt}: capacity of recycling facility p in period t (ton)
cap_{rt}: capacity of recycling facility r in period t (ton)
cap_{st}: capacity of recycling facility s in period t (ton)
cap_{ut}: capacity of landfill u in period t (ton)
α: weight percentage of hulk in ELV
β: weight percentage of ASR in hulk
$\mu 1$: weight percentage of reusable/remanufacturable ferrous materials in ELV
$\mu 2$: weight percentage of reusable/remanufacturable non-ferrous materials in ELV
μ_3: weight percentage of reusable/remanufacturable fluids in ELV
μ_4: weight percentage of reusable/remanufacturable batteries in ELV
μ_5: weight percentage of reusable/remanufacturable other materials (i.e. plastics, glass, textile, rubber) in ELV
λ_1: weight percentage of non-reusable fluids in ELV
λ_2: weight percentage of non-reusable tyres in ELV
λ_3: weight percentage of non-reusable batteries in ELV
$\gamma 1$: weight percentage of ferrous materials in hulk
$\gamma 2$: weight percentage of non-ferrous materials in hulk

3.3. Decision variables

A_{ijt}: amount of ELV shipped from ELV source i to collection center j in period t
B_{ikt}: amount of ELV shipped from ELV source i to dismantler k in period t

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X_{jkt}: amount of ELV shipped from collection center j to dismantler k in period t

Y_{klt}: amount of hulk shipped from dismantler k to shredder l in period t

Z_{lut}: amount of ASR shipped from shredder l to landfill u in period t

V_{kpt}: amount of non-reusable fluid shipped from dismantler k to recycling facility p in period t

W_{krt}: amount of non-reusable tyre shipped from dismantler k to recycling facility r in period t

U_{kst}: amount of non-reusable battery shipped from dismantler k to recycling facility s in period t

P_{1lnt}: amount of ferrous material shipped from shredder l to recycling facility n in period t

P_{2lnt}: amount of non-ferrous material shipped from shredder l to recycling facility n in period t

Q_{1kmt}: amount of ferrous material shipped from dismantler k to secondary market m in period t

Q_{2kmt}: amount of non-ferrous material shipped from dismantler k to secondary market m in period t

Q_{3kmt}: amount of fluid shipped from dismantler k to secondary market m in period t

Q_{4kmt}: amount of battery shipped from dismantler k to secondary market m in period t

Q_{5kmt}: amount of other material (i.e. plastics, glass, textile, rubber) shipped from dismantler k to secondary market m in period t

e_{kt}: if dismantler k is opened in period t, 1; otherwise, 0

e_{lt}: if shredder l is opened in period t, 1; otherwise, 0

3.4. Formulation

3.4.1. Minimize

$$\sum_k \sum_t f_{kt}\cdot e_{kt} + \sum_l \sum_t f_{lt}\cdot e_{lt} + \tag{1}$$

$$\begin{aligned}&\sum_i \sum_j \sum_t t_{ijt} A_{ijt}\cdot d_{ij} + \sum_i \sum_k \sum_t t_{ikt.} B_{ikt.}\cdot d_{ik} + \sum_j \sum_k \\ &\times \sum_t t_{jkt}\cdot X_{jkt}\cdot d_{jk} + \sum_k \sum_l \sum_t t_{klt}\cdot Y_{klt}\cdot d_{kl} + \\ &\sum_k \sum_p \sum_t t_{kpt}\cdot V_{kpt}\cdot d_{kp} + \sum_k \sum_r \sum_t t_{krt}\cdot W_{krt}\cdot d_{kr} + \sum_k \sum_s \\ &\times \sum_t t_{kst}\cdot U_{kst}\cdot d_{ks} + \sum_l \sum_u \sum_t t_{lut}\cdot Z_{lut}\cdot d_{lu} + \end{aligned} \tag{2}$$

$$\sum_i \sum_k \sum_t B_{ikt}\cdot dc_{kt} + \sum_j \sum_k \sum_t X_{jkt}\cdot dc_{kt} + \tag{3}$$

$$\sum_k \sum_l \sum_t sc_{lt}\cdot Y_{klt} + \tag{4}$$

$$\begin{aligned}&\sum_k \sum_p \sum_t rc_{pt}\cdot V_{kpt} + \sum_k \sum_r \sum_t rc_{rt}\cdot W_{krt} + \sum_k \sum_s \\ &\times \sum_t rc_{st}\cdot U_{kst} + \end{aligned} \tag{5}$$

$$\sum_l \sum_u \sum_t lc_{ut}\cdot Z_{lut} - \tag{6}$$

$$\begin{aligned}&\sum_k \sum_m \sum_t (s_{1t}\cdot Q_{1kmt} + s_{2t}\cdot Q_{2kmt} + s_{3t}\cdot Q_{3kmt} + s_{4t}\cdot Q_{4kmt} \\ &+ s_{5t}\cdot Q_{5kmt}) - \end{aligned} \tag{7}$$

$$\sum_l \sum_n \sum_t (z_{1t}\cdot P_{1\ln t} + z_{2t}\cdot P_{2\ln t}) \tag{8}$$

3.4.2. Constraints

$$\sum_j A_{ijt} + \sum_k B_{ikt} = R_{it} \quad \forall i, t \tag{9}$$

$$\sum_i A_{ijt} = \sum_k X_{jkt} \quad \forall j, t \tag{10}$$

$$\sum_l Y_{klt} = \alpha\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{11}$$

$$\sum_m Q_{1kmt} = \mu_1\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{12}$$

$$\sum_m Q_{2kmt} = \mu_2\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{13}$$

$$\sum_m Q_{3kmt} = \mu_3\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{14}$$

$$\sum_m Q_{4kmt} = \mu_4\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{15}$$

$$\sum_m Q_{5kmt} = \mu_5\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{16}$$

$$\sum_p V_{kpt} = \lambda_1\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{17}$$

$$\sum_r W_{krt} = \lambda_2\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{18}$$

$$\sum_s U_{kst} = \lambda_3\cdot \left(\sum_j X_{jkt} + \sum_i B_{ikt}\right) \quad \forall k, t \tag{19}$$

$$\sum_u Z_{lut} = \beta\cdot \sum_k .Y_{klt} \quad \forall l, t \tag{20}$$

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$$\sum_n P_{1\ \mathrm{ln}\ t} = \gamma_1 \cdot \sum_k .Y_{klt} \quad \forall l,t \tag{21}$$

$$\sum_n P_{2\ \mathrm{ln}\ t} = \gamma_2 \cdot \sum_k .Y_{klt} \quad \forall l,t \tag{22}$$

$$\sum_i A_{ijt} \le \mathrm{cap}_{jt} \quad \forall j,t \tag{23}$$

$$\sum_i B_{ikt} + \sum_j X_{jkt} \le \mathrm{cap}_{kt} \cdot e_{kt} \quad \forall k,t \tag{24}$$

$$\sum_k Y_{klt} \le \mathrm{cap}_{lt} \cdot e_{lt} \quad \forall l,t \tag{25}$$

$$\sum_k V_{kpt} \le \mathrm{cap}_{pt} \quad \forall p,t \tag{26}$$

$$\sum_k W_{krt} \le \mathrm{cap}_{rt} \quad \forall r,t \tag{27}$$

$$\sum_k U_{kst} \le \mathrm{cap}_{st} \quad \forall s,t \tag{28}$$

$$\sum_l Z_{lut} \le \mathrm{cap}_{ut} \quad \forall u,t \tag{29}$$

$$A_{ijt}, B_{ikt}, X_{jkt}, Y_{klt}, Z_{lut}, V_{kpt}, W_{krt}, U_{kst}, P_{1\ \mathrm{ln}\ t}, P_{2\ \mathrm{ln}\ t}, Q_{1kmt}, Q_{2kmt}, Q_{3kmt}, Q_{4kmt}, Q_{5kmt} \ge 0 \quad \forall i,j,k,l,m,n,p,r,s,u,t \tag{30}$$

$$e_{kt}, e_{lt} = \{0,1\} \quad \forall k,l,t \tag{31}$$

The objective function has eight components. The first component represents the fixed costs associated with locating the dismantlers and shredders (1). The second component represents the cost of transportation on each arc of the network (2). The third, fourth, fifth and sixth components represent the cost of dismantling, shredding, recycling and disposal, respectively (3–6). The seventh component is the total revenue obtained from selling reusable/remanufacturable parts of ELVs to secondary markets (7). The last component is the total revenue obtained from selling ferrous and non-ferrous materials to recycling facilities/material suppliers (8). Constraint (9) determines the returned quantities of ELV from ELV sources to the collection centers and dismantlers. Constraint (10) is the balance equation for collection centers. Constraints (11–19) stipulate the transported quantities from dismantlers to shredders, secondary markets and recycling facilities. Constraints (20–22) provide the transported amount of the materials from shredders to landfills and recycling facilities. Constraints (23–29) stipulate that the transportation amounts must not exceed the capacity of collection centers, dismantlers, shredders, fluid, tyre and battery recycling facilities and landfills at each period, respectively. Constraint (30) enforces the non-negativity restriction on the decision variables. Lastly, constraint (31) represents the binary variables.

4. A case study

We applied the proposed model in the previous section on a case study inspired by a real life problem in Ankara for ELVs recycling. Using real data, we attempted to answer several questions: Where and how many dismantlers and shredders to locate? How much ELV, component, material and waste to flow between facilities?

Table 2
Composition of Typical ELV over time.

Material/fraction	Kg per ton of ELV		
	2002	2006	2015
Ferrous metal	680	680	650
Non-ferrous metal	80	80	90
Plastics and process polymers	100	100	120
Tyres	30	30	30
Glass	30	30	30
Batteries	13	13	13
Fluids	17	17	17
Textiles	10	10	10
Rubber	20	20	20
Other	20	20	20
Total	1000	1000	1000

4.1. *Description of the problem*

Ankara is the capital of Turkey and the country's second largest city after Istanbul. The city is located at 39°52′30″ North, 32°52′ East, about 450 km to the southeast of Istanbul. Centrally located in Anatolia, Ankara is an important commercial and industrial city. According to the Turkish Statistical Institute, as of 2011 the city of Ankara had a population of 4,890,893 (Turkstat, 2012a). Ankara has important ELV generating rates and it is in the second order in Turkey after Istanbul. The volume of in-use vehicles in Ankara was reported as 1,367,427 by the end of 2011 (Turkstat, 2012b). Number of ELVs deregistered from traffic was reported as 7670 whereas number of cars was 1824 during the year 2011 (Turkstat, 2012b). There were 32 collection centers and 27 dismantlers in service in Ankara according to 2011 data obtained from Ministry of Environment and Forestry. In addition, 9 shredders, 3 landfills, 23 ferrous and non-ferrous material recycling facilities, 83 fluid recycling facilities, 25 tyre recycling facilities and 3 battery recycling

Table 3
Districts of Ankara province.

District	Latitude	Longitude	Population in 2011	No. of ELVs in 2011
Akyurt	40.11667	33.11667	26780	10
Altındağ	39.96361	32.90333	365915	137
Ayaş	40.01667	32.31667	13166	5
Bala	39.55	33.26667	18861	7
Çankaya	39.92444	32.88556	813339	303
Çubuk	40.23861	33.03306	82156	31
Elmadağ	39.91667	33.21667	44140	16
Etimesgut	39.94583	32.66944	414739	155
Gölbaşı	39.76667	32.81667	105006	39
Kalecik	40.11667	33.41667	13969	5
Kazan	40.23167	32.68389	42090	16
Keçiören	40	32.86667	831229	310
Mamak	39.94222	32.92306	558223	208
Pursaklar	40.11872	32.87093	114833	43
Sincan	39.95944	32.57667	468129	175
Yenimahalle	39.96667	32.8	668586	249
Beypazarı	40.2175	31.92111	47018	18
Çamlıdere	40.49	32.46972	6993	3
Evren	39.01667	33.8	3227	1
Güdül	40.21111	32.24278	8891	3
Haymana	39.43111	32.49556	32705	12
Kızılcahamam	40.46667	32.65	24635	9
Nallıhan	40.18361	31.35056	30299	11
Polatlı	39.56667	32.1	119349	45
Şereflikoçhisar	38.94444	33.54194	35042	13

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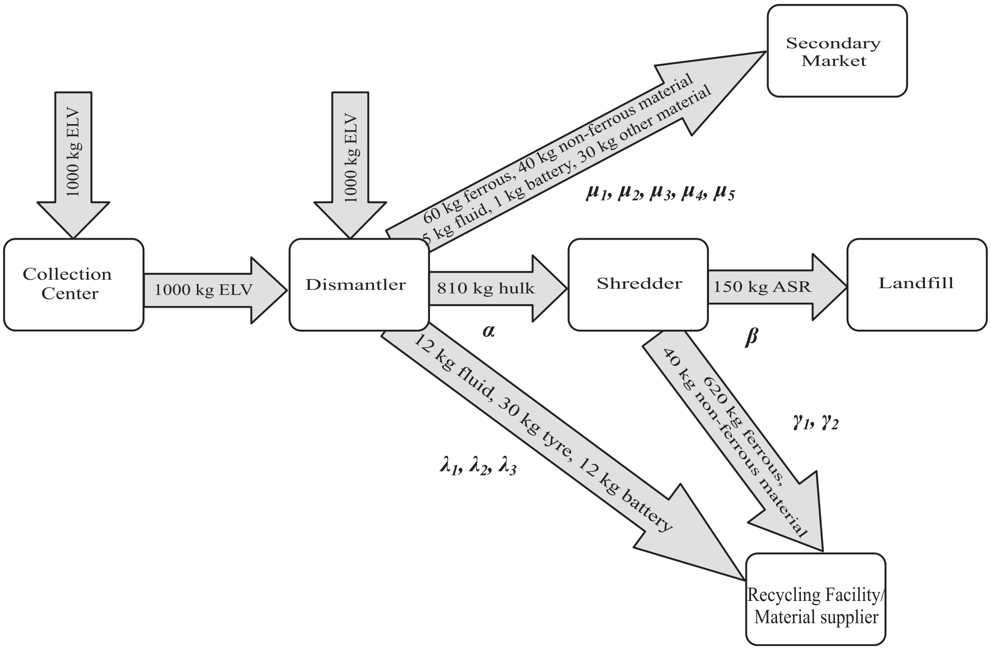

Fig. 2. Movement of an ELV and its components in the recycling network.

facilities were servicing in different cities of Turkey. All of the points, where the dismantlers and shredders are located, are taken as potential sites for dismantling and shredding processes. Centers of 25 districts of Ankara are taken as ELV sources in the problem. The quantities of materials and components in a typical ELV, at the past and present time and as expected to arise in 2015 are given in Table 2 (GHK, 2006).

In order to optimize the amount of transported quantities between the facilities, the available data on number of vehicles deregistered from traffic in Ankara in 2011 (Turkstat, 2012b) and ELV composition currently valid are considered (Second column in Table 2). Since lack of data on ELV returns from districts of Ankara in 2011, number of vehicles deregistered from traffic in 2011 is split up to the districts based on the population data in 2011. Districts of Ankara, populations and number of ELVs are given in Table 3.

The average weight of an ELV is taken as 1000 kg. Part and material flows obtained from an ELV in the recycling network is shown in Fig. 2.

We utilized Turkish Statistical Institute reports and in-depth literature review besides industry survey in order to develop the cost estimation framework. The transportation costs of ELV from the ELV sources to collection centers and dismantlers are taken as 1.0 TL/kilometer-ton whereas the transportation costs of ELV between collection centers and dismantlers are 0.4 TL/kilometer-ton. The transportation costs of hulk between dismantlers and shredders and ASR between the shredders and landfills are taken as 0.2 TL/kilometer-ton and 0.5 TL/kilometer-ton and the transportation costs of non-reusable fluid, tyre and battery between the dismantlers and recycling facilities are also determined as 0.5 TL/kilometer-ton. The opening costs of dismantlers and shredders are 625,000 TL and 2,500,000 TL, respectively. The other data on costs of processing parts and materials and revenues obtained from selling the valuable parts and materials are given in Table 4. Percentages of weight of parts/materials sold from dismantlers and shredders can also be seen in Table 4.

The number and geographic locations of all units in the network are determined and then the distances between them are calculated. Distances from dismantlers to shredders and battery recycling facilities; shredders to landfills are given in Table 5. Since we couldn't get detailed information on the capacities of each existing collection centers, dismantlers, shredders, etc., the average value of capacities are determined depending on industry survey and assumed to be the same for all facilities. Considered capacities in the model are 1000, 5000, 15,000 and 100,000 tons for collection centers, dismantlers, shredders and landfills for the year 2011, respectively. Capacities of fluid and tyre recycling facilities are taken as 7300 tons whereas battery recycling facility capacity is considered 25,000 tons in 2011. Other parameters are set as: λ_1: 0.012; λ_2: 0.03; λ_3: 0.012 which are the values calculated using the ELV composition by 2006 (See Table 2).

Table 4
ELV recycling network data.

Cost	Dismantling (dc_{kt}) (TL/ton)	Shredding (sc_{lt}) (TL/ton)	Fluid recycling (rc_{pt}) (TL/ton)	Tyre recycling (rc_{rt}) (TL/ton)	Battery recycling (rc_{st}) (TL/ton)	Landfill (lc_{ut}) (TL/ton)	
	980	135	450	500	450	250	
Price	S_{1t}/μ_1 (TL/ton)	S_{2t}/μ_2 (TL/ton)	S_{3t}/μ_3 (TL/ton)	S_{4t}/μ_4 (TL/ton)	S_{5t}/μ_5 (TL/ton)	Z_{1t}/γ_1 (TL/ton)	Z_{2t}/γ_2 (TL/ton)
	1200/0.06	6000/0.04	6250/0.005	3100/0.001	6000/0.03	250/0.765	750/0.05

S_{1t}, S_{2t}, S_{3t}, S_{4t}, S_{5t}: unit prices of selling of dismantlers to secondary markets for reusing or remanufacturing for ferrorus material, non-ferrorus material, fluid, battery and other materials in period t (2011), respectively.
Z_{1t}, Z_{2t}: unit prices of selling of shredders to recycling facilities for ferrous and non-ferrous material in period t (2011).

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Table 5
Distance matrix (km).

	Shredders									Battery recycling facilities		
	1	2	3	4	5	6	7	8	9	1	2	3
Dismantlers												
1	299.6	440.3	367.6	356.4	394.3	486.3	752.2	246.5	251.5	490.1	513.7	219.6
2	286.9	450.7	380.4	367.3	403.1	474.8	764.9	233.8	238.8	478.5	502.4	227.9
3	301.0	436.8	367.6	359.1	390.1	484.3	750.9	247.9	252.8	488.0	511.6	215.2
4	293.0	446.4	373.9	361.1	399.8	481.2	758.8	239.9	244.9	485.0	508.8	224.9
5	300.5	437.2	368.1	359.5	390.5	483.8	751.4	247.4	252.3	487.6	511.1	215.5
6	299.7	440.3	367.6	356.4	394.3	486.3	752.2	246.5	251.5	490.1	513.7	219.5
7	301.9	437.6	365.8	355.8	391.6	487.2	750.0	248.7	253.7	491.0	514.6	216.9
8	300.7	436.9	368.0	359.7	390.1	483.7	751.2	247.5	252.5	487.4	511.0	215.1
9	300.6	436.9	368.1	359.7	390.1	483.7	751.2	247.5	252.4	487.4	510.9	215.1
10	300.1	439.9	367.1	356.1	394.0	486.7	751.8	246.9	251.0	490.4	514.1	219.2
11	299.6	440.7	367.5	356.1	394.7	486.6	752.3	246.4	251.5	490.3	514.0	220.0
12	299.7	440.3	367.5	356.4	394.3	486.3	752.2	246.5	251.6	490.1	513.8	219.5
13	294.4	445.3	372.5	359.9	398.8	482.5	757.4	241.3	246.3	486.3	510.0	223.9
14	300.6	436.9	368.1	359.7	390.1	483.6	751.2	247.5	252.4	487.4	510.9	215.1
15	299.7	440.3	367.5	356.4	394.3	486.3	752.2	246.5	251.6	490.1	513.7	219.5
16	300.6	436.9	368.1	359.7	390.1	483.7	751.2	247.5	252.4	487.4	510.9	215.1
17	302.5	435.5	366.1	357.9	389.0	485.5	749.4	249.4	254.3	489.3	512.8	214.1
18	300.5	437.2	368.1	359.5	390.4	483.8	751.4	247.4	252.3	487.5	511.1	215.5
19	300.7	436.9	367.9	359.5	390.1	483.9	751.1	247.6	252.5	487.6	511.2	215.2
20	299.9	437.9	368.5	359.7	391.1	483.6	751.9	246.8	251.7	487.3	510.9	216.2
21	300.6	436.9	368.1	359.7	390.1	483.7	751.2	247.5	252.4	487.4	511.0	215.2
22	300.8	436.6	367.9	359.7	389.8	483.7	751.1	247.7	252.6	487.4	510.9	214.8
23	300.1	437.7	368.4	359.6	390.9	483.6	751.8	247.0	251.9	487.4	510.9	216.0
24	301.2	436.8	367.3	358.7	390.2	484.6	750.7	248.0	253.0	488.4	511.9	215.3
25	299.1	441.8	367.6	355.4	396.1	487.2	752.8	246.0	251.0	490.9	514.6	221.4
26	300.6	437.2	367.8	359.1	390.5	484.1	751.2	247.5	252.5	487.9	511.4	215.6
27	286.7	460.4	377.1	355.1	415.8	486.5	766.1	233.7	239.1	490.2	514.5	241.3
Landfills												
1	276.8	452.2	396.3	389.2	400.5	453.8	776.0	223.9	228.5			
2	265.3	912.3	907.5	873.1	835.5	190.6	1278.9	310.7	304.1			
3	46.9	676.3	615.7	567.0	615.2	324.0	1005.1	7.2	8.3			

4.2. *Computational results and managerial insights*

The settings described above resulted in a problem with 36 binary variables, 6155 continuous variables, and 526 constraints. We took all of our runs on a server with 3.00 GHz Intel Core processor and 2 GB of RAM and the computation time required to solve the model optimality using the GAMS-CPLEX solver is less than 13 CPU seconds. One of the potential dismantlers (twenty fourth) and potential shredders (eighth) are opened in the optimal solution. The optimal values of the decision variables are given in Table 6.

Table 6 shows that ELVs are transported to collection centers with number 3,6,7,19, 23,26,27,31 and 32 and there is no transportation between the ELV sources and other collection centers. The most admitted quantity of ELVs from the ELV sources is 664 which is actualized by twenty third collection center. Minimum transportation is occurred to seventh collection center (28 units of ELV). According to optimal results, in total 1824 ELVs are transported to collection centers from ELV sources and there is no directly transportation between the ELV sources and dismantlers. All ELVs are transported to the twenty fourth dismantler servicing in Ankara from collection centers. Hulks are transported from the twenty fourth dismantler to only eighth shredder located in Kocaeli province which is approximately 250 km away from Ankara. Transported hulk quantity from dismantler to shredder is determined as 1477.44 tons.

Total disposal quantity is determined as 273.326 tons and all of ASR is disposed in the third landfill located in Kocaeli. Totally, 1130.242 tons ferrous and 73.872 tons non-ferrous materials are sold to recycling facilities/material suppliers from shredders in the optimal solution.

In addition to the distribution flow of the optimal solution, in the performance measures frame of the ELV recycling network, the total cost is calculated at 4,039,693 TL. Table 7 gives the primary performance measures (incomes and costs) as a percentage of the total income and cost.

The results given in Table 7 show the following indicators:

Table 6
The results obtained by GAMS-CPLEX program for the year 2011.

Variable	Value	Variable	Value	Variable	Value	Variable	Value	Variable	Value
$A_{1,19}$	10	$A_{11,7}$	16	$A_{21,27}$	12	$X_{26,24}$	310	$P2_{8,23}$	73.872
$A_{2,23}$	137	$A_{12,26}$	310	$A_{22,7}$	9	$X_{27,24}$	72	$Q1_{24,1}$	109.44
$A_{3,6}$	5	$A_{13,23}$	208	$A_{23,6}$	11	$X_{31,24}$	43	$Q2_{24,1}$	72.96
$A_{4,27}$	7	$A_{14,31}$	43	$A_{24,6}$	45	$X_{32,24}$	249	$Q3_{24,1}$	9.12
$A_{5,23}$	303	$A_{15,6}$	175	$A_{25,27}$	13	$Y_{24,8}$	1477.44	$Q4_{24,1}$	1.824
$A_{6,19}$	31	$A_{16,32}$	249	$X_{3,24}$	155	$V_{24,20}$	21.888	$Q5_{24,1}$	54.720
$A_{7,23}$	16	$A_{17,6}$	18	$X_{6,24}$	257	$W_{24,6}$	54.72		
$A_{8,3}$	155	$A_{18,7}$	3	$X_{7,24}$	28	$U_{24,3}$	21.888		
$A_{9,27}$	39	$A_{19,27}$	1	$X_{19,24}$	46	$Z_{8,3}$	273.326		
$A_{10,19}$	5	$A_{20,6}$	3	$X_{23,24}$	664	$P1_{8,23}$	1130.242		

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Table 7
Results of each performance measure for the problem instance.

Performance criteria	Definition	Value (*10^6)	Percentage of total income (%)	Percentage of total cost (%)
1	Objective function	4.039693	–	75.68
2	Total cost of the system	5.337720	–	100.00
3	Total fixed costs	3.125000	–	58.55
4	Total transportation costs	0.110355	–	2.07
5	Total dismantling costs	1.787520	–	33.49
6	Total shredding costs	0.199454	–	3.74
7	Total recycling costs	0.047059	–	0.88
8	Total disposal costs	0.068332	–	1.28
9	Total income of the system	1.298027	100.00	24.32
10	Total sales of dismantlers	0.960063	73.96	–
11	Total sales of shredders	0.337964	26.04	–

- The objective function accounts for a 75.68%, while total income of the system accounts for a 24.32% in the overall total cost.
- The objective function is greater than approximately 3.1 times the total income of the system.
- In the cost frame, while the maximum share is actualized by the total fixed costs of 58.55%, the minimum share is actualized by the total recycling costs of 0.88%.
- While the total reverse processes (dismantling, shredding, recycling, disposal) account for 39.39% of the total cost, the dismantling costs seem to be dominant in this percentage.
- In the income frame, while the maximum contribution is provided by dismantlers' sales with 73.96% (which is greater than 2.84 times the shredders' sales) the rest of the income is provided by shredders' sales of 26.04%.

On the other hand, the maximum contribution to income obtained from dismantlers' sales is provided by the sales of nonferrous materials with 45.60% and the minimum share is actualized by the income of battery sales with 0.59%. Similarly, the maximum contribution is provided by ferrous material sales with 83.61%, the rest of the income of shredders is provided by nonferrous material sales of 16.39%.

5. Projections and scenario analysis

5.1. Car ownership and ELV projections

In this section we aimed to model the generation of ELVs and presented a projection of the number of ELVs from the 2012 to 2022. In order to analyze the behavior of the proposed network and mathematical model in the future, we generated different scenarios using ELVs projections. For projecting the number of ELVs, we used the framework adopted by Dargay and Gately (1999) and Andersen and Larsen (2008). We combined the historical data, mainly from OECDSTAT and TURKSTAT on population, GDP and the number of cars per capita and the vintage distribution of cars to project the number of ELVs in the future. Firstly, since the relationship between the car density and the number of ELVs cannot be ignored, we made projections of the car ownership in Ankara to the year 2022. As in the literature, GDP-dependent Gompertz function is used to model the development in car ownership which is an S-curve that increases towards a saturation level and Weibull distribution is used to determine the attrition rates of car vintages (Dargay and Gately, 1999; Andersen and Larsen, 2008). We assumed zero import and export of old cars for simplicity. The Gompertz equation relating car ownership per capita (C_t) to the income per capita (GDP_t) can be expressed in Eq. (1) where γ is the saturation level and α and β are negative parameters defining the shape, or curvature of the function (Dargey and Gately, 1997).

Table 9
Scenario analyzes.

Year	Scenario	Projected no. of ELVS
2011	0 (Base Case)	1824
2012	1	2304
2013	2	3262
2014	3	4504
2015	4	6084
2016	5	8068
2017	6	10,532
2018	7	13,565
2019	8	17,270
2020	9	21,766
2021	10	27,189
2022	11	33,691

$$C_t = \gamma \cdot e^{\alpha \cdot e^{\beta \cdot GDP_t}} \qquad \text{Eq. (1)}$$

The estimated saturation level (γ) of 246.15 per thousand capita for Turkey by Medlock and Soligo (2002) is used and α and β are estimated as -9.761 and -1.785 depending on this γ.

Having C_t, the stock of cars is calculated as:

$$S_t = C_t \cdot P_t \qquad \text{Eq. (2)}$$

where P_t is the population.

For a specific vintage of cars, the lifetime is obtained by Weibull distribution given by:

Table 8
Estimation results.

Year	Per-capita income (2005 $ PPP)	Population of Ankara	Car ownership per 1000 population	Total vehicles in Ankara	No of ELVs in Ankara
2012	13,643	4,965,542	117.0700	581,316	2304
2013	13,901	5,056,126	121.2559	613,085	3262
2014	14,378	5,146,307	129.3429	665,638	4504
2015	15,160	5,235,807	143.6328	752,034	6084
2016	15,972	5,324,705	159.8741	851,283	8068
2017	16,751	5,413,000	176.9358	957,753	10,532
2018	17,499	5,500,577	194.7431	1,071,200	13,565
2019	18,227	5,587,439	213.5728	1,193,325	17,270
2020	18,949	5,673,544	233.7608	1,326,252	21,766
2021	19,674	5,758,868	255.6208	1,472,087	27,189
2022	20,404	5,843,435	279.4207	1,632,776	33,691

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Table 10
Solutions of the model with different scenarios for the amount of ELVs.

Scenarios	Dismantler locations	Shredder locations	Obj. Function ($\times 10^6$)	CPU time (s)
0	24	8	4.0397	12.7
1	24	8	4.2805	7.6
2	24	8	4.7610	6.9
3	24	8	5.3841	2.8
4	2,17	8	6.7954	23.8
5	2,17	8	7.7941	14.4
6	2,7,17	8	9.6534	40.2
7	2,7,17	8	11.1771	26.8
8	2,7,17,22	8	13.6640	187.7
9	2,7,17,22,27	8,9	19.0520	3329.0
10	2,7,17,22,24,27	8,9	22.4091	2743.6
11	2,3,7,17,22,24,27	8,9	26.3170	2860.8

$$F(T) = e^{-\left(\left(T-\theta\right)/\lambda\right)^{k}} \text{ and } F(T) = 1 \text{ for } T \leq \theta \qquad \text{Eq. (3)}$$

where λ and k are the positive scale and shape parameters and θ is the location parameter of Weibull distribution. T is the age of cars, $F(T)$ is the lifetime function determining the fraction of cars of vintage v still in operation in year t, ($T = t - v$). We regarded the fraction of cars being scrapped in the first year because of accidents and set $\theta = 0$. With the assumption that the lifetime of individual vintages of cars follows the same Weibull distribution, we considered 30 years mean lifetime of cars in Turkey and calibrated the parameter λ as 33.44. For a symmetric and bell-shaped weibull distribution the shape parameter k is taken as 3.3.

In the year t, the remaining stock of a given vintage of cars is calculated by Eq. (4).

$$S_{v,t} = S_{v,v} \cdot F(t - v) \qquad \text{Eq. (4)}$$

where $S_{v,v}$ is the initial stock of vintage v cars. ELVs of vintage v cars in the year t is calculated as given in Eq. (5).

$$\mathrm{ELV}_{v,t} = S_{v,t-1} - S_{v,t} \qquad \text{Eq. (5)}$$

The total number of ELVs in year t is calculated as:

$$\mathrm{ELV}_t = \sum_{v} \mathrm{ELV}_{v,t} \qquad \text{Eq. (6)}$$

The number of new cars in year t is calculated as given in Eq. (7).

$$S_{t,t} = S_t - S_{t-1} + \mathrm{ELV}_t \qquad \text{Eq. (7)}$$

Estimation results for projected development in the car density against GDP per capita and in the number of ELVs in Ankara using above framework are given in Table 8.

5.2. *Scenario analysis*

Amount of ELVs is rising rapidly in Turkey as throughout the world due to the increasing population, trend of consumption and number of vehicles on roads. In order to analyze the behavior of the model in the future, quantified developments in the number of ELVs obtained by the procedure given in the previous section is used.

We analyzed the sensitivity of the solutions to the changes in the amount of ELVs supplied from the ELV sources to gain a better sense of the proposed model. We used the projection of the number of ELVs from 2012 to 2022 and generated eleven different scenarios of the problem. We solved the proposed recovery network design problem for these scenarios and analyzed the results. Eleven different scenarios of the problem for the years 2012–2022 and predicted number of ELVs for Ankara are given in Table 9.

6. Discussion of results

The projections show that the number of ELVs for Ankara is likely to increase approximately 32,000 ELVs between 2011 and 2022. It is obvious that this situation will increase the waste generation and deteriorate the environmental and economical effects of ELVs in the future. GAMS-CPLEX is used for comprehension of proposed model behavior via increasing number of ELVs in the future. Optimum solutions for the base case in year 2011 and years 2012–2022 are summarized in Table 10.

Observe from the Table 10 that the highest CPU time requirement is about 55 min. On the average, the model is solved in about 13 min with all of the scenarios to optimality. The number of facilities to be located and the system cost increase while the number of ELVs are getting higher in the future. Only one of the dismantlers (24th) which is located in Yenimahalle district is to be opened in the scenarios until 2015, while seven dismantlers are to be opened in the year of 2022. One of the shredders (8th) located in Kocaeli province is to be opened until 2020 and two of the shredders are to be opened after this year. Other shredder (9th) to be opened in 2020, 2021 and 2022 is also located in Kocaeli. The relation

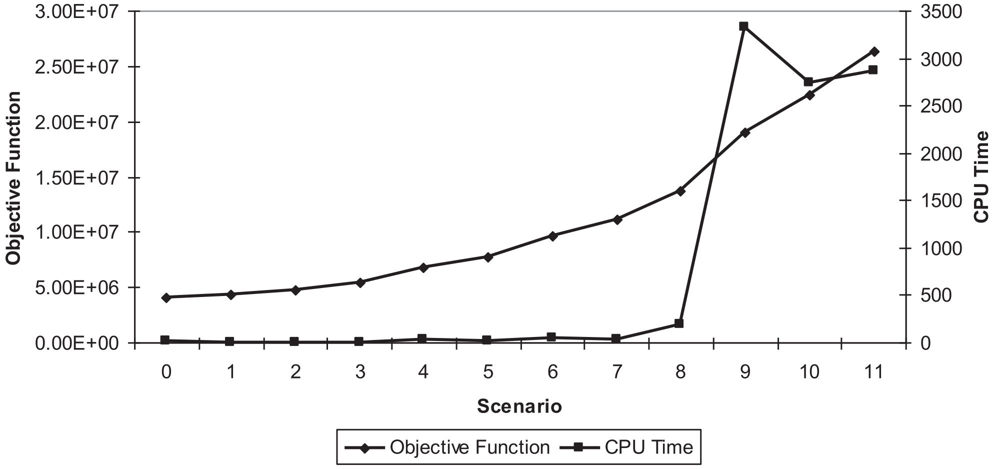

Fig. 3. The value of the objective function and CPU time for different scenarios.

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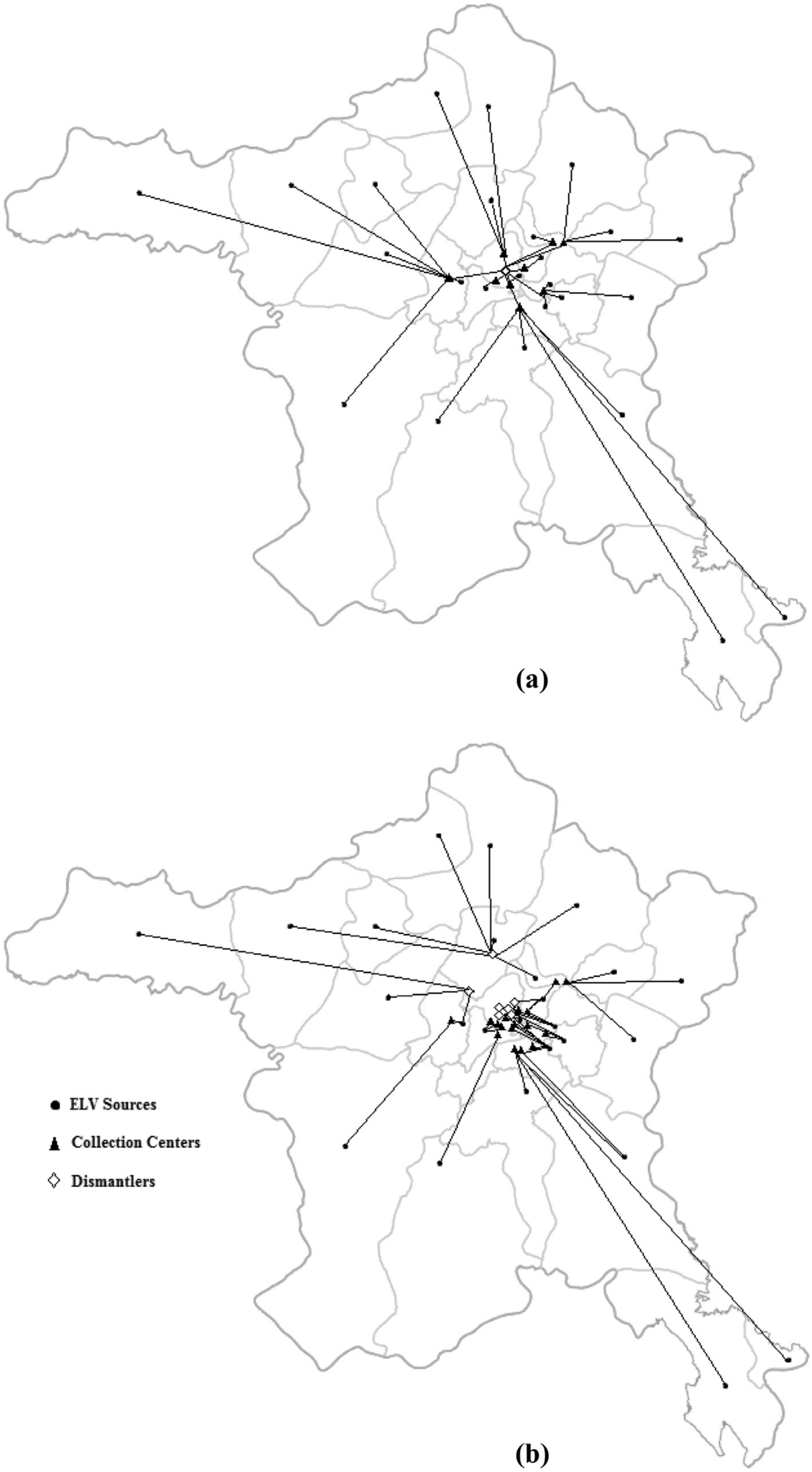

Fig. 4. Reverse logistics network of the problem a. Solution of the year 2011 b. Solution of the year 2022.

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between the scenarios and objective functions and CPU times are shown in Fig. 3.

The optimal reverse logistics network of the problem for 2011 and 2022 are given in Fig. 4(a) and (b). Fig. 4 shows the transportation links from ELV sources to collection centers and dismantlers. In the optimal solution of the year 2011, all ELVs are transported via collection centers to dismantler and there is no direct transportation from ELV sources to twenty-fourth dismantler which is located in Yenimahalle district. In 2022, five of seven dismantlers (3, 7, 17, 22, 24) are located in the centre of Ankara (in Yenimahalle district). Other two dismantlers (2, 27) are located in the Kazan district. Third and twenty-second dismantlers don't serve directly to ELV sources and get ELVs only from collection centers in 2022.

We hope that using the proposed network design model will assist logistics managers in European Union members and other countries in which manufacturers responsibilities are obligated by regulations in making integrated decisions for their complex recycling networks to cope with the following questions: How to collect their EOL products? How to recover them? How to minimize their operational and transportation costs? How to fulfill the relevant regulations? The analyzing method which permits future patterns of vehicle ownership and number of ELVs to be predicted will be used for all countries with adapting country specific parameters. The relation between the vehicle ownership and number of ELVs in the future, waste quantities arising from ELVs, environmental and economical effects of ELVs can be also analyzed via this procedure.

7. Conclusion

Although the effect of rapid pace of development and population growth on increasing waste production rates cannot be ignored, lack of organization and planning are also reasons for increasing all types of waste quantities in Turkey. In this study, ELVs which have been a great concern in all of the world, are taken into consideration and in order to minimize the environmental and economic problems arising from improper management of ELVs, a mixed integer linear programming model is developed. The model is successful in optimizing the costs associated with opening facilities, recovery processes, transportation of ELVs and its components/materials through the network and revenues associated with selling reusable/remanufacturable parts and scrap metals. The proposed model is applied to a case study comprising reverse logistics network design for ELVs in Ankara. Furthermore, the car ownership is modeled by using Gompertz curve which is one of the S-curve models. In order to obtain long-term average developments in number of ELVs, a systematic approach is used combining the projections of car ownership, historical data on population, GDP per capita and the vintage distribution of cars. Lastly, proposed mathematical model is solved with different scenarios for the number of ELVs and the behavior of the model in the future is analyzed. Future research should examine a CLSC network consisting forward and reverse activities for ELV recycling simultaneously and analyzing how much of the total cost is of which manufacturer's responsibility.

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