REPUBLIC OF TURKEY

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A STOCHASTIC OPTIMIZATION MODEL FOR REVERSE LOGISTICS NETWORK DESIGN OF END OF LIFE VEHICLES: A CASE STUDY OF ISTANBUL

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Selman KARAGÖZ

Signature

Dedicated to my family

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I would like to thank my family, my friends and my lecturers for supporting me during the difficult times…

Selman KARAGÖZ

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LIST OF SYMBOLS

K	ADC
R_{it}^{ω}	Amount of ELVs Collected from the ELV Owner i in Period t and Scenario ω
A	Annual Amount
cap_{jt}	Annual Capacity of Collection Center j in Period t (ton)
cap_{kt}	Annual Capacity of ADC k in Period t (ton)
cap_{lt}	Annual Capacity of Shredder Center l in Period t (ton)
cap_{pt}	Annual Capacity of Fluid Recovery Center p in Period t (ton)
cap_{rt}	Annual Capacity of Tyre Recovery Center r in Period t (ton)
cap_{st}	Annual Capacity of Battery Recovery Center s in Period t (ton)
cap_{ut}	Annual Capacity of Landfilling Center u in Period t (ton)
rc_{st}	Battery Recycling Cost at Battery Recovery Center s in Period t (₺/ton)
e_{kt}	Binary Decision Variable for Opening ADC k in Period t
e_{lt}	Binary Decision Variable for Opening Shredder Center l in Period t
J	Collection Centers
C_t	Car Ownership per Capita
dc_{kt}	Dismantling Cost at ADC k in Period t (₺/ton)
lc_{ut}	Disposal Cost at Landfilling Center u in Period t (₺/ton)
d_{ij}	Driving Distance between ELV Owner i and Collection Center j (km)
d_{ik}	Driving Distance between ELV Owner i and Recovery k (km)
d_{jk}	Driving Distance between Collection Center j and ADC k (km)
d_{kl}	Driving Distance between ADC k and Shredder Center l (km)

d_{kp}	Driving Distance between ADC *k* and Fluid Recovery Center *p* (km)
d_{ks}	Driving Distance between ADC *k* and Battery Recovery Center *s* (km)
d_{lu}	Driving Distance between Shredder Center *l* and Landfilling Center *u* (km)
I	ELV Owner
€	Euros
f_{kt}	Facility Opening Cost for ADC *k* in Period *t* (₺)
f_{lt}	Facility Opening Cost for Shredder Center *l* in Period *t* (₺)
rc_{pt}	Fluid Recycling Cost at Fluid Recovery Center *p* in Period *t* (₺/ton)
GDP_t	Income per Capita
I	Interest Rate
U	Landfilling Centers
α, β	Negative Parameters
N	Number of Corresponding Time Period
p_ω	Occurrence Probability for Scenario ω
T	Periods
P	Present Amount
γ_1	Ratio of Ferrous Materials to Hulk ($0 \leq \gamma_1 \leq 1$)
β	Ratio of ASR to Hulk ($0 \leq \beta \leq 1$)
α	Ratio of Hulk to ELV ($0 \leq \alpha \leq 1$)
λ_3	Ratio of Non-reusable Batteries to ELV ($0 \leq \lambda_3 \leq 1$)
λ_1	Ratio of Non-reusable Fluids to ELV ($0 \leq \lambda_1 \leq 1$)
γ_2	Ratio of Non-ferrous Materials to Hulk ($0 \leq \gamma_2 \leq 1$)
λ_2	Ratio of Non-reusable Tyres to ELV ($0 \leq \lambda_2 \leq 1$)
μ_4	Ratio of Reusable Batteries to ELV ($0 \leq \mu_4 \leq 1$)

μ_1	Ratio of Reusable Ferrous Materials to ELV ($0 \leq \mu_1 \leq 1$)
μ_3	Ratio of Reusable Fluids to ELV ($0 \leq \mu_3 \leq 1$)
μ_2	Ratio of Reusable Non-ferrous Materials to ELV ($0 \leq \mu_2 \leq 1$)
μ_5	Ratio of Reusable Other Materials (i.e. glass, plastic, textile et al.) to ELV ($0 \leq \mu_5 \leq 1$)
S	Recovery Centers for Batteries
N	Recovery Centers for Ferrous and Non-ferrous Materials
P	Recovery Centers for Fluids
R	Recovery Centers for Tyres
γ	Saturation Level
Ω	Scenario
M	Second-hand Markets
s_{1t}	Selling Price of Ferrous Material from ADC to Second-hand Markets in Period t (₺/ton)
s_{2t}	Selling Price of Non-ferrous Material from ADC to Second-hand Markets in Period t (₺/ton)
s_{3t}	Selling Price of Fluid from ADC to Second-hand Markets in Period t (₺/ton)
s_{4t}	Selling Price of Battery from ADC to Second-hand Markets in Period t (₺/ton)
s_{5t}	Selling Price of Other Type of Materials (i.e. glass, plastic et al.) from ADC to Second-hand Markets in Period t (₺/ton)
z_{1t}	Selling Price of Ferrous Material from Shredder Center to Recovery Center in Period t (₺/ton)
z_{2t}	Selling Price of Non-ferrous Material from Shredder Center to Recovery Center in Period t (₺/ton)
sc_{lt}	Shredding Cost at Shredder Center l in Period t (₺/ton)

L	Shredder Center
FC	Total Fixed Cost (₺)
OC	Total Operational Cost (₺)
RV	Total Revenue (₺)
TC	Total Transportation Cost (₺)
t_{ijt}	Transportation Cost from ELV Owner *i* to Collection Center *j* in Period *t* (₺/ton)
t_{ikt}	Transportation Cost from ELV Owner *i* to ADC *k* in Period *t* (₺/ton)
t_{jkt}	Transportation Cost from Collection Center *j* to ADC *k* in Period *t* (₺/ton)
t_{klt}	Transportation Cost from ADC *k* to Shredder Center *l* in Period *t* (₺/ton)
t_{kpt}	Transportation Cost from ADC *k* to Fluid Recovery Center *p* in Period *t* (₺/ton)
t_{krt}	Transportation Cost from ADC *k* to Tyre Recovery Center *r* in Period *t* (₺/ton)
t_{kst}	Transportation Cost from ADC *k* to Battery Recovery Center *s* in Period *t* (₺/ton)
t_{lut}	Transportation Cost from Shredder Center *l* to Landfilling Center *u* in Period *t* (₺/ton)
₺	Turkish Lira
rc_{rt}	Tyre Recycling Cost at Tyre Recovery Center *r* in Period *t* (₺/ton)
A_{ijt}^{ω}	Weight of ELV Transferred from ELV Owner *i* to Collection Center *j* in Scenario ω
B_{ikt}^{ω}	Weight of ELV Transferred from ELV Source *i* to ADC *k* in Period *t* and Scenario ω

X_{jkt}^{ω} Weight of ELV Transferred from Collection Center j to ADC k in Period t and Scenario ω

Y_{klt}^{ω} Weight of Hulk Transferred from ADC k to Shredder Center l in Period t and Scenario ω

Z_{lut}^{ω} Weight of ASR Transferred from Shredder Center l to Landfilling Center u in Period t and Scenario ω

V_{kpt}^{ω} Weight of Non-reusable Fluid Transferred from ADC k to Fluid Recovery Center p in Period t and Scenario ω

W_{krt}^{ω} Weight of Non-reusable Tyre Transferred from ADC k to Tyre Recovery Center r in Period t and Scenario ω

U_{kst}^{ω} Weight of Non-reusable Battery Transferred from ADC k to Battery Recovery Center s in Period t and Scenario ω

Q_{1kmt}^{ω} Weight of Ferrous Material Transferred from ADC k to Second-hand Market m in Period t and Scenario ω

Q_{2kmt}^{ω} Weight of Non-ferrous Material Transferred from ADC k to Second-hand Market m in Period t and Scenario ω

Q_{3kmt}^{ω} Weight of Fluid Transferred from ADC k to Second-hand Market m in Period t and Scenario ω

Q_{4kmt}^{ω} Weight of Battery Transferred from ADC k to Second-hand Market m in Period t and Scenario ω

Q_{5kmt}^{ω} Weight of Other Materials Transferred from ADC k to Second-hand Market m in Period t and Scenario ω

P_{1lnt}^{ω} Weight of Ferrous Material Transferred from Shredder Center l to Recovery Center n in Period t and Scenario ω

P_{2lnt}^{ω} Weight of Non-ferrous Material Transferred from Shredder Center l to Recovery Center n in Period t and Scenario ω

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
ABC	Artificial Bee Colony Algorithm
ANN	Artificial Neural Network
ADC	Authorized Dismantler Center
CL	Closed-loop
CA	Content Analysis
CBA	Cost-Benefit Analysis
DEA	Data Envelope Analysis
DEM	Dematel
Det.	Deterministic
DC	Dismantling Cost
EA	Emergy Analysis
ELV	End-of-life Vehicle
EU	European Union
E	Exact
EFA	Exploratory Factor Analysis
FC	Fixed Cost
FC	Forecasting
FAHP	Fuzzy Analytical Hierarchy Process
FGDM	Fuzzy Group Decision Making
FILP	Fuzzy Interval Linear Programming
FMLP	Fuzzy Mixed-integer Linear Programming
FTP	Fuzzy Topsis

FVK	Fuzzy Vikor
GA	Genetic Algorithm
GP	Goal Programming
HEU	Heuristics
ILP	Integer Linear Programming
INLP	Integer Linear Programming
OICA	International Organization of Motor Vehicle Manufacturers
IOT	Internet of Things
ILP	Interval Linear Programming
LFC	Landfilling Cost
LCA	Life-cycle Assessment
LCC	Life-cycle Cost
LCI	Life-cycle Inventory
LP	Linear Programming
LS	Literature Survey
LA	Location-allocation
MBM	Mass Balance Method
MM	Mathematical Modeling
MFA	Material Flow Analysis
MFE	Material Flow & Economical Exchange Model
Max	Maximization
MH	Meta-heuristics
Min	Minimization
MGP	Mixed-integer Goal Programming
MILP	Mixed-integer Linear Programming

MINP	Mixed-integer Non-linear Programming
MO	Multi-objective
MCDM	Multi-criteria Decision Making
MOP	Multi-objective Mixed-integer Programming
ND	Network Design
NLP	Non-linear Programming
OV	Objective Variable
OECD	Organization for Economic Cooperation and Development
OL	Open-loop
OC	Operational Cost
PSO	Particle Swarm Optimization
PPP	Polluter Pays Principle
Prob.	Probabilistic
PP	Production Planning
PR	Profit
PR	Promethee
RC	Recycling Cost
RP	Recycling Planning
RL	Reverse Logistics
RLND	Reverse Logistics Network Design
RPP	Recycling, Production & Planning
RR	Regulations Review
SOM	Self-organizing Map
SC	Shredding Cost
SO	Single-objective

SP	Stochastic Programming
SEM	Structural Equation Modeling
SW	Swot
SD	System Dynamics
TSA	Tabu Search Algorithm
TCM	Technical Cost Modeling
TP	Topsis
TC	Transportation Cost
TUIK	Turkish Statistical Institute
VK	Vikor
WEEE	Waste of Electrical and Electronic Equipment
WA	Waste Input-Output Analysis

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ABSTRACT

A Stochastic Optimization Model for Reverse Logistics Network Design of End of Life Vehicles: A Case Study of Istanbul

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Department of Industrial Engineering

Doctor of Philosophy Thesis

Advisor: Assoc. Prof. Dr. Nezir AYDIN

Waste management is gaining crucial importance as recycling aims at transforming produced waste into value for economy in recent years. As automotive is one of the fastest growing industries worldwide, recycling of end-of-life vehicles (ELV) gains importance day by day. Due to legislations and new regulations, multiple players like users, producers, treatment facilities, municipalities, etc. require cooperative engagement and they are being conferred new responsibilities in recycling process. Participations of multiple actors in the recycling process of ELV bring various uncertainties to the case. Additionally, parameters of the recycling process, like number of vehicles withdrawn per year, cost items, percentages of material types in the vehicles are tended to change due to technological, social and economic developments. Automotive industry has a crucial importance in Turkish economy which is highly effected by socio-political and economic developments. Furthermore, Istanbul is a metropolitan area which has maximum rate of vehicle ownership in Turkey. For that purpose, this paper aims to propose a scenario-based real-life stochastic optimization model for management of supply chain network of the ELVs' recycling process in Istanbul. Consequently, sensitivity analysis and scenario analysis are applied to question the consistency of the study and to review the results with different scenarios.

Keywords: End-of-life vehicles, decision making, stochastic modelling, scenario based optimization

ÖZET

Ömrünü Tamamlamış Araçların Tersine Lojistik Ağ Tasarımı İçin Bir Stokastik Optimizasyon Modeli: İstanbul Uygulaması

Selman KARAGÖZ

Endüstri Mühendisliği Anabilim Dalı

Doktora Tezi

Danışman: Doç. Dr. Nezir AYDIN

Atık yönetimi, atıkların geri dönüştürülerek ekonomiye katılmaya başlamasıyla birlikte daha fazla önem kazanmaya başlamıştır. Otomotiv, dünya genelinde en hızlı gelişen sektörlerden biri olduğu için; ömrünü tamamlamış araçların (ÖTA) geri dönüşümü gün geçtikçe daha fazla önem kazanmaya başlamıştır. Yeni yasal yükümlülüklerle birlikte üreticiler, geri dönüşüm tesisleri, belediyeler gibi aktörlere yeni sorumluluklar yüklenmiştir ve bu aktörlerin işbirliği zorunlu kılınmıştır. Çoklu aktörlerin ELV geri dönüşüm sürecine dahil olması, bir dizi belirsizliği beraberinde getirmektedir. Bununla birlikte bir yilda trafikten kaydı silinen araç miktarı, maliyet kalemleri, araçların yapısını oluşturan malzeme yüzdeleri gibi parametrelerin ekonomik ve teknolojik gelişmelerle birlikte değisimler göstermesi beklenmektedir. Otomotiv endüstrisi, Türkiye'deki en önemli endüstrilerden birini oluşturmaktadır ve Türkiye ekonomisi sosyo-politik ve ekonomik gelişmelerden etkilenmektedir.

Bununla birlikte İstanbul, Türkiye'de en fazla araç sahibi olma oranına sahip olan büyükşehirdir. Bu nedenle, bu çalışmada İstanbul'da ÖTA'ların geri dönüşüm sürecinin tedarik zinciri yönetimi için senaryo tabanlı bir gerçek hayat stokastik optimizasyon modeli uygulaması amaçlanmıştır. Bununla birlikte duyarlılık analizleri uygulanarak çalışmanın tutarlılığı ve farklı senaryolarda elde edilen sonuçlar araştırılmıştır. Duyarlılık analizleri üretilen ELV miktarları, maliyet kalemleri, olasılık değerleri ve tesis kapasiteleri gibi parametrelerin değişimi sonucunda amaç fonksiyonunda değişimler incelenerek tamamlanmıştır. Bununla birlikte iki farklı senaryo analizi yapılarak, senaryo sonuçlarında ortaya çıkan amaç fonksiyonu kalemleri ve karar değişkenleri karşılaştırılmıştır. Bunun dışında, model sonucu tesis kullanım kapasiteleri incelenmiştir. Sonuçlar kısmında mevcut model, yönetimsel bir prespektifle yorumlanarak gelecek çalışmalar için önerilerde bulunulmuştur.

Anahtar Kelimeler: Ömrünü tamamlamış araçlar, karar verme, stokastik modelleme, senaryo tabanlı optimizasyon

1
INTRODUCTION

1.1 Literature Review

ELVs are one of the most crucial hazardous wastes and they have a high potential for environmental pollution (Simic, 2016). As they have a complex structure and various composition, processing of ELVs are difficult to manage properly. In this thesis, 232 peer-reviewed publications in the ELVs management field are systematically investigated. The main purpose of this literature review is to provide an extensive overview of state–of–the–art research published in the period 2000-2019. Studies in this literature survey are classified based on their objectives, methodology, parameter types used in the case, type of supply chains, number, and type of objective functions. Moreover, studies with mathematical optimization are analyzed separately based on the type of decision variables, optimization model types, single-multi objectivity, and solution approach. Gaps in the current literature are analyzed and future research directions are suggested.

1.2 Objective of the Thesis

As a result of rapidly growing industrialization, environmental pollution is becoming a more crucial issue to cope with day by day. According to International Organization of Motor Vehicle Manufacturers` (OICA) World's Automotive Industry report, over sixty-six million vehicles (e.g. cars, vans, trucks, and buses) were manufactured in 2005, which are essential for the global economy and the wellbeing of the world's citizens. The output of this production is equivalent to a global turnover of €1.9 trillion which means that it would be the sixth-largest economy in the world if vehicle manufacturing was a country (OICA, 2006). Furthermore, a research made by Organization for Economic Cooperation and Development (OECD) shows that the total number of vehicles in OECD countries was expected to grow 32% within the period of 1997-2020 (Kanari et al., 2003).

The waste management of special products like end-of-life vehicles (ELVs), waste of electrical and electronic equipment (WEEE), batteries, oils, medical waste, etc. is a critical ecological problem that world faces with today because of its rapidly increasing amount and significant composition of hazardous substances (Simic, 2015b). As automotive sector generates about 5% of industrial waste in the entire world (Simic, 2013), recycling of ELVs is not only an environmental issue to deal with, but also a financial source for the industries. As the number of in-use vehicles is increasing worldwide (Levizzari et al., 2002), ELVs comprise an important portion of waste in the world's ecology. The recycling of ELVs is an important part of circular economy. Reuse of the discarded autos is not only important for economic outputs, but also for environmental benefits. Furthermore, the vehicles which are not withdrawn from the traffic at their retirement age will yield both environmental pollution and traffic accidents (Xia et al., 2016). This fact is obliging authorities (e.g. European Parliament and Council of the European Union) to take serious steps and to provide an action plan to increase the recovery, reuse and recycle ratios of ELVs to avoid the cause of excessive waste of material, labor hour, and natural resources (Kuşakcı et al., 2019). Correspondingly, the European Union (EU) has constituted an ELVs Directive (2000/52/EC) in 2000 to attempt reducing the amount of waste and to encourage reusing the materials of used vehicles.

Figure 1.1 presents that Turkey is fifteenth largest automotive producer country in the world according to OICA report (OICA, 2018). Concerning the amount of produced vehicles in Turkey, the number of vehicles needed to be recycled in the future is increasing day by day. Furthermore, vehicles at the retirement age are becoming a bigger threat as number of the vehicles on the road is increasing every year. As a developing country, Turkey, which is in the process of EU membership, implements EU Directives to ELV's recycling has crucial importance for the future.

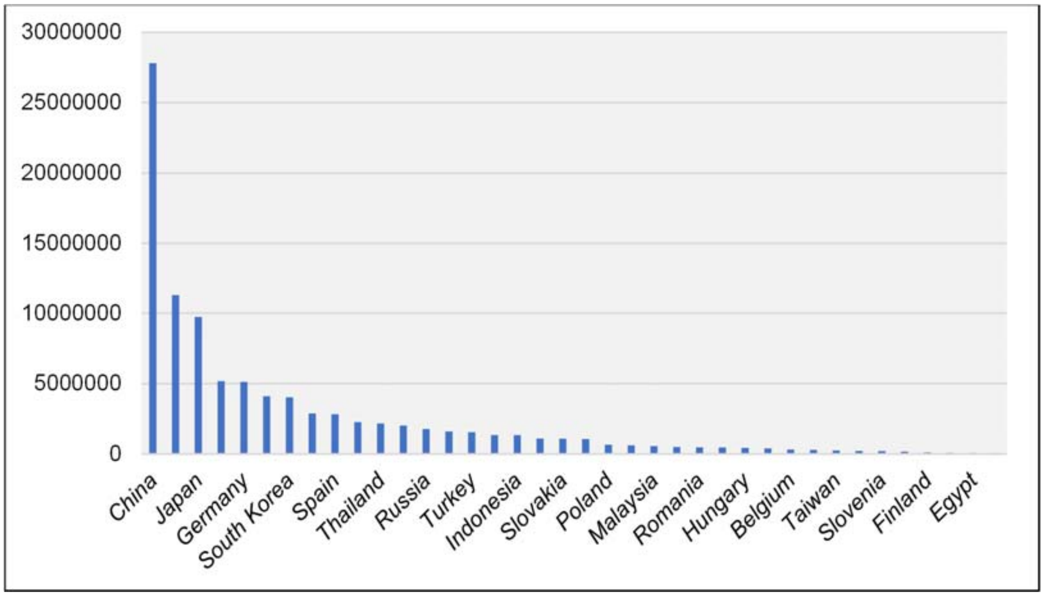


Figure 1.1 Number of motor vehicles produced by countries in 2018

According to the reports of Turkish Statistical Institute (TUIK, 2018a), Table 1.1 shows that Istanbul has the highest number of vehicles in the traffic within the time period of 2015-2018. As its being a metropolitan, Istanbul has a very high rate of domestic migration rate due to social and economic factors. Istanbul's rapid population increase has correlation with the increasing number of the vehicles in the traffic. Apart from these, abundance of the vehicles, its geographical location, high-skilled labor force availability, financial opportunities et al. are making Istanbul an advantaged city for recycling business. For the reasons mentioned above, Istanbul is a critical city to cope with ELV management in Turkey.

Table 1.1 Number of vehicles in the traffic by year and city in Turkey

City	2015	2016	2017	2018
Istanbul	3 537 866	3 751 547	4 013 551	4106140
Ankara	1 638 839	1 728 066	1 859 604	1916967
Izmir	1 184 500	1 243 533	1 330 258	1365044
Antalya	912 562	953 412	1 008 977	1031758
Bursa	711 571	760 787	830 078	856520
Konya	631 246	663 791	700 551	716498
Adana	576 338	598 305	630 046	642000
Mersin	528 120	552 305	584 510	597443
Manisa	517 356	539 740	567 795	579214
Gaziantep	441 651	460 259	483 065	495998

1.3 Hypothesis

A Reverse Logistics Network Design (RLND) is complicated by the uncertainty of return products in terms of quantity, quality and supply timing, integrating and coordinating different forward and reverse flows. A high level of uncertainty is one of the characteristics of Reverse Logistics (RL) networks (Fleischmann et al., 2000). Uncertainties with the data in decision making play a crucial role in design of reverse and closed-loop supply chain networks (Ayvaz et al., 2015). Figure 1.2 presents the number of motor vehicles produced in Turkey within the time period of 2010-2018, and Figure 1.3 presents the rate of change of motor vehicles produced within the same time period (OICA, 2018).

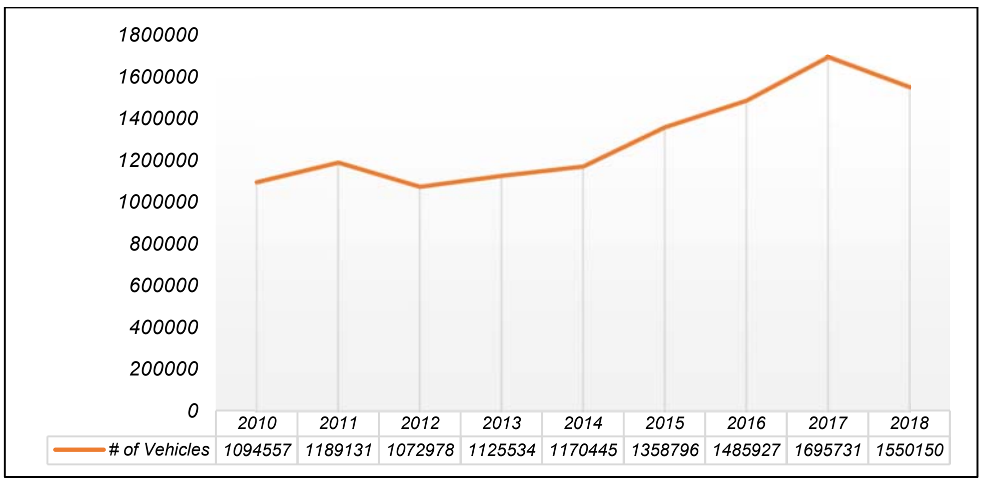


Figure 1.2 Number of motor vehicles produced in Turkey

As it is shown in Figure 1.2 and 1.3, the number of vehicles produced in Turkey does not have consistency in a significant time period. Variation in the number of vehicles produced has relation with the number of vehicles in the traffic. As a consequence, there is no corresponding consistent rate of the number of vehicles that complete the life-cycle.

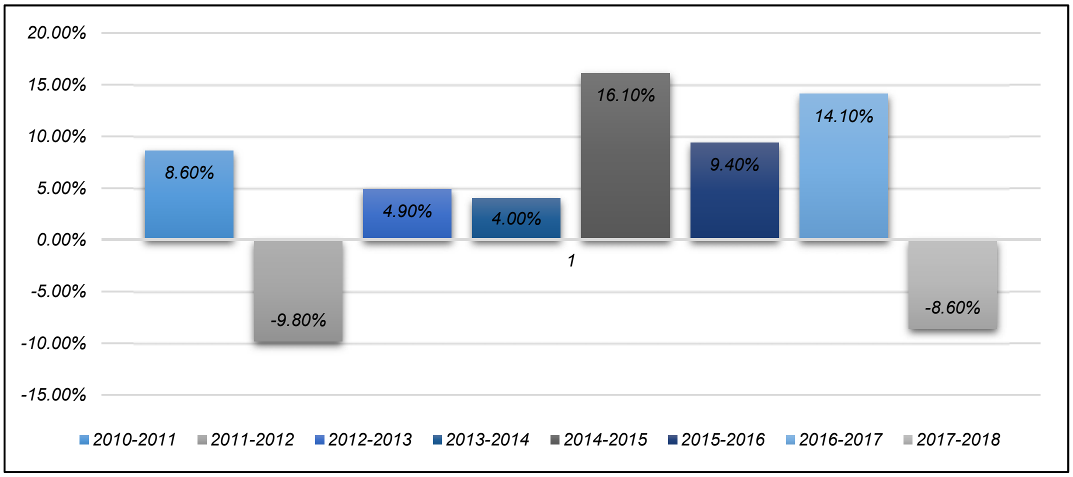
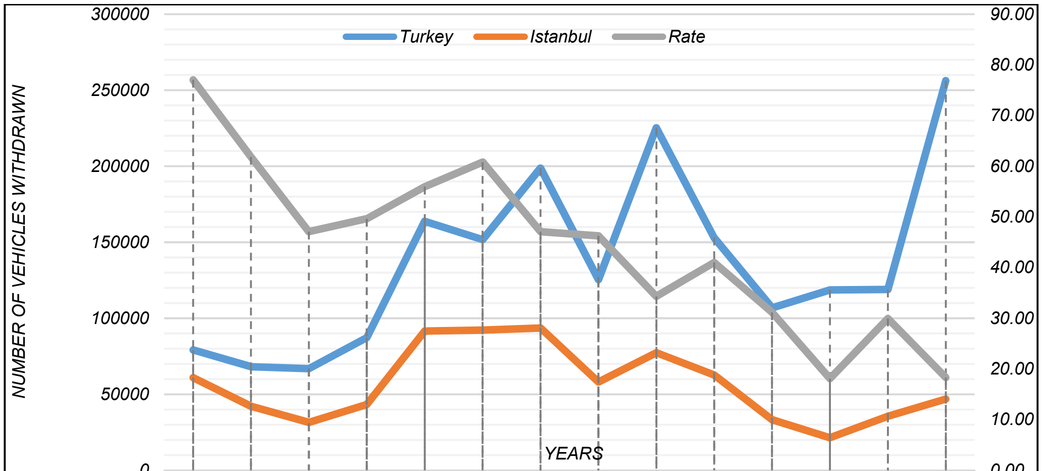


Figure 1.3 Rate of change in motor vehicles production in Turkey

According to TUIK reports, Figure 1.4 shows the number and rates of vehicles withdrawn from traffic in Istanbul and Turkey within time period of 2005-2018 (TUIK, 2018b). The number of vehicles withdrawn from traffic is not consistent within the time period. Figure 1.4 presents the proportion of the number of withdrawn vehicles from traffic in Istanbul to the total withdrawn amount in Turkey (TUIK, 2018b).



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Turkey	79151	68177	66840	87230	163785	151700	198801	125407	225356	153054	106838	118658	118928	256298
Istanbul	60986	42164	31485	43306	91652	92256	93616	58025	77345	62753	33303	21475	35616	46914
Rate	77.05	61.84	47.11	49.65	55.96	60.81	47.09	46.27	34.32	41.00	31.17	18.10	29.95	18.30

Figure 1.4 Number of vehicles withdrawn from traffic in Istanbul and Turkey

Figure 1.4 underlines the following facts:

1. The number of withdrawn vehicles in Istanbul and Turkey has uncertain characteristics within a specific time period.

2. According to the rates of the number of withdrawn vehicles, Istanbul has a crucial role in Turkey for ELV's recycling management.

Bearing in mind the issues discussed above, this study aims to develop a mathematical optimization model for an open-loop reverse logistic network for ELV in Istanbul in accordance with the ELV directive implementations. The mathematical model determines the optimum number and locations for the facilities in the network and allocates the optimum amount of material between the facilities in the flow. A generic deterministic version of the proposed model is presented in the study. However, the problem considered includes uncertainties such as the number of discarded vehicles. To handle the uncertainty, a stochastic mixed-integer linear programming technique is developed.

2
LITERATURE SURVEY

2.1 Literature Survey

ELVs are one of the most crucial hazardous wastes and they have a high potential for environmental pollution (Simic, 2016c). As they have a complex structure and various composition, processing of ELVs are difficult to manage properly. The number of ELVs is expected to reach to approximately 80 million units per year by 2020 (WRME, 2014). This is one of the reasons why there is a strong motivation to manage this rapidly increasing waste flow efficiently. As ELVs management is an emergent research area, some review papers have been published in this field. Table 1 represents the review papers that have been published in ELVs management.

Table 2.1 presents 21 of the most relevant reviews in ELVs management. These reviewers are classified regarding their research focus, analyzed period and number of reviewed papers (Karagoz et al., 2019). Table 2.1 indicates that available review papers are focused only on a limited scope of the ELV management, such as reverse logistics, recovery infrastructure, treatment processes. In addition, a review of state–of–the–art mathematical models for the ELVs management are not studied by the researchers. The last line in Table 2.1 explains the role of this review in covering the identified gap of the literature. It is crucial to have a comprehensive study of the ELVs management field to open up horizon for researchers for future studies.

Table 2.1 Summary of review publications in ELVs management

Author(s) and year	**Research focus**	**Analyzed period**	**Number of reviewed papers**
Nourreddine (2007)	(Automotive) shredder residue treatment	1991–2004	26
Vermeulen et al. (2011)		1994–2011	~150
Zorpas and Inglezakis (2012)		1978–2010	~110
Cossu and Lai (2015)		2005–2014	~120
De Almeida and Borsato (2019)	Vehicle recovery infrastructure	1999–2016	76

Table 2.1 Summary of review publications in ELVs management (continued)

Author(s) and year	Research focus	Analyzed period	Number of reviewed papers
Kumar and Sutherland (2008)	Vehicle recovery infrastructure	1986–2007	73
Hiratsuka et al. (2014)		1995–2012	26
Go et al. (2011)	Disassemblability	1992–2010	38
Mayyas et al. (2012)	Sustainability of the automotive industry	1984–2011	~90
Bari et al. (2011)	Automotive waste	2010	103
Kindzierski et al. (2013)		2012	107
Simic (2013)	Environmental engineering issues	2003–2012	93
Lashlem et at. (2013)	Management practices	1995–2012	20
Sakai et al. (2014)		1991–2012	~90
Li et al. (2014)		2005–2012	16
Gan and He (2014)	Reverse logistics	2002–2013	38
Cin and Kusakci (2017)		2005–2016	23
Zhang and Chen (2014)	Automotive plastics	1993–2012	63
Buekens and Zhou (2014)	Automotive shredder residue plastics	1977–2012	76
Cucchiella et al. (2016)	Automotive electronics	2000–2014	~50
Rosa and Terzi (2016)		2001–2015	35
This review	The whole ELV management area	2000–2019	232

In this section, 232 peer-reviewed publications in the ELVs management field are systematically investigated. The main purpose of this literature review is to provide an extensive overview of state–of–the–art research published in the period 2000-2019. Studies in this literature survey are classified based on their objectives, methodology, parameter types used in the case, type of supply chains, number, and type of objective functions. Moreover, studies with mathematical optimization are analyzed separately based on the type of decision variables, optimization model types, single-multi objectivity, and solution approach. Gaps in the current literature are analyzed and future research directions are suggested.

2.2 Methodology of the Review

In this literature review, Content Analysis (CA) was inspired and applied. CA is a research technique based on interpreting and coding textual material to convert qualitative data into quantitative data (Karagoz et al., 2019).

Only peer-reviewed publications (i.e., international journals, book chapters, etc.) are reviewed. Databases such as ACS Publications, ASCE Library, ASME Digital Library, Cambridge Journals, EBSCOhost, EmeraldInsight, Google Scholar, IEEE Xplore, Inderscience, IntegraConnect, IOPScience, J-STAGE, JSTOR, ProQuest, RSCPublishing, SAGE journals, ScienceDirect, SciVerse, SpringerLink, and WILEY are searched with the keyword of "End of life vehicles". Furthermore, the references cited in each relevant literature are examined to find out additional sources of information.

2.3 Classification

In this study, ELVs related publications are classified into four major categories: (1) Literature survey, (2) Recycling, production & planning, (3) Network design, and (4) Regulations review. Methods of the studies are presented as a sub-category. Figure 2.1 presents the major classification of the study (Karagoz et al., 2019).

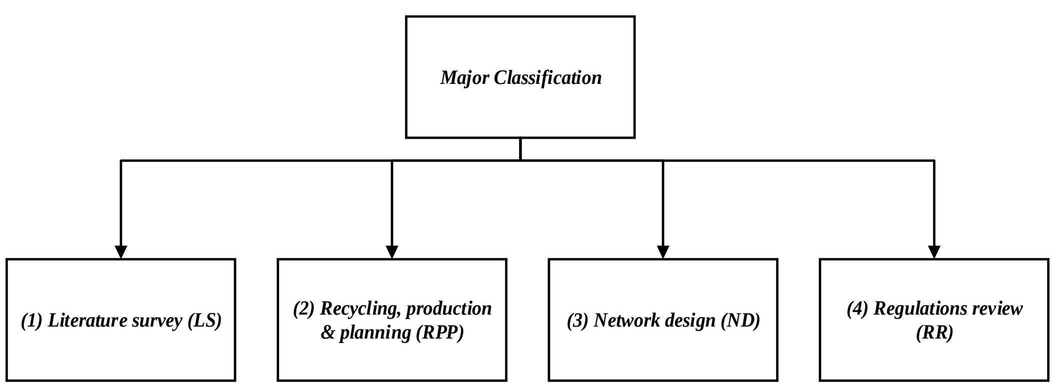


Figure 2.1 Major classification of the literature review

Furthermore, publications with mathematical models are analyzed separately. The main purpose of these classifications is to categorize the studies and make them more visible for the researchers.

2.4 Details of the Major Classification

The reviewed publications in the literature are classified into four major categories: (1) Literature survey (LS), (2) Recycling, production & planning (RPP), (3) Network design (ND) and (4) Regulations review.

(1) Literature survey (LS): In this sub-category, surveys that are in the scope of ELVs are reviewed.

(2) Recycling, production & planning (RPP): In this sub-category, studies aiming to analyze and suggest tactical approaches about recycling processes, material types, product design, and production planning are reviewed.

(3) Network design (ND): Studies that are suggesting approaches to manage strategical decisions about supply chain problems in the ELVs network management are reviewed in this sub-section.

(4) Regulations review (RR): As legislations have a crucial role in ELVs' recycling, publications related to regulation analyses are reviewed under this sub-category.

2.5 Applied Methods in the Review

The studies reviewed in this section are classified into twenty-three categories and twenty-nine sub-categories by the applied methods. Figure 2.2 presents a summary of applied methods in the reviewed publications.

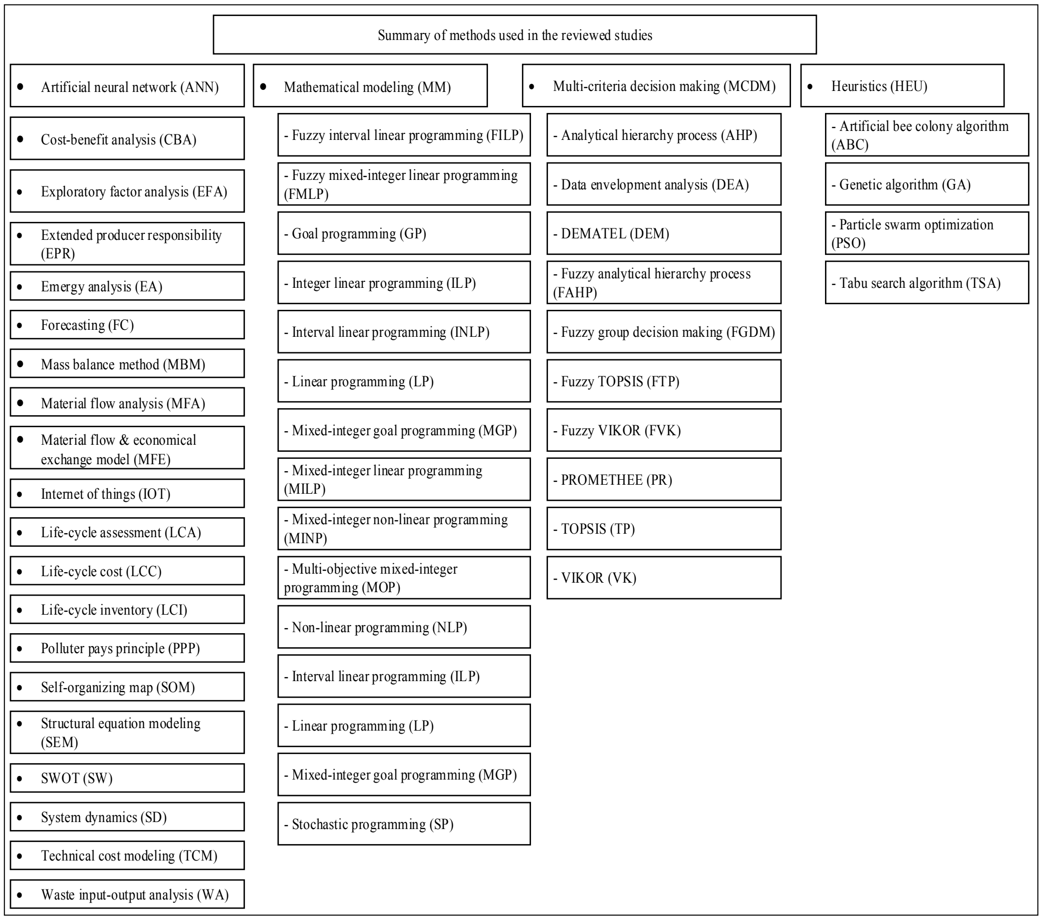


Figure 2.2 Classification of applied methods in the literature review

2.6 Single – Multi Objectivity

In this classification, studies with mathematical models are classified into two sections: (1) Single-objective (SO) and (2) Multi-objective (MO).

2.7 Type of Objective Function

Publications with a mathematical model were classified regarding the type of their objective functions: (1) Maximization (Max) and (2) Minimization (Min).

2.8 Type of Parameter

In this category, studies were classified into three sub-categories regarding parameter type used in the studies: (1) Deterministic (Det.), (2) Probabilistic (Prob.) and (3) Fuzzy.

2.9 Type of Supply Chain

In this section, the reviewed studies are classified into two sub-categories based on supply chain type: (1) Open-loop (OL), and (2) Closed-loop (CL).

2.10 Type of Decision Variables

Publications with mathematical model were classified based on the type of decision variables into three sub-categories: (1) Location-allocation (LA), (2) Recycling planning (RP), (3) Production planning (PP).

2.11 Optimization Model

Publications with mathematical models were classified into four sub-categories: (1) Linear programming (LP), (2) Non-linear programming (NLP), (3) Mixed-integer linear programming (MILP), (4) Mixed-integer non-linear programming (MINP).

2.12 Solution Approach

In this category, studies are classified into three sub-categories regarding to their solution approaches: (1) Exact (E), (2) Heuristics (H) and (3) Meta-heuristics (MH).

2.13 Results of the Literature Review

As directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on ELVs was introduced in 2000, 232 publications within the time period of 2000 - 2019, are analyzed. This classification generates the main framework of the review. A summary of the overall literature review according to their classification is presented in Table 2.2.

2.13.1 Literature Survey

Table 2.1 represents 21 of the most relevant review publication based on their research focus, analyzed period and number of reviewed publications. They should be presented here to emphasis the need for a detailed literature research. Nourreddine (2007) provided a general overview of several automobile shredder residue (ASR) treatment processes. Kumar and Sutherland (2008) presented an overview of publications on the ELVs recovery. A review of the literature published in the years 2010 and 2012 on topics relating to automotive wastes was presented in Bari et al. (2011) and Kindzierski et al. (2013), respectively. Vermeulen et al. [16] reviewed ELV processing-related topics. Go et al. (2011) presented a review of several disassemblability methods, including a spreadsheet-like chart, end-of-life value and time for disassembly. Zorpas and Inglezakis (2012) studied the ASR problem and the solutions for its processing. Mayyas et al. (2012) researched the sustainability within the vehicle industry, through a review of the different studies in vehicles' life cycle, disposal, and ELVs' recovery. Lashlem et al. (2013) published a review of global ELV management practices. Simic (2013) reviewed the environmental engineering scope of ELV recycling management. Gan and He (2014) presented a limited review of ELVs' logistics management. Li et al. (2014) presented an overview of current ELV management practices in China. Sakai et al. (2014) studied a comparative analysis of ELV management practices. Hiratsuka et al. (2014) questioned the background of the establishment of the ELV recycling system in Japan. Buekens and Zhou (2014) analyzed the most significant options for recycling plastics from ASR. Zhang and Chen (2014) discussed regulations of ELV management issues in the USA, the EU, Japan, Korea, and China. Cossu and Lai (2015) presented an overview of post shredder treatment technologies of ASR. Cucchiella et al. (2016) studied a limited review on the automotive electronics recycling area. Rosa and Terzi (2016) compared ELV and WEEE waste streams through a literature analysis by analyzing current differences and potential commonalities. Cin and Kusakci (2017) published a brief review of reverse logistics networks for ELVs. De Almeida and Borsato (2019) studied a bibliometric literature review to assess the efficiency of the available treatment of end-of-life products.

2.13.2 Recycling, Production and Planning

As process and material analyses, product design, production and recycling planning are strategic and a tactical issue to deal with for decision makers, there are a significant number of studies published in this category.

Kirkpatrick et al. (2000) analyzed the environmental issues of ELV disposal in the UK. Bellman and Khare (2000) studied financial sources of the ELV management and suggested various producer responsibility approaches. Hartman et al. (2000) aimed to develop and demonstrate a method for the business potential in re-using components from ELVs. Díaz and Fernández (2001) questioned future treatment facilities for ELV recovery. Mark et al. (2001) suggested a demanufacturing chain under different scenarios and they presented economic analyses for vehicle instrument panels. Johnson and Wang (2001) proposed an optimization model for demanufacturing process to evaluate economics and material destinations to fulfill new ELV management regulations. Petrov (2001) proposed a new concept for ELV recycling management in the Russian automotive industry.

Johnson and Wang (2002) proposed a tool for demanufacturing optimization to evaluate the economics and material destinations. Van Schaik et al. (2002) presented a dynamic optimization model for recycling aluminum from passenger vehicles. Boon et al. (2003) developed a Goal Programming model to assess the materials streams and process profitability for clean vehicles. Petrov (2003) analyzed recyclability of all basic LADA family automobiles regarding to ecological legislations in Europe. Castro et al. (2003) published the Life cycle impact assessment of passenger vehicles in Netherlands, with perspective of current dismantling and recycling practices.

Gesing (2004) reviewed current and future recycling technologies of light material content. Mark and Kamprath (2004) reviewed various bonding applications and their materials aspect for vehicle lightweighting. Van Schaik and Reuter (2004) applied dynamic modeling and simulation approaches to illustrate the influence of parameters on the recycling rate. Van Schaik et al. (2004) developed a nonlinear optimization model to analyze the relationship between particle size reduction and liberation of ELVs' shredding and recycling processes. Kim et al. (2004) surveyed processing rates and management applications status of ELV management policies in Korea. Schmidt et al. (2004) focused on environmental impacts and their combinations of recycling/recovery and lightweight vehicle design options over the life cycle. Pelletiere and Reinert (2004) published a database on second-hand automobile protection, and proposed gravity models of the second-hand automobile trade. Bandivadekar et al. (2004) used a simulation model to analyze material flows and economic exchanges of future changes in vehicle material compositions in US.

Sawyer-Beaulieu and Tam (2005) studied Life-cycle assessment (LCA) to review and improve the ELV management process in North America. Seo et al. (2005) published a study about ASR characterization for ELV management in Korea. Choi et al. (2005) proposed a mixed-integer programming model for process planning in the case of traditional US automotive shredders. Castro et al. (2005) developed a simulation model to analyze the relationships between product design and the liberation level attained by the shredding of passenger seats. Forslind (2005) reviewed the consequences of implementing EPR for vehicle recyclers in Sweden.

Chen (2006) published a study to highlight the sustainable recycling of Chinese automobile products within the period of 2006–2010. Ferrao et al. (2006) reviewed the influence of the ELV Directive on the profitability of vehicle dismantlers and shredders. Krinke et al. (2006) compared the environmental characteristics of two ELV recycling methods. Reuter et al. (2006) investigated the limits of ELV recycling. Forton et al. (2006) outlined ELV management in the UK and its actual effects on present practice. Finkbeiner et al. (2006) invastigated the use of LCA on Mercedes-Benz S-Class vehicles. Mazzanti and Zoboli (2006) analyzed the ways of economic instruments reflecting the producer responsibility principle in ELVs' management policy. Amaral et al. (2006) questioned how far recycling technology innovation can be a major driver for the automobile industry. Ferrao and Amaral (2006) developed technical cost models to assess the economics of dismantling and shredding activities. Pelletiere and Reinert (2006) proposed gravity models for second-hand automobile exports of Japan and the USA.

Coates and Rahimifard (2007) reviewed the stakeholders and their relationships within the UK recovery chain and developed an ELV costing framework. Jeong et al. (2007) analyze ELV management system in Korea by using LCA methodology and evaluated its environmental performance. Joung et al. (2007) questioned the recycling rate and management status of ELV management practices in Korea. Mergias et al. (2007) presented PROMETHEE method to select the best compromise scheme for the ELV management in Cyprus. Dalmijn and De Jong (2007) reviewed the vehicle recycling industry in the EU. Giannouli et al. (2007) developed a technical model to evaluate the waste of road vehicles. Sakai et al. (2007) analyzed the unintentional formation, decomposition, and emission-control performance of POPs during ASR incineration. Williams et al. (2007) developed an MILP model for making tactical decisions regarding what extent to process and reprocess materials. Alonso et al. (2007) published a research project to contribute cost-effective and eco-efficient electrical and electronic systems components in the automotive industry. Frad and Revnic (2007) proposed a method to assure the achievement of the required eco-efficiency rates for car manufacturing. Ribeiro et al. (2007) modified a car component which is a part of the current automotive brake system, by its original manufacturer. Fuse et al. (2007) analyzed the outflow of base metals exported from Japan in the form of ELVs.

Ignatenko et al. (2008) improved the optimization model proposed by Reuter et al. (2006) to add thermal treatment processes and energy recovery constraints. Qi and Hongcheng (2008) developed an MILP model for designing an ELV recovery network constituted from dismantling centers and processing facilities. Sawyer-Beaulieu and Tam (2008) used LCA to analyze ELV dismantling and shredding processes. Smith and Keoleian (2008) analyzed the energy savings and pollution prevention in the US through remanufacturing a midsized automotive gasoline engine. Fuse and Kashima (2008) proposed an automobile recycling input-output analysis to examine the appropriateness of the recycling scheme for ELVs imported from Japan. Qu and Williams (2008) presented a nonlinear programming model to develop an approximate supply function for hulks in automotive reverse production planning and pricing problems.

Chondros (2009) evaluated ELV treatment alternatives to propose an effective ELV management practices in different conditions. Puri et al. (2009) reviewed material alternatives and end-of-life strategies for automotive components. Amelia et al. (2009) reviewed the automotive reuse in Malaysia by interviewing local automotive and component manufacturers. Chen and Zhang (2009) focused on ELV management in China. Kumar and Sutherland (2009) studied profit-enhancement strategies to ensure the economic sustainability of ELVs. Fuse et al. (2009) published an estimation method for calculating the number of used passenger cars employed in world trade. Differently, Fuse et al. (2009) proposed a regression analysis application to estimate the global flow of base metals in the used automobile trade.

Santini et al. (2010) studied the impact that pre-shredder treatment could have on achieving 85% recyclability rate in 2015. Chen et al. (2010) analyzed the characteristics of the vehicle recycling system in Taiwan. Go et al. (2010) aimed to optimize the disassembly sequence for recovery of automotive components. Mathieux and Brissaud (2010) developed a method to elaborate end-of-life product-specific material flow analysis.

Agbo (2011) focused on quantifying the available salvage value and service materials potential from imported second-hand vehicles in Nigeria. Duranceau and Sawyer-Beaulieu (2011) analyzed current ELV disposition rates regarding to their age and material content. Hedayati and Subic (2011) published a decision-making support framework for the recovery of ELVs. Kibira and Jain (2011) highlighted the impact of hybrid and electric vehicles on the profitability of the recycling infrastructure. Santini et al. (2011) reviewed a shredder campaign trial developed in Italy. Xi et al. (2011) developed a prediction approach for residual strength and life of reused components of ELVs. Zoraga et al. (2009) studied energy consumption and carbon dioxide emissions of ELV recycling. Che et al. (2011) compared ELV recycling system of Japan, China and Korea and in developing countries. Nazmi et al. (2011) developed an ANN-based prediction tool for critical stress life of a vehicle door with regarding to its efficient reusability.

Filho (2012) compared various constituent vehicle materials and analyzed their impact on the environment in Brazil. Fiore et al. (2012) published a characterization and valorization study about ASR in Italy. Millet et al. (2012) developed an impact module on recycling rate indicators for identifying the worst recycling case. Nakamura et al. (2012) proposed a hybrid input-output analysis to quantify quality and dilution losses. Santini et al. (2012) reviewed ASR pre-treatment and pyrolysis to determine whether the ELV recycling target could be achieved by car fluff mechanical separation. Cheng et al. (2012) examined the operational characteristics of the ELV recycling business in Taiwan. Hatayama et al. (2012) focused on the next-generation vehicles and scrap sorting technology until 2050. Wang and Chen (2012) reviewed the ELV recycling management in China and introduced a roadmap for automotive component recycling technology. Simic and Dimitrijevic (2012a) improved the linear programming modeling framework proposed by Simic and Dimitrijevic (2012b) for a vehicle hulk selection problem. Simic and Dimitrijevic (2012b) studied a production planning problem for vehicle recycling factories in the EU legislations.

Arena et al. (2013) studied a performance measurement system for automotive producers to assess their technological options. Simic and Dimitrijevic (2013a) developed an ASR recycling planning model for the Japanese vehicle recycling industry. Simic and Dimitrijevic (2013b) presented a risk explicit MINP model for optimal long-term planning in the EU vehicle recycling facilities. Berzi et al. (2013) proposed a simulation model for layout planning of ELV dismantling facilities. Tasala Gradin et al. (2013) used the LCA method to compare manual disassembly and shredding. Saavedra et al. (2013) analyzed the current remanufacturing scenario in the Brazilian automotive sector. Schmid et al. (2013) applied quantitative and qualitative characterization of different material flows on an industrial site. Hu and Kurasaka (2013) published a model for ELV distribution per population at the provincial level in China.

Miller et al. (2014) reviewed the characteristics of plastics recycling in the North American automotive industry. Ruffino et al. (2014) applied an economic assessment of a hypothetical industrial recovery process of light ASR. Sawyer-Beaulieu et al. (2014) analyzed strategies and actions for decreasing the lifecycle impact passenger vehicles. Tian and Chen (2014) exemplified the challenges of handling polymers from a vehicle dashboard. Ahmed et al. (2014) analyzed the current situation of the ELV management in Malaysia. Lu et al. (2014) analyzed new joining solutions in the automotive industry and reviewed the current use of adhesive technology in ELVs. Yano et al. (2014) applied a population balance model for estimating the number of generated ELVs in Japan within the time period of 1990–2020.

El Halabi et al. (2015) analyzed the environmental effect of using a multi-dismantling machine for material separation process. Chen et al. (2015) developed a dynamic model and they applied a cost-benefit analysis to investigate the effect on the recycling of ELVs in China. Despeisse et al. (2015) proposed policy, technical and business suggestions to improve reuse, recycling, and recovery rates. Ohno et al. (2015) investigated the content of alloying elements in ELVs and they applied a waste input-output material flow analysis. Sawyer-Beaulieu and Tam (2015) questioned the challenges with the development of ELV management systems. Yi and Park (2015) proposed a dismantling monitoring and smart trolley system for ELV recycling process. Simic and Dimitrijevic (2015) published a model for long-term planning of vehicle recycling in the Republic of Serbia. Oguchi and Fuse (2015) developed a straightforward method for estimating the lifespan distribution of passenger vehicles.

Belboom et al. (2016) presented an environmental evaluation of hybrid vehicles recycling in Belgium. Desnica et al. (2016) published an AHP approach to select equipment for detoxification of ELVs. Inghels et al. (2016) analyzed the influence of material composition, amount and lifespan of passenger vehicles on the ELV management in Belgium. Junior et al. (2016) highlighted vehicle recycling processes and manufacturer responsibility and the benefits to the economy, society, and environment. Pan and Li (2016) applied an improved emergy analysis to evaluate the efficiency and sustainability of ELV recycling enterprises. Ahmed et al. (2016a, 2016b) used DEMATEL and extent analysis method on the fuzzy AHP to rank ELV management alternatives. Pourjavad and Mayorga (2016a) proposed an integrated fuzzy DM framework to evaluate sustainable ELV strategies. Pourjavad and Mayorga (2016b) combined the fuzzy AHP and fuzzy TOPSIS methods to rank ELV management strategies. Raja Mamat et al. (2016) published a framework for the ELV management in Malaysia. Li et al. (2016) evaluated the environmental impacts of ELV recycling processes in China. Tian and Chen (2016) applied the fuzzy AHP technique and cost-benefit analysis to compare dismantling scenarios in China. Xia et al. (2016) used cost-benefit analysis to perform the construction and investment analysis of an ELV disassembly plant in China. Zhou et al. (2016) evaluated ELV recycling service providers by using a multi-criteria model based on the fuzzy VIKOR technique. Diener and Tillman (2016) focused on a case of an automotive component manufacturer and investigated its ELV management. Xu et al. (2016) applied a scenario analysis to determine the amount of rare earth elements that can be recovered from ELVs in Japan. Yano et al. (2016) conducted a population balance model for estimating the number of end-of-life hybrid electric vehicles generated in Japan within the time period of 2010–2030.

Andersson et al. (2017) identified key functions of ELV iron recycling in Sweden within the time period of 1910 to 2010 by using the technological innovation system framework. Ene and Öztürk (2017) predicted the number of ELVs that will be generated in the future. Gan and Luo (2017) studied a fuzzy-based DEMATEL method to identify critical factors of the recycling rate of ELVs. Karaeen et al. (2017) published a concept for the second life cycle of vehicles. Soo et al. (2017a) compared the environmental performance of the current ELV recycling processes in Australia and Belgium. Soo et al. (2017b) reviewed the joining technologies used in the automotive industry to identify the recycling performance of ELVs. Nakano and Shibahara (2017) applied the LCA method to quantify the amounts of greenhouse gases emitted when recycling ELVs by using the traditional shredding approach and the whole recycling approach. Endo and Fuse (2017) focused on reducing the uncertainty in international trade for used automobiles and engines.

Khodier et al. (2018) highlighted challenges of ASR processing and disposal in the UK. Zhang and Chen (2018) compared various ELV dismantling planning scenarios with AHP approach. Hao et al. (2018) aimed to improve the management of the reverse supply chain of the automotive industry in the context of green, circular, and sustainable development. Mohan and Amit (2018) pulished a system dynamics model approach to analyze informal dismantling facilities in India. Raja Mamat et al. (2018) developed a performance evaluation tool based on the Analytic Hierarchy Process for the Malaysian ELV management system. Rosa and Terzi (2018) proposed a system dynamics simulation approach to analyze the current economic performances of the Italian ELV rcycling system. Zhang and Chen (2018a) developed an Arena-based simulation tool to analyze four scenarios of an ELV disassembly line in China. Wong et al. (2018) published a new concept of a processing framework to utilize ELV waste to construction industries in Malaysia. Ortego et al. (2018) published a downcycling assessment approach for exposing quantity and quality of the materials lost during the ELV recycling process. Lin et al. (2018) proposed a population balance model for predicting the number of generated ELVs in Kinmen, Taiwan, within the time period of 1960–2050. Xu et al. (2018) applied a scenario analysis to determine the amount of five precious metals that could be returned to material streams from ELVs.

Miskolczi et al. (2019) aimed to modify zeolite catalysts by metal loading for using ELV plastic waste pyrolysis. Sato et al. (2019) assessed benefits of enabling energy consumption and carbon dioxide emission. Arora et al. (2019) studied a shared responsibility based framework for a business model of the ELV management in India. Mohamad-Ali et al. (2019) applied a survey to identify the issues and factors of the ELV recycling system in Malaysia. Qiao et al. (2019) focused on the economic and environmental benefits of electric vehicle recovery in China. Wang et al. (2019) reviewed the efficiency of the ELV reverse logistics industry in China. Yang et al. (2019) published a systematic index system approach for criteria selection in ELV management. Yano et al. (2019) presented a study of dismantling survey and chemical analysis of six ELVs to estimate the content of valuable and toxic elements.

Used lead-acid battery recycling has a crucious importance in hazardous industry. Hoffmann and Wilson (2000) reviewed characterization of the lead-acid battery recycling industry in the Philippines. Haefliger et al. (2009) analyzed a mass lead intoxication that occurred as a result of informal automotive battery recycling in Senegal. Gottesfeld et al. (2018) focused on soil contamination around used lead-acid recycling plants in seven African countries. Several studies assessed soil contamination and human health exposure in the battery recycling craft village, Dong Mai, Vietnam. For instance, Ericson et al. (2018) analyzed the efficiency of a novel soil lead mitigation project, Noguchi et al. (2014), Daniell et al. (2015), and Eguchi et al. (2018) assessed human lead exposure, while Fujimori et al. (2016) focused on the lead contamination level in surface soil on roads. Ericson et al. (2016) aimed to estimate the number of informal lead-acid battery recyclers and the number of exposed people in 90 developing.

The previous studies, related to recycling processes and analyses of materials, mostly focused on solutions for local problems. More global approaches and solutions are highly needed. Furthermore, material concepts and perceptions of the vehicles tend to change. For this reason, more studies regarding this issue are needed in the future studies. Thus, majority of the studies, considering the managerial perspective, are suggesting solution approaches for economic and/or material issues. However, there are not enough studies that focusing on social aspect. The participation of the public has a crucial impact for an effective ELV management. Owners need to be encouraged to withdraw their vehicles from the traffic. For this reason, social awareness and acceptance also have crucial impact on an effective ELV management.

Apart from these, there are not enough studies comparing the designing and planning systems as before and after. Impacts of recycling friendly product design and production planning could be monitored via customer feedbacks, financial analyses, etc.

Due to new ELV regulations, researchers need to focus on producers' responsibilities. Decision makers are expected to make their designs and revise their production plans according to legislation. On the other hand, there are a few types of studies published by the researchers.

Table 2.2 Reviewed publications in the scope of RPP

Year	Author(s)	Method(s) used in the study															
		FC	GP	LCA	LCC	LCI	LP	MBM	MFE	MILP	MM	MOP	NLP	PPP	PR	SD	TCM
2000	Kirkpatrick et al.			✓													
2000	Bellman and Khare													✓			
2000	Hartman et al.			✓													
2000	Hoffmann and Wilson			✓													
2001	Díaz and Fernández			✓													
2001	Mark et al.				✓												
2001	Johnson and Wang																✓
2001	Petrov			✓													
2002	Johnson and Wang								✓								
2002	Van Schaik et al.										✓					✓	
2003	Boon et al.		✓														
2003	Petrov			✓													
2003	Castro et al.			✓													
2004	Gesing			✓													
2004	Mark and Kamprath			✓													
2004	Van Schaik and Reuter															✓	
2004	Van Schaik et al.												✓				
2004	Kim et al.							✓									
2004	Schmidt et al.			✓													
2004	Pelletiere and Reinert	✓															
2004	Bandivadekar et al.								✓							✓	
2005	Sawyer-Beaulieu and Tam			✓													
2005	Seo et al.			✓													
2005	Choi et al.									✓							
2005	Castro et al.															✓	
2005	Forslind			✓													
2006	Chen			✓													
2006	Ferrao et al.			✓													
2006	Krinke et al.			✓													
2006	Reuter et al.						✓										
2006	Forton et al.			✓													
2006	Finkbeiner et al.			✓													
2006	Mazzanti and Zoboli															✓	
2006	Amaral et al.															✓	
2006	Ferrao and Amaral																✓
2006	Pelletiere and Reinert	✓															
2007	Coates and Rahimifard										✓						✓
2007	Jeong et al.			✓													
2007	Joung et al.			✓													
2007	Mergias et al.														✓		
2007	Dalmijn and De Jong			✓													
2007	Giannouli et al.	✓															
2007	Sakai et al.			✓													
2007	Williams et al.									✓							
2007	Alonso et al.			✓	✓												
2007	Frad and Revnic			✓													
2007	Ribeiro et al.			✓													
2007	Fuse et al.	✓															
2008	Ignatenko et al.											✓					
2008	Qi and Hongcheng									✓							
2008	Sawyer-Beaulieu and Tam					✓											
2008	Smith and Keoleian					✓											
2008	Fuse and Kashima	✓															

Table 2.2 Reviewed publications in the scope of RPP (continued)

Year	Author(s)	Method(s) used in the study															
		FC	GP	LCA	LCC	LCI	LP	MBM	MFE	MILP	MM	MOP	NLP	PPP	PR	SD	TCM
2008	Qu and Williams											✓					
2009	Chondros									✓							
2009	Puri et al.					✓											
2009	Amelia et al.				✓	✓											
2009	Chen and Zhang																✓
2009	Kumar and Sutherland												✓				
2009	Fuse et al.				✓												
2009	Zoraga et al.				✓												
2009	Haefliger et al.				✓												
2010	Santini et al.														✓		
2010	Chen et al.				✓												
2010	Go et al.								✓								
2010	Mathieux and Brissaud	✓															
2011	Agbo	✓															
2011	Duranceau and Sawyer-Beaulieu													✓		✓	
2011	Hedayati and Subic				✓												
2011	Kibira and Jain		✓								✓						
2011	Xi et al.				✓												
2011	Santini et al.							✓									
2011	Che et al.				✓											✓	
2011	Nazmi et al.										✓						
2012	Filho				✓				✓								
2012	Fiore et al.				✓				✓								
2012	Millet et al.							✓			✓						
2012	Nakamura et al.																✓
2012	Santini et al.				✓			✓									
2012	Cheng et al.				✓			✓									
2012	Hatayama et al.							✓									
2012	Wang and Chen														✓		
2012	Simic and Dimitrijevic						✓										
2013	Arena et al.				✓												
2013	Simic and Dimitrijevic						✓										
2013	Simic and Dimitrijevic			✓													
2013	Berzi et al.								✓		✓						
2013	Tasala Gradin et al.				✓												
2013	Saavedra et al.				✓			✓									
2013	Schmid et al.							✓									
2013	Hu and Kurasaka	✓															
2014	Miller et al.	✓						✓									
2014	Ruffino et al.				✓				✓								
2014	Sawyer-Beaulieu et al.				✓			✓									
2014	Tian and Chen	✓						✓									
2014	Ahmed et al.				✓				✓								
2014	Lu et al.							✓									
2014	Yano et al.							✓									
2014	Noguchi et al.				✓												
2015	Chen et al.		✓														
2015	Despeisse et al.											✓		✓			
2015	Ohno et al.													✓			
2015	Sawyer-Beaulieu and Tam											✓	✓				
2015	Yi and Park										✓						
2015	Simic and Dimitrijevic									✓							
2015	Oguchi and Fuse							✓									
2015	Daniell et al.											✓					
2016	Belboom et al.											✓					
2016	Desnica et al.	✓															
2016	Inghels et al.											✓			✓		
2016	Junior et al.											✓		✓			
2016	Pan and Li					✓								✓			

Table 2.2 Reviewed publications in the scope of RPP (continued)

Year	Author(s)	Method(s) used in the study																
		EPR	FC	GA	ILP	LCA	LCI	LP	MFA	MFE	MILP	MM	MOP	NLP	SD	SW	TCM	WA
2016	Pourjavad and Mayorga							✓										✓
2016	Raja Mamat et al.					✓											✓	
2016	Li et al.												✓					
2016	Tian and Chen			✓				✓										
2016	Xia et al.			✓														
2016	Zhou et al.									✓								
2016	Diener and Tillman														✓			
2016	Yano et al.								✓						✓			
2016	Xu et al.								✓						✓			
2016	Fujimori et al.												✓					
2016	Ericson et al.												✓					
2017	Andersson et al.								✓									
2017	Ene and Öztürk								✓									
2017	Gan and Luo				✓													
2017	Karaeen et al.												✓					
2017	Soo et al.												✓					
2017	Soo et al.								✓									
2017	Nakano and Shibahara												✓					
2017	Endo and Fuse								✓									
2017	Miskolczi et al.												✓					
2018	Khodier et al.												✓					
2018	Zhang and Chen	✓														✓		
2018	Hao et al.		✓						✓									
2018	Mohan and Amit															✓		
2018	Raja Mamat et al.	✓																
2018	Rosa and Terzi															✓		
2018	Wong et al.												✓					
2018	Ortego et al.														✓			
2018	Lin et al.												✓					
2018	Gottesfeld et al.												✓					
2018	Ericson et al.												✓					
2018	Eguchi et al.												✓					
2018	Xu et al.														✓			
2019	Sato et al.												✓					
2019	Arora et al.														✓			
2019	Mohamad-Ali et al.					✓												
2019	Qiao et al.												✓					
2019	Wang et al.				✓													
2019	Yang et al.							✓										
2019	Yano												✓					

2.13.3 Network Design

The recycling process of ELVs necessitates effective supply chain management problem. There are various studies in the literature which are coping with supply chain management issues of the ELV management. Ahn et al. (2005) proposed an optimization tool for facility location problems of the German automobile industry. Schultmann et al. (2006) presented the peculiarities of establishing a closed-loop supply chain (CLSC) for ELVs. Mansour and Zarei (2008) developed a multi-period reverse logistics optimization model for location selection problem of ELV collection and dismantler centers. Cruz-Rivera and Ertel (2009) presented an uncapacitated facility location model for ELV collection design in Mexico.

Merkisz-Guranowska (2010, 2011) developed MILP models to determine the optimum locations of participants in the ELV recycling network. Zarei et al. (2010) proposed a reverse logistics network for the management of the ELV recovery process. Harraz and Galal (2011) developed a mixed-integer lexicographic goal programming approach for ELVs in Egypt. Mahmoudzadeh et al. (2011) aimed to determine locations for ELV collection centers with a capacitated location-allocation model. Vidovic et al. (2011) published a modeling approach to locate collection centers for ELVs.

Merkisz-Guranowska (2012, 2013) aimed to construct ELV recycling network in Poland by formulating a bi-objective mixed-integer linear programming model. Farel et al. (2013) proposed an MILP approach to determine the optimal material flow for ELV recycling network. Gołebiewski et al. (2013) developed a simulation model to determine optimum locations for ELV dismantlers. Mahmoudzadeh et al. (2013) presented a MILP model to solve a location-allocation problem of ELVs scrap yards in Iran.

Ene and Öztürk (2015) proposed a multi-period, multi-stage model for ELV network design problem. Simic (2015a) studied a two-stage interval-stochastic programming model to cope with uncertaincies in ELV recovery network management. Simic (2015b) developed a fuzzy risk explicit MINP model for ELV recycling planning in the EU. Subulan et al. (2015) formulated a fuzzy multi-objective MILP model for supply chain management of the lead-acid battery in Turkey.

Alsaadi and Franchetti (2016) aimed to find the optimum location for a processing facility for ELVs. Demirel et al. (2016) developed an MILP model for reverse logistics network design in the ELV recycling system. Simic (2016a) published a multi-stage interval-stochastic programming model for ELV allocation. Simic (2016b) developed an interval-parameter two-stage stochastic full-infinite programming model for ELV allocation management under multiple uncertainties. Simic (2016c) presented an interval-parameter chance-constraint programming model for uncertainty-based decision making in the ELV recycling industry.

Phuc et al. (2017) established a fuzzy MILP model for designing a multi-echelon, multi-product reverse logistics network. Özceylan et al. (2017) published a case study from Turkey based on CLSC for ELV recovery. Deng et al. (2018) developed a simulation-optimization model for location-allocation problem of ELV recycling process. Lin et al. (2018) presented an MILP model for the facility location-allocation problem of an ELV recovery network. Shankar et al. (2018) developed an MILP model for the CLSC network. Sun et al. (2018) aimed to locate ELV collection centers with a mixed-integer bi-level linear programming approach. Ma and Li (2018) developed a two-stage stochastic programming model for the lead-acid battery CLSC management.

Kuşakcı et al. (2019) proposed a fuzzy mixed-integer linear programming model for designing the ELV reverse logistics network in Istanbul. Xiao et al. (2019) formulated an MILP model for managing a four-tier reverse logistics network system of ELV recovery.

Table 2.3 summarizes the publications with mathematical models and they are categorized based on the type of decision variables, optimization model and solution approach.

Table 2.3 Reviewed publications in the scope of network design

Year	Author(s)	Type of decision variables			Optimization model				Single-multi objectivity		Type of objective function(s)		Type of parameter(s)			Type of supply chain		Solution approach		
		LA	RP	PP	LP	NLP	MILP	MINP	Single	Multi	Max	Min	Det.	Prob.	Fuzzy	OL	CL	E	H	MH
2002	Van Schaik et al.		✓		✓				✓		✓		✓	✓		✓		✓		
2003	Boon et al.		✓		✓				✓		✓		✓			✓		✓		
2004	Van Schaik et al.		✓			✓			✓			✓	✓			✓		✓		
2005	Ahn et al.	✓					✓		✓			✓	✓			✓			✓	
2005	Choi et al.		✓				✓		✓		✓		✓			✓		✓		
2006	Reuter et al.		✓		✓				✓		✓		✓			✓		✓		
2006	Schultmann et al.	✓					✓		✓			✓	✓			✓			✓	
2007	Williams et al.		✓				✓		✓		✓		✓			✓		✓		
2008	Ignatenko et al.		✓				✓			✓	✓	✓	✓				✓	✓		
2008	Mansour and Zarei	✓					✓		✓			✓	✓				✓		✓	
2008	Qu and Williams			✓		✓			✓		✓		✓			✓		✓		
2008	Qi and Hongcheng		✓				✓		✓			✓	✓				✓	✓		
2009	Cruz-Rivera and Ertel	✓					✓		✓			✓	✓				✓	✓		
2010	Zarei et al.	✓						✓	✓			✓	✓				✓		✓	
2010	Merkisz-Guranowska	✓					✓		✓			✓	✓			✓		✓		
2011	Vidovic et al.	✓					✓		✓		✓		✓			✓		✓		
2011	Merkisz-Guranowska	✓			✓				✓			✓	✓			✓		✓		
2011	Mahmoudzadeh et al.	✓			✓				✓			✓	✓			✓		✓		
2011	Harraz and Galal	✓					✓			✓	✓	✓	✓			✓		✓		
2012	Merkisz-Guranowska	✓			✓					✓	✓	✓	✓			✓		✓		
2012b	Simic and Dimitrijevic			✓	✓				✓		✓		✓			✓		✓		
2013a	Farel et al.	✓					✓		✓		✓		✓			✓		✓		
2013a	Simic and Dimitrijevic			✓	✓				✓		✓		✓			✓		✓		
2013	Gołębiewski et al.	✓			✓				✓			✓	✓			✓			✓	
2013	Merkisz-Guranowska	✓					✓			✓	✓	✓	✓			✓		✓		
2013b	Simic and Dimitrijevic			✓	✓					✓	✓	✓	✓			✓		✓		
2013	Mahmoudzadeh et al.	✓			✓				✓			✓	✓				✓	✓		
2015a	Simic	✓			✓					✓	✓	✓	✓	✓		✓		✓		

LA: Location-allocation, RP: Recycling planning, PP: Production planning, LP: Linear programming, NLP: Non-linear Programming, MILP: Mixed-integer linear programming, MINP: Mixed-integer non-linear programming, OL: Open-loop, CL: Closed-loop, E: Exact, H: Heuristics, MH: Meta-heuristics

Table 2.3 Reviewed publications in the scope of network design (continued)

Year	Author(s)	Type of decision variables			Optimization model				Single-multi objectivity		Type of objective function(s)		Type of parameter(s)			Type of supply chain		Solution approach		
		LA	**RP**	**PP**	**LP**	**NLP**	**MILP**	**MINP**	**Single**	**Multi**	**Max**	**Min**	**Det.**	**Prob.**	**Fuzzy**	**OL**	**CL**	**E**	**H**	**MH**
2015b	Simic	✓			✓					✓	✓	✓	✓		✓	✓		✓		
2015	Simic and Dimitrijevic			✓	✓				✓		✓		✓			✓		✓		
2015	Ene and Öztürk	✓					✓		✓		✓		✓			✓		✓		
2015	Subulan		✓				✓			✓	✓	✓	✓		✓		✓	✓		
2016a	Simic	✓			✓				✓		✓		✓	✓		✓		✓		
2016b	Simic	✓			✓				✓		✓		✓	✓		✓		✓		
2016c	Simic	✓					✓		✓		✓		✓	✓		✓		✓		
2016	Demirel et al.	✓					✓		✓			✓	✓			✓		✓		
2016	Alsaadi and Franchetti	✓					✓		✓			✓	✓			✓		✓		
2017	Phuc et al.	✓			✓				✓			✓	✓		✓		✓	✓		
2017	Özceylan et al.	✓			✓				✓		✓		✓				✓	✓		
2018	Lin et al.	✓					✓		✓			✓	✓			✓				✓
2018	Shankar et al.	✓			✓				✓		✓		✓				✓	✓		
2018	Sun et al.	✓			✓				✓			✓	✓			✓		✓		
2018	Deng et al.	✓					✓		✓			✓	✓			✓		✓		
2018	Ma and Li		✓				✓		✓		✓		✓	✓			✓	✓		✓
2019	Xiao et al.	✓			✓				✓			✓	✓			✓		✓		
2019	Kuşakcı et al.	✓			✓				✓			✓	✓		✓	✓		✓		

LA: Location-allocation, RP: Recycling planning, PP: Production planning, LP: Linear programming, NLP: Non-linear Programming, MILP: Mixed-integer linear programming, MINP: Mixed-integer non-linear programming, OL: Open-loop, CL: Closed-loop, E: Exact, H: Heuristics, MH: Meta-heuristics.

Available publications cope with supply chain issues of the ELV management are mostly performed with deterministic data. Real-life ELV management systems have many uncertain components. Furthermore, there are various uncertainties with economic and technical parameters, the amount of supplied ELV, etc. An extension of the reviewed modeling frameworks to address uncertainties can provide a more realistic representation of ELV management systems.

2.13.4 Regulations Review

Several regulations reviews are made in the ELV management literature. Levizzari (2002) analyzed the impacts of the ELV Directives on the automotive industry in Italy. Kanari et al. (2003) compared the current situation and future of the ELV management in the EU. Sakkas and Manios (2003) analyzed investment strategies for the ELV management in Greece. Smith et al. (2004) aimed to examine the future of the abandoned vehicle problem with the introduction of new laws.

Chen (2005) researched the ELV policy and legislation in China. Marsh (2005) published a survey about recycling collaborative combats legislation threat. Nakajima and Vanderburg (2005) reviewed the German ELV take-back system and its impact on the environment. Edwards et al. (2006) evaluated the potential direction of the recovery industry. Saman and Blount (2006) overviewed current practices in vehicle recycling in Europe, USA, Japan, and Australia.

Gerrard and Kandlikar (2007) studied a framework based on anticipated changes that could result from the ELV Directive. Smink (2007) analyzed the environmental regulations in the car-dismantling trade in Denmark. Manomaivibool (2008) investigated the impacts of network management on the environmental effects for the ELV management in the UK and in Sweden. Smith and Crotty (2008) explored the impact of the ELV Directive on vehicle component manufacturers in the UK.

Konz (2009) analyzed the ELV Directive with a survey study. Altay et al. (2011) investigated the recycling of metal from ELVs in Turkey with perspective of Kyoto Protocol. Zhao and Chen (2011) analyzed and compared ELV regulations in Japan and China. Wang and Chen (2013) studied ELV legislations of China, EU, Japan, and

Korea. Blume and Walther (2013) investigated the legislative influence on the German vehicle industry. Farel et al. (2013) developed a cost and benefit analyzed for the ELV glazing recycling network in France.

Table 2.4 summarizes the publications in the scope of regulations review in the literature. It depicts that most of the studies in this scope are considering local issues related to ELV management. However, regulations have global affects in the world simultaneously.

Table 2.4 Reviewed oublications in the scope of regulations review

Author(s) and year	Research focus
Levizzari (2002)	Italy
Kanari et al. (2003) Marsh (2005) Gerrard and Kandlikar (2007)	The European Union
Sakkas and Manios (2003)	Greece
Smith et al. (2004) Edwards et al. (2006) Smith and Crotty (2008)	England and the United Kingdom
Chen (2005) Wang and Chen (2013)	China
Nakajima and Vanderburg (2005) Blume and Walther (2013)	Germany
Saman and Blount (2006)	The European Union, the USA, Japan, and Australia
Smink (2007)	Denmark
Manomaivibool (2008)	The United Kingdom and Sweden
Konz (2009)	The USA
Altay et al. (2011)	Turkey and Kyoto Protocol
Zhao and Chen (2011)	China and Japan
Farel et al. (2013)	France

2.14 Discussion

The ELV management problem has a critical importance for the actors like governments, producers, treatment facilities, and users. Due to legislative improvements, it is becoming even more important both environmentally and economically. Furthermore, the ELV recovery and management problem is not only an operational process but it is also a strategic and tactical level process for decision-makers.

Figure 2.3 shows the distribution of studies per year between 2000 and 2019. Based on Figure 2.3, 61.6% of studies on the ELV management (143 out of 232) were published in the last nine years. Therefore, there is a significant increase in the number of publications in the area of the ELV management after the year 2011.

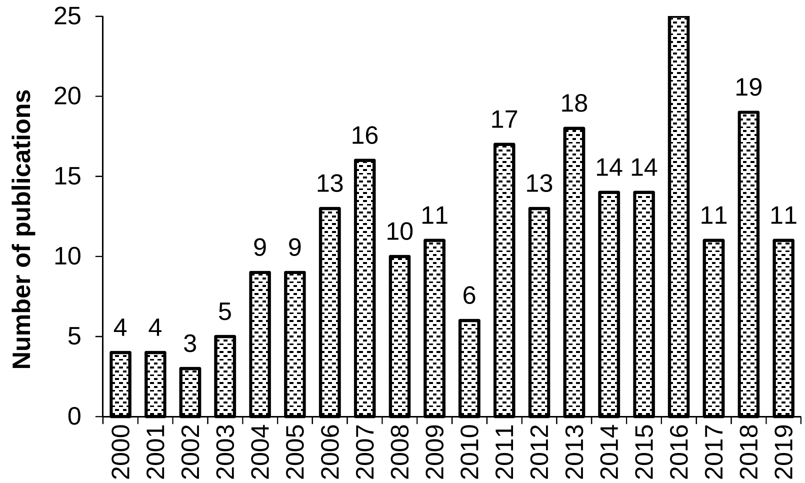


Figure 2.3 Distribution of studies per year within the period of 2000–2019

Figure 2.4 presents the quantity and percentage of studies based on their purpose. According to Figure 2.4, the majority is in the scope of "Recycling, production & planning" category. Although the ELV management has a multidisciplinary concept, the lack of hybrid studies can be clearly identified.

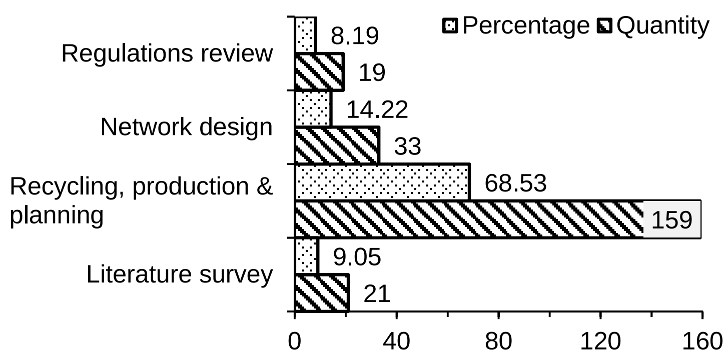


Figure 2.4 Reviewed studies based on their major classification

Figure 2.5 provides the distribution of the studies based on the applied method. Based on Fig 2.5, 32.08% of studies in the scope of "Recycling, production and planning" on the ELV management (51 out of 159) applied the LCA method. It is possible to see that publications are not homogenous based on the method applied.

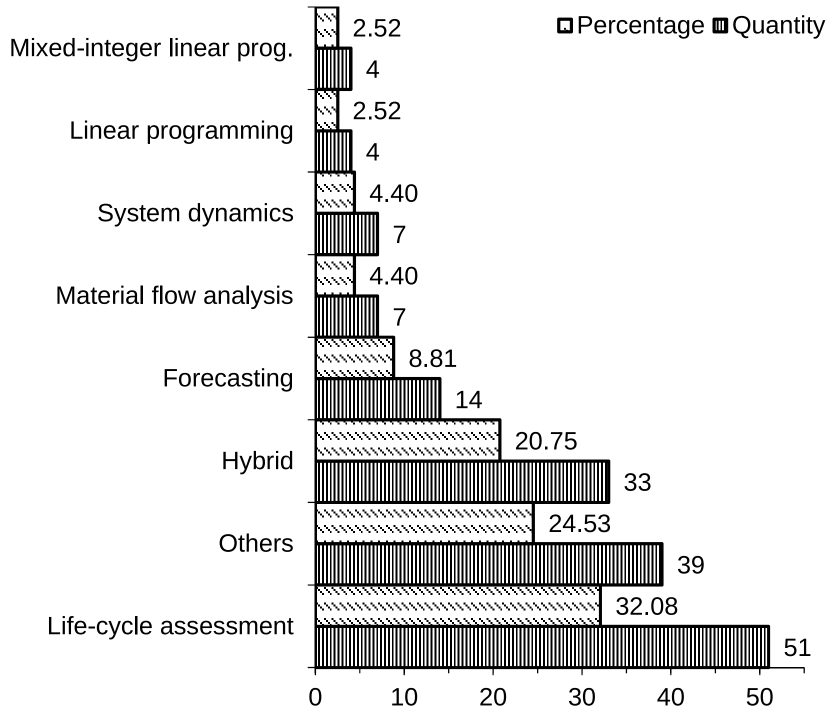


Figure 2.5 Applied method

Figure 2.6 presents the percentage and quantity of the publications with an optimization model based on the type of parameters used in the analyzed studies. According to Figure 2.6, the vast majority of researchers preferred to use deterministic parameters. It is not realistic to study with deterministic parameters for real-life cases. Therefore, new approaches with probabilistic and fuzzy parameters should be in the focus of future contributions.

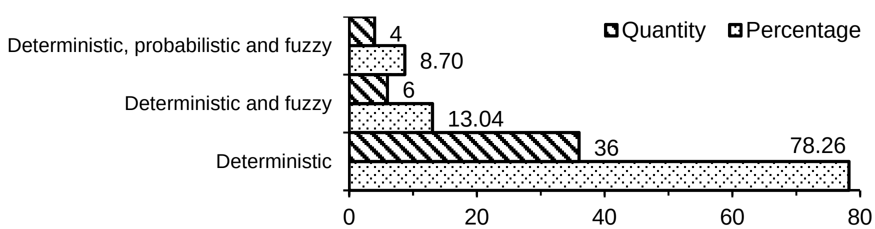


Figure 2.6 Type of parameters

Figure 2.7 shows the distribution of papers based on the studied type of supply chain network of ELVs and its components. Based on Figure 2.7, 76.09% of studies on the ELV management (35 out of 46) are dealing with open-loop supply chain problems. In fact, there is a lack of research suggesting a solution for both open- and closed-loop supply chains.

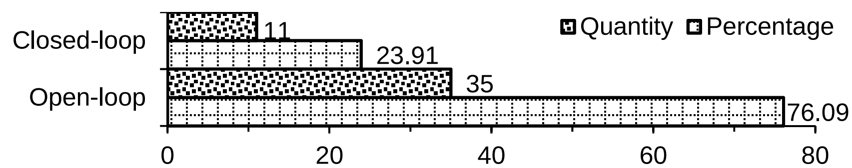


Figure 2.7 Type of supply chain

Figure 2.8 presents the number and percentage of the studies with a mathematical optimization model based on the type of decision variables. These studies mostly preferred to deal with location-allocation problems (31 out of 46). There are not enough hybrid approaches in this field. Furthermore, studies in the scope of production and recycling planning are very limited.

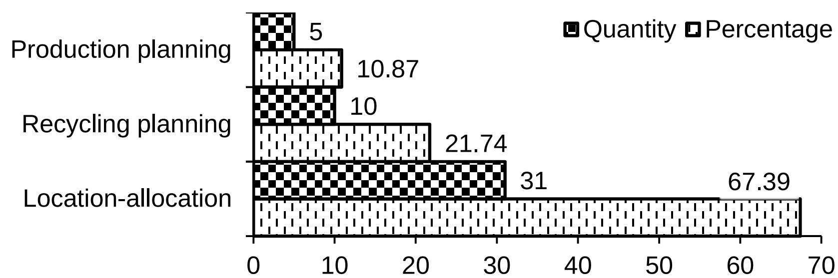


Figure 2.8 Studies with optimization model based on the type of decision variables

Figure 2.9 presents the quantity and percentage of the collected studies based type of optimization model. From Figure 2.9, it is evident that studies with a mathematical optimization model are mostly based on linear programming and MILP. Only 3 out of 46 studies developed non-linear optimization models.

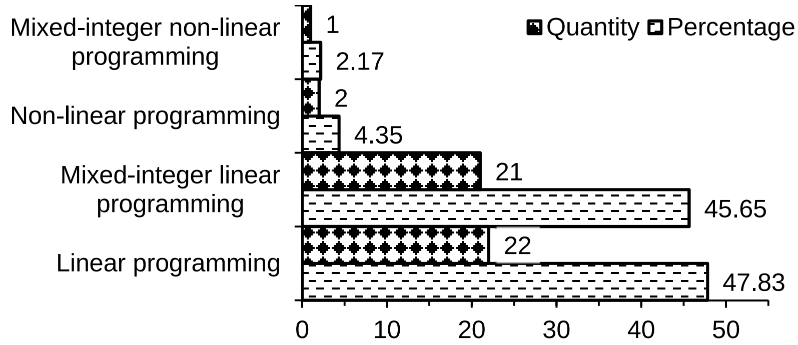


Figure 2.9 Type of optimization model

Figures 2.10 – 2.11 present distributions of studies with a mathematical optimization model based on single-multi objectivity and type of objective function, respectively. The lack of multi-objective approaches is more than evident; i.e., 82.61% for single-objective studies and 17.39% for multi-objective studies (Figure 2.10). According to Figure 2.11, both types of objective functions are considered in just 17.39% of the studies with a mathematical model. It should be mentioned that the majority of the studies with a mathematical model considered cost as its objective function (Figure 2.11). There are other objective targets either conflicting or non-conflicting to optimize in the ELV management models.

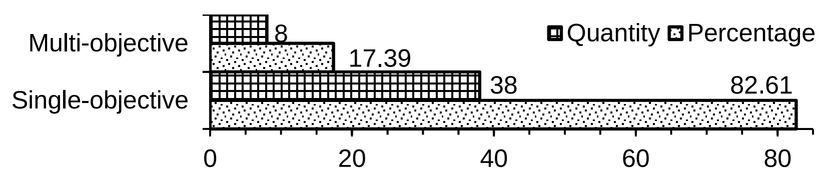


Figure 2.10 Studies with optimization model based on single-multi objectivity

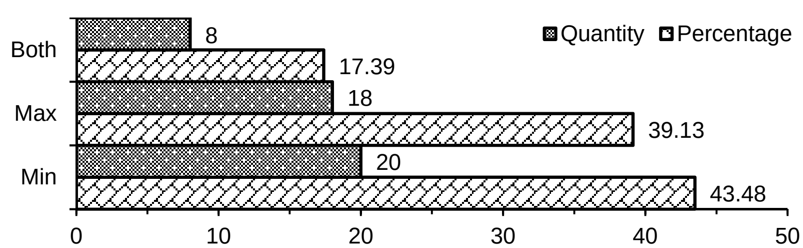


Figure 2.11 Studies with optimization model based on the type of objective function

Figure 2.12 presents the quantity and percentage of studies with a mathematical model based on the solution approach. It indicates that the vast majority of the approaches offered exact solutions instead of heuristics and meta-heuristics since most of them deal with either small or medium-size cases. Real-life ELV management problems usually need inexact colution approaches for generating reasonable solutions.

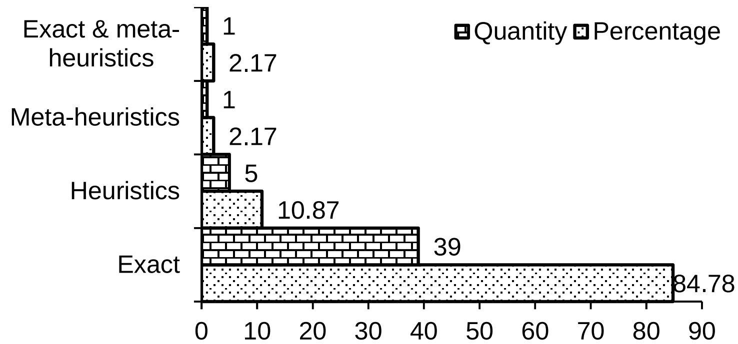


Figure 2.12 Studies with optimization model based on the solution approach

The distribution of studies on the ELV management based on the source of publication is presented in Table 2.5.

Table 2.5 Distribution of the studies based on the source of publication

Journal	Year of publication																				Total
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	
J. Cleaner Prod.	–	–	–	–	–	1	–	3	2	1	–	1	–	6	–	1	5	–	4	4	28
Resour. Conserv. Recycl.	–	–	–	–	2	–	1	1	–	1	2	2	4	5	–	2	2	–	1	2	25
Waste Manage.	–	–	–	–	1	–	–	–	–	–	1	1	2	1	2	2	4	2	2	–	18
J. Mater. Cycles Waste Manage.	–	–	–	–	–	–	–	2	1	1	–	–	–	1	7	–	3	1	–	2	18
JOM	–	–	–	1	1	1	1	1	–	1	–	–	–	–	–	–	–	–	–	–	6
Int. J. Life Cycle Assess.	–	–	–	1	1	–	2	1	–	1	–	–	–	–	–	–	–	–	–	–	6
Waste Manage. Res.	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	1	1	–	1	–	5
Others	4	4	3	3	4	7	9	8	7	6	3	13	5	5	5	8	10	8	11	3	126
Total	4	4	3	5	9	9	13	16	10	11	6	17	13	18	14	14	25	11	19	11	232

The primary publication outlets for the ELV management research area are: Journal of Cleaner Production (12.07% share), Resources, Conservation and Recycling (10.78% share), Journal of Material Cycles and Waste Management (7.76% share), and Waste Management (7.76% share), jointly publishing 38.4% of the total number of studies on the ELV management printed in the period 2000 - 2019. Moreover, these four journals have published almost 47% of the total identified number of studies in the past five years. On the other hand, the secondary publication outlets for the explored research area are JOM (2.59% share), The International Journal of Life Cycle Assessment (2.59% share), and Waste Management & Research (2.16% share). Finally, reviewing tables in this study confirmed that the ELV management is considered by numerous journals.

3
PROBLEM STATEMENT AND SOLUTIONS

3.1 Problem Statement

The EU has adopted Directive 2000/53/EC in 2000 for a sustainable ELV management. The main purpose of the directive is to limit the usage of hazardous substances in the vehicles and to set specific targets for the reuse, recovery and recycling from vehicles within time period of 2006-2015 (Demirel et al., 2016). As Turkey is a country which aims to be a member of EU and is in the harmonization process with the EU, Republic of Turkey Ministry of Environment and Urbanization has adopted ELV directives in 2009.

ELV's recycling network comprises of two main activities; transportation and processing. ELV's recycling journey starts with its transportation to collection centers of dismantling facilities (Kuşakçı et al., 2019). According to ELV Directives in Turkey, the owners of the vehicles have the responsibility of ELV's transportation and authorized collection centers are responsible for transferring the ELV to dismantling facilities within sixty days (Ministry of Environment and Urbanization, 2009). In dismantling facilities removal of fuel, oil, toxic and noxious fluids and other fluids e.g. coolant fluid is completed before starting dismantling operations. Afterwards, valuable parts from the vehicle are disassembled and sold to second-hand markets. Furthermore, some components are sent to recycling facilities in this stage. After these operations, the remaining of the ELV from dismantling operations (hulk) is transferred to shredder facilities. In shredder facilities, hulks are shredded and turned into auto-shredder residue (ASR). ASR is a combination of different materials such as glass, plastic, foam rubber, textile. Usable parts of ASR are transferred to recycling facilities and the remaining of ASR is sent to landfilling centers to be disposed. In the recycling facilities, incoming components are separated into recyclable and hazardous materials categories. The recycled materials are sold to other suppliers and the hazardous materials are sent to landfills to be disposed. Figure 3.1 presents the recycling process network of ELV in Turkey (Karagoz et al., 2020).

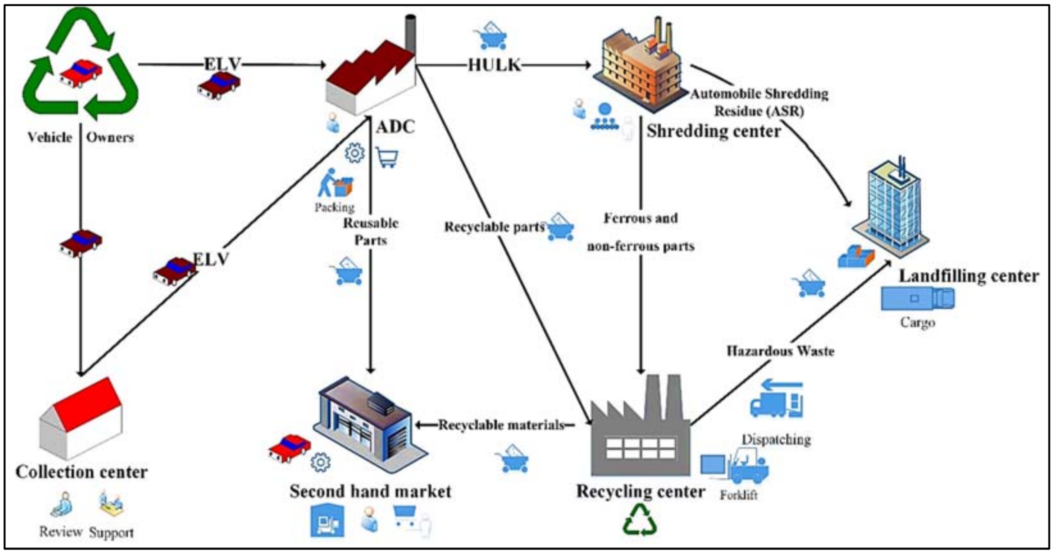


Figure 3.1 Recycling process network of ELV in Turkey

In this study, the following assumptions have been made in developing the mathematical model to consider the current ELV directives of Turkey:

1. The last owners are responsible for returning their vehicles to the collection centers.

2. Manufacturers are responsible for taking ELV back from the last owners without any charge.

3. The centers of 39 districts of Istanbul are accepted as ELV sources.

4. The distances between the facilities are determined via Google Maps as the longest driving distance from each other due to restrictions with the heavyweight highway transportation in Istanbul.

5. The reusable/recyclable materials are merchandised by the second hand markets and/or the materials suppliers.

6. The generated ELVs in the ELV sources are transferred to the collection or dismantling centers.

7. The generated ELVs are transferred via road transportation. The capacities of vehicles are not taken into account.

8. The candidate locations of shredder and ADCs (Authorized Dismantler Center) are determined from the existing facilities.

The proposed model is formulated as following:

3.1.1 Indices

I, i indices of ELV owners, i = 1, 2, …, I

J, j indices collection centers, j = 1, 2, …, J

K, k indices of ADC, k = 1, 2, …, K

L, l indices of shredder centers, l = 1, 2, …, L

M, m indices of second-hand markets, m = 1, 2, …, M

N, n indices of recovery centers for ferrous and non-ferrous materials, n = 1, 2, …, N

P, p indices of recovery centers for fluids, p = 1, 2, …, P

R, r indices of recovery centers for tyres, r = 1, 2, …, R

S, s indices of recovery centers for batteries, s = 1, 2, …, S

U, u indices of landfilling centers, u = 1, 2, …, U

T, t time periods, t = 1, 2, …, T

Ω, ω scenario, ω = 1, 2, …, Ω

3.1.2 Parameters

p_{ω}: *occurrence probability for scenario ω (0 ≤ p_{ω}≤ 1)*

R_{it}^{ω}: *ELVs collected from ELV owner i in period t and scenario ω (ton)*

f_k: *fixed-cost for ADC k (₺)*

f_l: *fixed-cost for shredder center l (₺)*

dc_{kt}: *dismantling cost at ADC k in period t (₺/ton)*

sc_{lt}: *shredding cost at shredder center l in period t (₺/ton)*

lc_{ut}: *disposal cost at landfilling center u in period t (₺/ton)*

rc_{pt}: *fluid recovery cost at fluid recovery center p in period t (₺/ton)*

rc_{rt}: *tyre recovery cost at tyre recovery center r in period t (₺/ton)*

rc_{st}: *battery recovery cost at battery recovery center facility s in period t (₺/ton)*

s_{1t}: *selling price of ferrous material from ADC to second-hand markets in period t (₺/ton)*

s_{2t}: *selling price of non- ferrous material from ADC to second- hand markets in period t (₺/ton)*

s_{3t}: *selling price of fluid from ADC to second-hand markets in period t (₺/ton)*

s_{4t}: *selling price of battery from ADC to second-hand markets in period t (₺/ton)*

s_{5t}: *selling price of other type of materials (i.e. glass, plastic, textile et al.) from ADC to second-hand markets in period t (₺/ton)*

z_{1t}: *selling price of ferrous material from shredder centers to recovery centers in period t (₺/ton)*

z_{2t}: *selling price of non-ferrous material from shredder centers to recovery centers in period t (₺/ton)*

t_{ijt}: *transportation cost from ELV owner i to collection center j in period t (₺/ton)*

t_{ikt}: *transportation cost from ELV owner i to ADC k in period t (₺/ton)*

t_{jkt}: *transportation cost from collection center j to ADC k in period t (₺/ton)*

t_{klt}: *transportation cost from ADC k to shredder center l in period t (₺/ton)*

t_{kpt}: *transportation cost from ADC k to fluid recovery center p in period t (₺/ton)*

t_{krt}: *transportation cost from ADC k to tyre recovery center r in period t (₺/ton)*

t_{kst}: *transportation cost from ADC k to battery recovery center s in period t (₺/ton)*

t_{lut}: *transportation cost from shredder center l to landfilling center u in period t (₺/ton)*

d_{ij}: *driving distance between ELV owner i and collection center j (km)*

d_{ik}: *driving distance between ELV owner i and ADC k (km)*

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

d_{kl}: *driving distance between ADC k and shredder center l (km)*

d_{kp}: *driving distance between ADC k and fluid recovery center p (km)*

d_{kr}: *driving distance between ADC k and tyre recovery center r (km)*

d_{ks}: *driving distance between ADC k and battery recovery center s (km)*

d_{lu}: *driving distance between shredder center l and landfilling center u (km)*

cap_{jt}: *annual capacity of collection center j in period t (ton)*

cap_{kt}: *annual capacity of ADC k in period t (ton)*

cap_{lt}: *annual capacity of shredder center l in period t (ton)*

cap_{pt}: *annual capacity of fluid recovery center p in period t (ton)*

cap_{rt}: *annual capacity of tyre recovery center r in period t (ton)*

cap_{st}: *annual capacity of battery recovery center s in period t (ton)*

cap_{ut}: *annual capacity of landfilling center u in period t (ton)*

α: *ratio of hulk to ELV* ($0 \leq \alpha \leq 1$)

β: *ratio of ASR to hulk* ($0 \leq \beta \leq 1$)

μ_1: *ratio of reusable ferrous materials to ELV* ($0 \leq \mu_1 \leq 1$)

μ_2: *ratio of reusable non-ferrous materials to ELV* ($0 \leq \mu_2 \leq 1$)

μ_3: *ratio of reusable fluids to ELV* ($0 \leq \mu_3 \leq 1$)

μ_4: *ratio of reusable batteries to ELV* ($0 \leq \mu_4 \leq 1$)

μ_5: *ratio of reusable other materials (i.e. glass, plastic et al.) to ELV* ($0 \leq \mu_5 \leq 1$)

λ_1: *ratio of non-reusable fluids to ELV* ($0 \leq \lambda_1 \leq 1$)

λ_2: *ratio of non-reusable tyres to ELV* ($0 \leq \lambda_2 \leq 1$)

λ_3: *ratio of non-reusable batteries to ELV* ($0 \leq \lambda_3 \leq 1$)

γ_1: *ratio of ferrous materials to hulk* ($0 \leq \gamma_1 \leq 1$)

γ_2: *ratio of non-ferrous materials to hulk* ($0 \leq \gamma_2 \leq 1$)

3.1.3 Decision Variables

FC: *total fixed cost (₺)*

TC: *total transportation cost (₺)*

OC: *total operational cost (₺)*

RV: *total revenue (₺)*

A_{ijt}^{ω}: *weight of ELV transferred from ELV owner i to collection center j in scenario ω*

B_{ikt}^{ω}: *weight of ELV transferred from ELV owner i to ADC k in period t and scenario ω*

X_{jkt}^{ω}: *weight of ELV transferred from collection center j to ADC k in period t and scenario ω*

Y_{klt}^{ω}: *weight of hulk transferred from ADC k to shredder center l in period t and scenario ω*

Z_{lut}^{ω}: *weight of ASR transferred from shredder center l to landfilling center u in period t and scenario ω*

V_{kpt}^{ω}: *weight of non-reusable fluid transferred from ADC k to fluid recovery center p in period t and scenario ω*

W_{krt}^{ω}: *weight of non-reusable tyre transferred from ADC k to tyre recovery center r in period t and scenario ω*

U_{kst}^{ω}: *weight of non-reusable battery transferred from dismantler facility k to battery recovery facility s in period t and scenario ω*

Q_{1kmt}^{ω}: *weight t of ferrous material transferred from ADC k to second-hand market m in period t and scenario ω*

Q_{2kmt}^{ω}: *weight of non-ferrous material transferred from ADC k to second-hand market m in period t and scenario ω*

Q_{3kmt}^{ω}: *weight of fluid transferred from ADC k to second-hand market m in period t and scenario ω*

Q_{4kmt}^{ω}: *weight of battery transferred from ADC k to second-hand market m in period t and scenario ω*

Q_{5kmt}^{ω}: *weight of other materials transferred from ADC k to second-hand market m in period t and scenario ω*

P_{1lnt}^{ω}: *weight of ferrous material transferred from shredder center l to recovery center n in period t and scenario ω*

P_{2lnt}^{ω}: *weight of non-ferrous material transferred from shredder center l to recovery center n in period t and scenario ω*

e_{kt}: *binary decision variable for opening ADC k in period t*

e_{lt}: *binary decision variable for opening shredder center l in period t*

e_k: *binary fixed-cost decision variable for opening ADC k*

e_l: *binary fixed-cost decision variable for opening shredder center l*

3.1.4 Formulation of the Stochastic Mathematical Model

$$Min\ FC + TC + OC - PR \tag{3.1}$$

$$FC = \sum_{k=1}^{K} f_k . e_k + \sum_{l=1}^{L} f_l . e_l \tag{3.2}$$

$$\begin{aligned} TC = \sum_{\omega=1}^{\Omega} p_\omega \Bigg(& \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} t_{ijt}\, A_{ijt}^{\omega} . d_{ij} + \sum_{i}^{I}\sum_{k}^{K}\sum_{t}^{T} t_{ikt} . B_{ikt}^{\omega} . d_{ik} \\ & + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} t_{jkt} . X_{jkt}^{\omega} . d_{jk} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} t_{klt} . Y_{klt}^{\omega} . d_{kl} \\ & + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} t_{kpt} . V_{kpt}^{\omega} . d_{kp} + \sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{t=1}^{T} t_{krt} . W_{krt}^{\omega} . d_{kr} \\ & + \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{t=1}^{T} t_{kst} . U_{kst}^{\omega} . d_{ks} + \sum_{l=1}^{L}\sum_{u=1}^{U}\sum_{t=1}^{T} t_{lut} . Z_{lut}^{\omega} . d_{lu} \Bigg) \end{aligned} \tag{3.3}$$

$$\begin{aligned} OC = \sum_{\omega=1}^{\Omega} p_\omega \Bigg(& \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} B_{ikt}^{\omega} . dc_{kt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} X_{jkt}^{\omega} . dc_{kt} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} sc_{lt} . Y_{klt}^{\omega} \\ & + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} rc_{pt} . V_{kpt}^{\omega} + \sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{t=1}^{T} rc_{rt} . W_{krt}^{\omega} \\ & + \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{t=1}^{T} rc_{st} . U_{kst}^{\omega} + \sum_{l=1}^{L}\sum_{u=1}^{U}\sum_{t=1}^{T} lc_{ut} . Z_{lut}^{\omega} \Bigg) \end{aligned} \tag{3.4}$$

$$\begin{aligned} PR = \sum_{\omega=1}^{\Omega} p_\omega \Bigg(& \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{t=1}^{T} (s_{1t} . Q_{1kmt}^{\omega} + s_{2t} . Q_{2kmt}^{\omega} + s_{3t} . Q_{3kmt}^{\omega} + s_{4t} . Q_{4kmt}^{\omega} \\ & + s_{5t} . Q_{5kmt}^{\omega}) + \sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{t=1}^{T} (z_{1t} . P_{1lnt}^{\omega} + z_{2t} . P_{2lnt}^{\omega}) \Bigg) \end{aligned} \tag{3.5}$$

$$\sum_{j=1}^{J} A_{ijt}^{\omega} + \sum_{k=1}^{K} B_{ikt}^{\omega} = R_{it}^{\omega} \quad \forall \omega, i, t \tag{3.6}$$

$$\sum_{i=1}^{I} A_{ijt}^{\omega} = \sum_{k=1}^{K} X_{jkt}^{\omega} \quad \forall \omega, j, t \tag{3.7}$$

$$\sum_{l=1}^{L} Y_{klt}^{\omega} = \alpha . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.8}$$

$$\sum_{m=1}^{M} Q_{1kmt}^{\omega} = \mu_1 . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.9}$$

$$\sum_{m=1}^{M} Q_{2kmt}^{\omega} = \mu_2 . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.10}$$

$$\sum_{m=1}^{M} Q_{3kmt}^{\omega} = \mu_3 . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.11}$$

$$\sum_{m=1}^{M} Q_{4kmt}^{\omega} = \mu_4 . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.12}$$

$$\sum_{m=1}^{M} Q_{5kmt}^{\omega} = \mu_5 . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.13}$$

$$\sum_{p=1}^{P} V_{kpt}^{\omega} = \lambda_1 . \left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega} \right) \quad \forall \omega, k, t \tag{3.14}$$

$$\sum_{r=1}^{R} W_{krt}^{\omega} = \lambda_2.\left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega}\right) \quad \forall \omega, k, t \tag{3.15}$$

$$\sum_{s=1}^{S} U_{kst}^{\omega} = \lambda_3.\left(\sum_{j=1}^{J} X_{jkt}^{\omega} + \sum_{i=1}^{I} B_{ikt}^{\omega}\right) \quad \forall \omega, k, t \tag{3.16}$$

$$\sum_{u=1}^{U} Z_{lut}^{\omega} = \beta.\sum_{k=1}^{K} Y_{klt}^{\omega} \quad \forall \omega, l, t \tag{3.17}$$

$$\sum_{n=1}^{N} P_{1lnt}^{\omega} = \gamma_1.\sum_{k=1}^{K} Y_{klt}^{\omega} \quad \forall \omega, l, t \tag{3.18}$$

$$\sum_{n=1}^{N} P_{2lnt}^{\omega} = \gamma_2.\sum_{k=1}^{K} Y_{klt}^{\omega} \quad \forall \omega, l, t \tag{3.19}$$

$$\sum_{i=1}^{I} A_{ijt}^{\omega} \leq cap_{jt} \quad \forall \omega, j, t \tag{3.20}$$

$$\sum_{i=1}^{I} B_{ikt}^{\omega} + \sum_{j=1}^{J} X_{jkt}^{\omega} \leq cap_{kt}.e_{kt} \quad \forall \omega, k, t \tag{3.21}$$

$$\sum_{k=1}^{K} Y_{klt}^{\omega} \leq cap_{lt}.e_{lt} \quad \forall \omega, l, t \tag{3.22}$$

$$\sum_{k=1}^{K} V_{kpt}^{\omega} \leq cap_{pt} \quad \forall \omega, p, t \tag{3.23}$$

$$\sum_{k=1}^{K} W_{krt}^{\omega} \leq cap_{rt} \quad \forall \omega, r, t \tag{3.24}$$

$$\sum_{k=1}^{K} U_{kst}^{\omega} \leq cap_{st} \quad \forall \omega, s, t \tag{3.25}$$

$$\sum_{l=1}^{L} Z_{lut}^{\omega} \leq cap_{ut} \quad \forall \omega, u, t \tag{3.26}$$

$$e_{kt} \leq e_{kt+1} \quad \forall k, t \leq T-1 \tag{3.27}$$

$$e_{lt} \leq e_{lt+1} \quad \forall l, t \leq T-1 \tag{3.28}$$

$$\sum_{t=1}^{T} e_{kt} \leq M_1.\ e_k\ \forall k \tag{3.29}$$

$$\sum_{t=1}^{T} e_{lt} \leq M_1.\ e_l\ \forall k \tag{3.30}$$

$$p_{\omega}, A_{ijt}^{\omega}, B_{ikt}^{\omega}, X_{jkt}^{\omega}, Y_{klt}^{\omega}, Z_{lut}^{\omega}, V_{kpt}^{\omega}, W_{krt}^{\omega}, U_{kst}^{\omega}, P_{1lnt}^{\omega}, P_{2lnt}^{\omega}, Q_{1kmt}^{\omega}, Q_{2kmt}^{\omega}, Q_{3kmt}^{\omega}, Q_{4kmt}^{\omega}, Q_{5kmt}^{\omega} \geq 0 \quad \forall \omega, i, j, k, l, m, n, p, r, s, u, t \tag{3.31}$$

$$e_k, e_l, e_{kt}, e_{lt}\ \{0,1\} \qquad \forall\ k, l, t \tag{3.32}$$

The mathematical model consists of thirty equations. The objective function (3.1) has four sub-components, which are fixed-cost (FC), transportation cost (TC), operating cost (OC) and revenue (RV). FC represents fixed costs needs to be compromised to set up new dismantling and shredding center (3.2). TC represents the cost of transportation in the whole network (3.3). OC represents the cost of dismantling, shredding, recovering and disposal operations in the network (3.4). Apart from cost components, RV represents total revenue comes from selling reusable/remanufacturable, ferrous-non-ferrous items of ELV to second-hand markets and recycling facilities (3.5). Equation (3.6-3.19) represents the balance equations in the network. Equation (3.6) represents amount of ELV transferred from sources to collection centers and ADCs. Equations (3.7-3.16) secure the amount of transported ELV from ADCs to shredding centers, second-hand markets and recycling centers. Equations (3.17-3.19) provide the balance of material amounts transported from shredding centers to landfilling and recycling facilities. Equations (3.20-3.26) secure that amount of ELV transported must be less than or equal to the capacity of collection centers, ADCs, shredding centers, recycling centers in the network. Equations (3.27-3.28) provide that dismantling and shredding facilities opened in a specific time period must not be closed in the next time periods. Equation (3.29-3.30) ensure the harmony of binary variables. M_1 refers a large number. Equation (3.31) secures the non-negativity of the decision variables. Equation (3.32) presents the binary variables in the model.

3.2 Description of the Case Study and Data Collection

Istanbul is one of the most crucial cities in Turkey with its higher population and bigger economy. According to report of Turkish Statistical Institute, there are 15067724 inhabitants living in Istanbul and it is the most populous city in Turkey (TUIK, 2018c). Istanbul consists of thirty-nine districts. In this study, centers of the districts are assumed as ELV sources. There are fifty-two collection centers, five ADCs, four shredder facilities are active and working with the license of The Ministry of Environment and Urbanization of Turkey. Thus, three recycling centers and twenty-nine second-hand markets are located within the different parts of Istanbul (Kuşakçı et al., 2019). Figure 3.2 represents the regions and facilities of Istanbul.

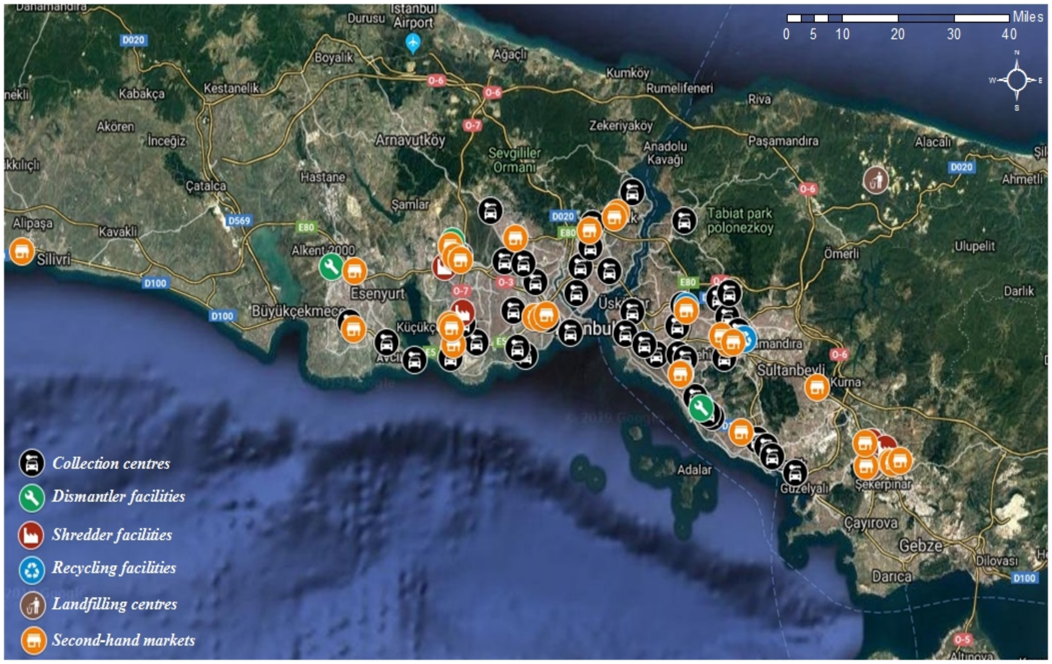


Figure 3.2 Locations for the current members of ELV network in Istanbul

During estimation of the parameters, data was collected through field studies, interviews with experts from both academy and industry, technical reports published by ministries and institutes and literature survey.

It is assumed that the opening cost of dismantler facility is 887500₺ (Kuşakçı et al., 2019) and opening cost of shredder facility is 2500000₺ (Ene and Öztürk, 2015; Demirel et al., 2016).

Average weight of an ELV is assumed as 1000 kg according to Özceylan et al. (2017). The unit operating costs of each dismantler facility, shredder facility, recycling facility and landfilling centre are assumed as 980 ₺/ton, 135 ₺/ton, 500 ₺/ton and 250₺/ton, respectively (Kuşakçı et al., 2019; Özceylan et al., 2017). Assumptions of fixed-cost, transportation cost and operation cost items of the model is presented in Table 3.1 and Table 3.2.

Table 3.1 Assumed cost items in the network

Cost items					
Fixed-cost		Transportation cost		Operation cost	
f_k (₺)	2500000	t_{ijt} (₺/km-ton)	1.0	dc_{kt} (₺/ton)	980
f_{lt} (₺)	887500	t_{ikt} (₺/km-ton)	1.0	sc_{lt} (₺/ton)	135
		t_{jkt} (₺/km-ton)	0.4	lc_{ut} (₺/ton)	250
		t_{klt} (₺/km-ton)	0.2	rc_{pt} (₺/ton)	450
		t_{kpt} (₺/km-ton)		rc_{rt} (₺/ton)	500
		t_{krt} (₺/km-ton)		rc_{st} (₺/ton)	500
		t_{kst} (₺/km-ton)	0.5		
		t_{lut} (₺/km-ton)			

Table 3. 2 Assumed prices of reusable/recycled components/materials

Prices (₺/ton)						
s_{1t}	s_{2t}	s_{3t}	s_{4t}	s_{5t}	z_{1t}	z_{2t}
1200	6000	6250	3100	6000	250	750

According to Wong et al. (2018), decomposition components of ELV are; ferrous metals (69%), non-ferrous metals (7%), plastics and process polymers (%13.5), tyres (4%), glass (3%), textiles (1.3%), fluids (1.2%) and rubber (1%). The ratio of hulk to ELV after disassembling operations is 81% and the ratio of ASR to hulk is assumed as 18.5% (Kuşakçı et al., 2019). In this study, material composition rate assumptions from Kuşakçı et al. (2019) and Demirel et al. (2016) are used. Table 3.3 presents assumed composition rates of ELV.

Table 3.3 Assumed composition rates of ELV

Composition rates of ELV											
α	β	μ_1	μ_2	μ_3	μ_4	μ_5	λ_1	λ_2	λ_3	γ_1	γ_2
0.81	0.185	0.06	0.04	0.005	0.001	0.03	0.012	0.03	0.012	0.765	0.05

Capacities of collection centres, dismantler facilities, shredder facilities and landfilling centres are considered as 1000 tons/year, 17600 tons/year, 22500 tons/year and 25000 tons/year respectively. Capacity assumptions for fluid and tyre recycling facilities are 7300 tons/year and battery recycling facilities are 25000 tons/year (Özceylan et al., 2017). Table 3.4 presents capacity assumptions for the facilities in the network.

Table 3.4 Assumed capacities of the facilities

Capacities (ton/year)						
cap_{jt}	cap_{kt}	cap_{lt}	cap_{pt}	cap_{rt}	cap_{st}	cap_{ut}
1000	19800	22500	7300	7300	25000	25000

In this model, estimated amount of ELV from 2019 to 2028 are aimed to be generated by GDP-dependant Gompertz function as first step. The car ownership equation of Gompertz function is presented in Equation 3.33. In this equation C_t represents car ownership per capita, GDP_t represents income per capita, γ represents saturation level and α and β represent negative parameters defining the curative shape of the function (Dargey and Gately, 1997).

$$C_t = \gamma . e^{\alpha . e^{\beta . GDP_t}} \quad (3.33)$$

It is assumed that there is no international trade of used cars. Estimated values of γ, α and β are obtained from Demirel et al. (2016) as 246.15, -9.761 and -1.785 respectively. GDP data for Turkey in time period of 1990-2018 is collected from World Bank (World Bank, 2019). GDP data for the time of 2019-2029 is calculated via GDP change rate data obtained from IMF (IMF, 2019) and PWC (PWC, 2017) reports.

Equation 3.34 calculates the stock of cars. P_t represents population in year t. Historical population data for 39 districts of Istanbul in the time period of 1995-2018 and expected population growth rate in the time period of 2019-2029 are taken from database of TUIK and Istanbul Metropolitan Municipality.

Estimated amount of ELV collected from 39 districts of Istanbul is distributed to the districts proportionally to their population rates in Istanbul.

$$S_t = C_t . P_t \tag{3.34}$$

Equation 3.35 calculates the lifetime of a specific vintage of cars by Weibull distribution. λ and k represent positive scale and shape parameters. θ represents the location parameter of Weibull distribution. T represents the age of cars, F(T) represents the lifecycle function of cars for vintage υ still in operation in year t, ($T = t - \upsilon$). Estimated values of θ, λ and k are taken as 0, 33.44 and 3.3 respectively from Demirel et al. (2016).

$$F(T) = e^{-(\frac{T-\theta}{\lambda})^k} \text{ and } F(T) = 1 \text{ for } T \leq \theta \tag{3.35}$$

Equation 3.36 calculates remaining stock of a vintage υ car in year t. $S_{\upsilon,\upsilon}$ represents the initial stock of vintage υ cars.

$$S_{\upsilon,t} = S_{\upsilon,\upsilon} . F(t-\upsilon) \tag{3.36}$$

Equation 3.37 calculates ELV of vintage υ cars in the year t.

$$ELV_{\upsilon,t} = S_{\upsilon,t-1} - S_{\upsilon,t} \tag{3.37}$$

Equation 3.38 calculates the total quantity of ELV in year t.

$$ELV_t = \sum_{\upsilon} ELV_{\upsilon,t} \tag{3.38}$$

Equation 3.39 calculates the quantity of new cars in year t.

$$S_{t,t} = S_t - S_{t-1} + ELV_t \tag{3.39}$$

Although GDP-dependant Gompertz function is a well-known forecasting approach for predicting amount of ELVs generated in the future, three other forecasting approaches are applied individually and their validities are questioned by calculating their R^2, MAPE (Mean Absolute Percentage Error) and MAD (Mean Absolute Deviation) values. These approaches are Moving Average (m=3), Single Exponential Smoothing, Regression Analysis (parameters of GDP, number of accidents in a year, population of the city for a year, number of registered vehicles in the traffic are used as continuous predictors). These approaches are applied via Minitab 19 Statistical Software. Table 3.5 shows that Moving Average has the highest accuracy scores. For this reason, Moving Average is selected for forecasting the number of ELVs generated in Istanbul for the next ten years of time period.

Table 3.5 Comparison for accuracy values of the forecasting approaches

Forecasting Approach	R^2 (%)	*MAPE*	*MAD*
Moving Average	54	30	13252
Single Exp. Smoothing	21	33	16577
Regression Analysis	18	35	16978
Gompertz Function	-1.53	70	35005

Table 3.6 presents the estimated amount of ELV generated in Istanbul within the time period of 2019 -2028.

Table 3.6 Estimated amount of ELVs in Istanbul

Year	Estimated Amount of ELV in Istanbul (Ton)
2019	34668
2020	39066
2021	40216
2022	37984
2023	39089
2024	39096
2025	38723
2026	38969
2027	38929
2028	38874

4
CONCLUSION AND MANAGERIAL IMPLICATIONS

4.1 Computational Results

The scenario-based stochastic model presented above resulted in a problem with 62 blocks of equations, 56 blocks of variables, 1594863 non-zero elements, 33673 single equations, 249632 single variables and 99 discrete variables. The model is solved on GAMS 23.5 software and CPLEX is used as solver. The model is solved to optimality on an Intel Core i7 processor within 8.003 CPU seconds.

In the first computation, our mathematical model was solved to optimality with seven scenario (ω = A, B, C, D, E, F, G) and p_ω (occurrence probability for scenario ω) was assumed as 0.143 for each scenario. In this assumption, the objective function attains the value of 185087909₺. The components of the objective function attain values as; 10162500₺ for FC (fixed cost), 7672609₺ for TC (transportation cost), 436795500₺ for OC (operational cost) and 269542700₺ for RV (total revenue). Figure 4.1 presents cost and revenue items in the object function.

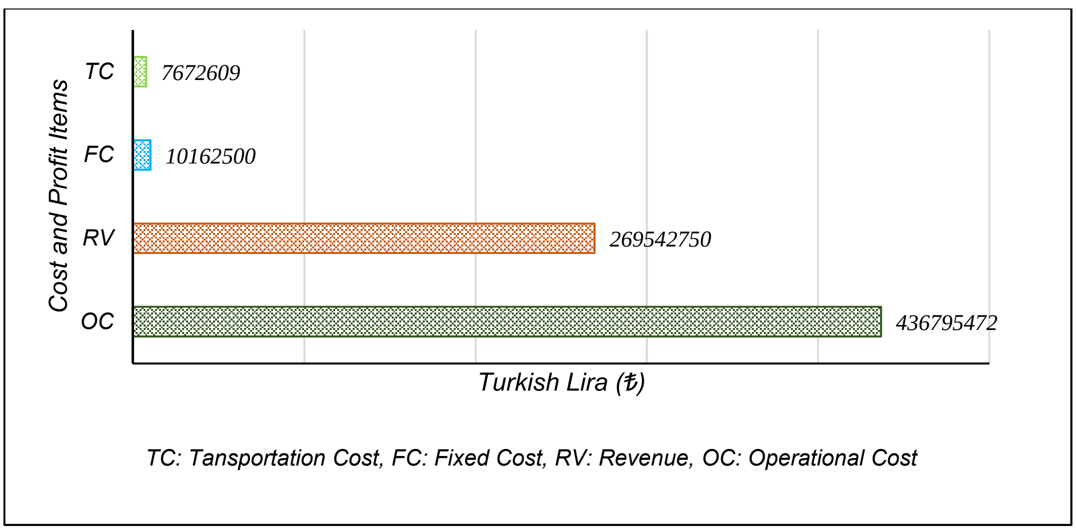


Figure 4.1 Distribution of cost items in the objective function

If we look closer at the components of the objective function, OC has the highest proportion as 96.22% in the cost items. The proportions of the other cost items are as fixed-cost; 2.08%, transportation cost; 1.70% simultaneously. It can be observed from the decomposition of the cost items that the operational cost (OC) has the highest proportion. If we look closer to the decomposition of cost item (Figure 4.2), proportions and values are as dismantling cost; 81.65% and 371188800₺, shredding cost; 9.11% and 41417850₺, landfilling cost; 3.12% and 14189450₺ recycling cost; 2.20% and 9999372₺, fixed-cost; 2.24% and 10162500₺, transportation cost; 1.69% and 7672609₺. Figure 4.2 presents decomposition of cost items in the objective function.

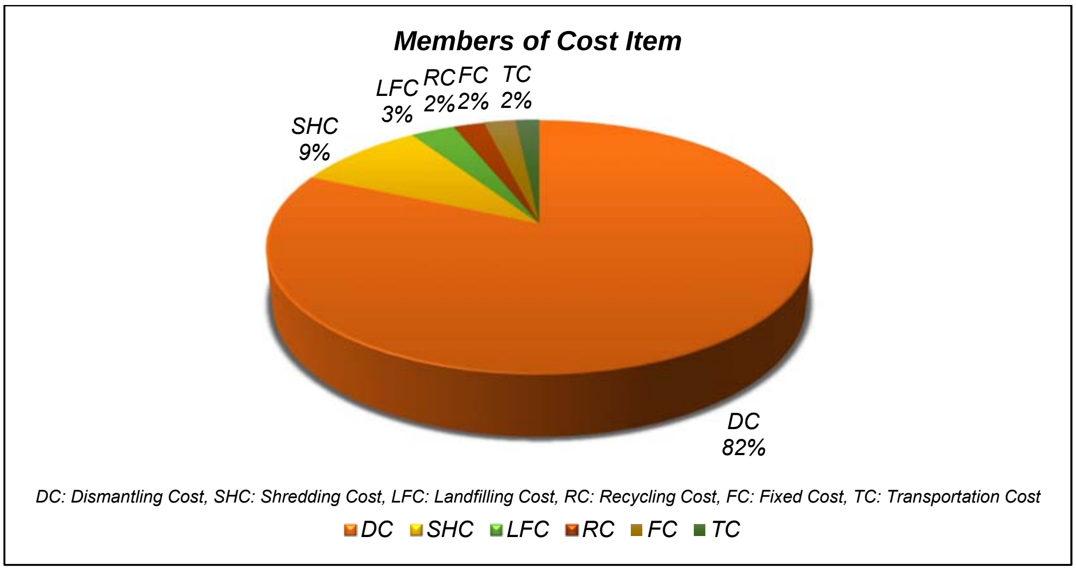


Figure 4.2 Decomposition of the cost items in the objective function

On the other hand, total profit comprises of revenue come from sales of dismantlers to second-hand markets (74% and 199362500₺) and from sal

es of shredder facilities to recycling facilities (26% and 70180250₺). Decomposition of revenue item shows that sales of dismantler facilities to the second-hand markets has the highest proportion and value. Figure 4.3 presents decomposition of total revenue item in the cost function.

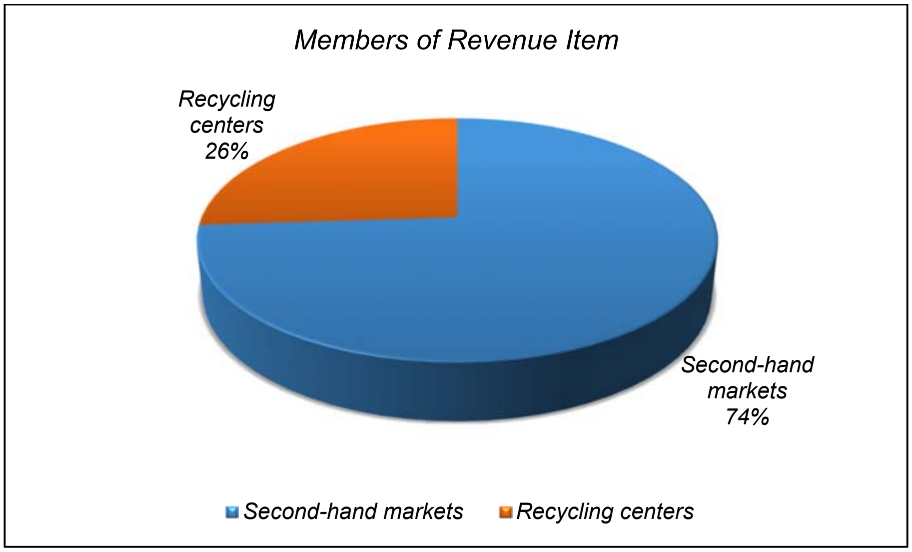


Figure 4.3 Decomposition of total revenue in the objective function

According to the results of optimal solution, three of the five dismantling facilities and three of the four shredding facilities must be opened in 10 years of time period. Total amount of ELV that must be collected by 34 collection centers are 180032 tons for ω=A, 229132 tons for ω=B, 274942 tons for ω=C, 321755 tons for ω=D, 356672 tons for ω=E, 376904 tons for ω=F and 406073 tons for ω=G (Table 4.1). The rest of ELVs (27416 tons for ω=A, 34893 tons for ω=B, 45660 tons for ω=C, 63859 tons for ω=D, 77085 tons for ω=E, 113431 tons for ω=F and 140838 tons for ω=G) must be transported to the dismantler facilities (ADCs) directly (Table 4.2).

Table 4.1 Material flow between ELV owners and collection centers (A_{ij})

ELV sources	Collection center			ELV sources	Collection center	
I_3	J_{21}			I_{10}	J_{42}	J_{46}
	A. 6170				A. 2614	A. 5067
	B. 7853				B. 3327	B. 6754
	C. 9536				C. 4040	C. -
	D. 9451				D. 4753	D. -
	E. 6561				E. 5466	E. -
	F. 2244				F. 5917	F. 262
	G. 6347				G. 2551	G. 4340
I_4	J_{16}	J_{22}	J_{40}	I_{11}	J_{24}	
	A. 5055	A. -	A. -		A. 3431	
	B. 6434	B. -	B. -		B. 4367	
	C. 7812	C. -	C. -		C. 5303	
	D. 9919	D. 304	D. -		D. 6239	
	E. 10000	E. 57	E. 512		E. 7175	
	F. 9932	F. -	F. 1847		F. 8111	
	G. 10000	G. -	G. 206		G. 9047	

Table 4.1 Material flow between ELV owners and collection centers (A_{ij}) (continued)

ELV sources	Collection center				ELV sources	Collection center				
I_6	J_7	J_{20}			I_{12}	J_{36}				
	A. 7413	A. -				A. 2750				
	B. 9435	B. -				B. 3500				
	C. 10000	C. 1457				C. 1780				
	D. 10000	D. 4992				D. 72				
	E. 10000	E. 5500				E. -				
	F. 10000	F. 7522				F. -				
	G. 10000	G. 9544				G. -				
I_7	J_{20}	J_{22}	J_{29}		I_{13}	J_{32}				
	A. -	A. 1855	A. 1236			A. 3394				
	B. -	B. 1967	B. 1967			B. 4319				
	C. -	C. 2607	C. 2170			C. 5245				
	D. -	D. 562	D. 5690			D. 6171				
	E. -	E. -	E. 6464			E. 7097				
	F. 2337	F. 1932	F. 3038			F. 8022				
	G. 273	G. 2354	G. 5523			G. 8948				
I_8	J_{37}				I_{14}	J_{36}				
	A. 4003					A. 3298				
	B. 5095					B. 4197				
	C. 6187					C. 5096				
	D. 8096					D. 5996				
	E. 8370					E. 6895				
	F. 8340					F. 7795				
	G. 9214					G. 8694				
I_9	J_4	J_{23}			I_{15}	J_{36}	J_{40}			
	A. 4161	A. -				A. 1134	A. -			
	B. 5295	B. -				B. 1444	B. -			
	C. 6430	C. -				C. 1753	C. -			
	D. 8415	D. -				D. 575	D. 1487			
	E. 8700	E. -				E. -	E. 2372			
	F. 9835	F. -				F. -	F. 2682			
	G. 10000	G. 970				G. -	G. 2991			
I_{16}	J_{10}				I_{24}	J_{18}	J_{42}		J_{51}	
	A. 3586					A. 6665	A. -		A. -	
	B. 4564					B. 8483	B. -		B. -	
	C. 5543					C. 9926	C. -		C. 374	
	D. 6521					D. 10000	D. -		D. 2118	
	E. 7499					E. 10000	E. 2300		E. 1636	
	F. 8477					F. 10000	F. 3560		F. 2193	
	G. 9455					G. 9875	G. 7433		G. 263	
I_{17}	J_{26}	J_{50}			I_{25}	J_{14}	J_{44}			
	A. 7115	A. -				A. 6314	A. -			
	B. 9055	B. -				B. 8037	B. -			
	C. 9988	C. 1007				C. 9741	C. 17			
	D. 10000	D. 2936				D. 10000	D. 1481			
	E. 10000	E. 4876				E. 10000	E. 3203			
	F. 10000	F. 6817				F. 10000	F. 4926			
	G. 10000	G. 8684				G. 10000	G. 6648			
I_{18}	J_5	J_{36}	J_{40}	J_{50}	I_{26}	J_{16}	J_{22}	J_{25}	J_{29}	J_{37}
	A. 4539	A. 2817	A. 7115	A. -		A. -	A. 855	A. 10000	A. 583	A. -
	B. 8504	B. 858	B. 9055	B. -		B. -	B. 3578	B. 10000	B. 980	B. -
	C. 10000	C. 1368	C. 9988	C. -		C. -	C. 2842	C. 10000	C. 4836	C. -
	D. 10000	D. 3354	D. 10000	D. 20		D. -	D. 9134	D. 10000	D. 1664	D. -
	E. 10000	E. 3104	E. 10000	E. 2277		E. -	E. 9943	E. 10000	E. 3388	E. 586
	F. 10000	F. 2204	F. 10000	F. 5171		F. 67	F. 8067	F. 10000	F. 6961	F. 1659
	G. 10000	G. 1305	G. 6802	G. 910		G. -	G. 7645	G. 10000	G. 4476	G. 785

Table 4.1 Material flow between ELV owners and collection centers (A_{ij}) (continued)

ELV sources	Collection center				Collection center			
I_{20}	J_{19}	J_{52}		I_{27}	J_{11}	J_{28}		J_{35}
	A. -	A. 7305			A. 8028	A. -		A. -
	B. -	B. 9297			B. 9918	B. -		B. 298
	C. 1289	C. 10000			C. 10000	C. -		C. 2406
	D. 3282	D. 10000			D. 10000	D. -		D. 4596
	E. 5274	E. 10000			E. 10000	E. -		E. 6785
	F. 552	F. 1261			F. 10000	F. 411		F. 8564
	G. -	G. -			G. 10000	G. 5544		G. 5620
I_{21}	J_{4}	J_{33}		I_{28}	J_{27}	J_{34}	J_{35}	J_{43}
	A. -	A. 6872			A. 5186	A. -	A. -	A. 4774
	B. -	B. 8747			B. 3873	B. -	B. -	B. 8804
	C. 666	C. 9954			C. 2560	C. -	C. -	C. 10000
	D. 1464	D. 10000			D. 3787	D. -	D. -	D. 10000
	E. 1299	E. 10000			E. 7260	E. -	E. -	E. 10000
	F. 164	F. 10000			F. 9675	F. 10000	F. 1141	F. 10000
	G. 9214	G. 9214			G. 9993	G. 1887	G. 4379	G. 10000
I_{22}	J_{17}	J_{23}	J_{31}	I_{29}	J_{3}	J_{10}	J_{15}	J_{47}
	A. 5186	A. -	A. -		A. -	A. -	A. 5513	A. -
	B. 6600	B. -	B. -		B. -	B. -	B. 7017	B. -
	C. 8014	C. -	C. -		C. -	C. -	C. 8521	C. -
	D. 9429	D. -	D. -		D. -	D. 1026	D. 8998	D. -
	E. 9974	E. -	E. 868		E. -	E. 2300	E. 8858	E. 369
	F. 10000	F. 1769	F. 309		F. 2750	F. 1522	F. 8709	F. 49
	G. 10000	G. 229	G. -		G. 5431	G. 544	G. 8561	G. -
I_{30}	J_{1}	J_{6}		I_{36}	J_{34}			
	A. 5440	A. -			A. 3077			
	B. 6924	B. -			B. 3916			
	C. 8408	C. -			C. 4755			
	D. 9852	D. 39			D. 5594			
	E. 9901	E. 1474			E. 6433			
	F. 3703	F. 9156			F. 7273			
	G. 4343	G. 10000			G. 8112			
I_{32}	J_{21}	J_{27}	J_{47}	I_{37}	J_{9}	J_{13}	J_{21}	J_{30}
	A. -	A. 4813	A. -		A. -	A. -	A. 1209	A. 10000
	B. -	B. 6126	B. -		B. 2120	B. -	B. 2146	B. 10000
	C. -	C. 7439	C. -		C. 6860	C. -	C. 464	C. 10000
	D. -	D. 6212	D. 2539		D. 9832	D. -	D. 549	D. 10000
	E. -	E. 2739	E. 7326		E. 10000	E. -	E. 3438	E. 10000
	F. 1259	F. 324	F. 9793		F. 10000	F. -	F. 6495	F. 10000
	G. 2684	G. 6	G. 10000		G. 10000	G. 8584	G. 968	G. 10000
I_{33}	J_{49}			I_{38}	J_{8}	J_{12}	J_{48}	
	A. 6981				A. -	A. 7460	A. -	
	B. 8886				B. -	B. 9495	B. -	
	C. 9970				C. 1327	C. 10000	C. 202	
	D. 10000				D. 3564	D. 10000	D. -	
	E. 10000				E. 4437	E. 10000	E. 1161	
	F. 10000				F. 6260	F. 10000	F. 1373	
	G. 10000				G. 4682	G. 10000	G. 4986	
I_{34}	J_{15}			I_{39}	J_{2}	J_{31}		
	A. 545				A. -	A. 4501		
	B. 694				B. -	B. 5729		
	C. 843				C. -	C. 6956		
	D. 992				D. -	D. 8184		
	E. 1141				E. 439	E. 8972		
	F. 1290				F. 949	F. 9690		
	G. 1438				G. 1867	G. 10000		

Table 4.1 Material flow between ELV owners and collection centers (A_{ij}) (continued)

ELV sources	Collection center		
I_{35}	J_{18}	J_{32}	J_{51}
	A. 3305	A. -	A. 833
	B. 1516	B. -	B. 3751
	C. 73	C. -	C. 6322
	D. -	D. 48	D. 7476
	E. -	E. 290	E. 8363
	F. -	F. 1977	F. 7806
	G. 124	G. 1051	G. 9736

Table 4.2 Material flow between ELV owners and ADCs (B_{ik})

ELV sources	Dismantler facility	ELV sources	Dismantler facility
I_1	K_3	I_{12}	K_1
	A. 231		A. -
	B. 293		B. -
	C. 356		C. 2469
	D. 468		D. 4927
	E. 482		E. 5750
	F. 545		F. 6500
	G. 608		G. 7250
I_2	K_5	I_{17}	K_5
	A. 2832		A. -
	B. 3605		B. -
	C. 4378		C. -
	D. 5728		D. -
	E. 5923		E. -
	F. 6695		F. -
	G. 7468		G. 73
I_3	K_3	I_{18}	K_5
	A. -		A. -
	B. -		B. -
	C. -		C. -
	D. 3027		D. -
	E. 6340		E. -
	F. 12340		F. -
	G. 9920		G. 374
I_4	K_1	I_{19}	K_1
	A. -		A. 5072
	B. -		B. 6455
	C. -		C. 7839
	D. -		D. 9222
	E. -		E. 10605
	F. 168		F. 11989
	G. 3120		G. 13372
I_5	K_5	I_{20}	K_1
	A. 8344		A. -
	B. 10620		B. -
	C. 12895		C. -
	D. 16875		D. -
	E. 17447		E. -
	F. 19722		F. 15453
	G. 21998		G. 19259

Table 4.2 Material flow between ELV owners and ADCs (B_{ik}) (continued)

ELV sources	Dismantler facility	ELV sources	Dismantler facility	
I_8	K_5	I_{21}	K_1	K_5
	A. -		A. -	A. -
	B. -		B. -	B. -
	C. -		C. -	C. -
	D. -		D. -	D. 1031
	E. -		E. -	E. 3071
	F. 1122		F. 4754	F. 1326
	G. 1340		G. 8119	G. -
I_{22}	K_1	I_{31}	K_1	
	A. -		A. 2508	
	B. -		B. 3192	
	C. -		C. 3876	
	D. -		D. 4560	
	E. -		E. 5245	
	F. 178		F. 5929	
	G. 3443		G. 6613	
I_{23}	K_3	I_{33}	K_5	
	A. 8427		A. -	
	B. 10726		B. -	
	C. 13024		C. 820	
	D. 15323		D. 2694	
	E. 17621		E. 4598	
	F. 19920		F. 6502	
	G. 22218		G. 8407	
I_{26}	K_5			
	A. -			
	B. -			
	C. -			
	D. -			
	E. -			
	F. 281			
	G. 7249			

Table 4.3 presents the amount of ELV must be transferred from collection centers to ADCs. Total amount is 180032 tons for ω=A, 229132 tons for ω=B, 274942 tons for ω=C, 321755 tons for ω=D, 356672 tons for ω=E, 376904 tons for ω=F and 406073 tons for ω=G.

Table 4.3 Material flow between collection centers and ADCs (X_{jk})

Collection center	ADC				ADC	
J1	K1	K3		J7	K1	K5
	A. -	A. 5440			A. -	A. 7413
	B. -	B. 6924			B. -	B. 9435
	C. -	C. 8408			C. -	C. 10000
	D. -	D. 9852			D. -	D. 10000
	E. -	E. 9901			E. -	E. 10000
	F. -	F. 3703			F. -	F. 10000
	G. 4054	G. 289			G. 8000	G. 2000
J2	K1	K3	K5	J8	K3	
	A. -	A. -	A. -		A. -	
	B. -	B. -	B. -		B. -	
	C. -	C. -	C. -		C. 1327	
	D. -	D. -	D. -		D. 3564	
	E. -	E. 439	E. -		E. 4437	
	F. -	F. 314	F. 635		F. 6260	
	G. 1601	G. -	G. 266		G. 4682	

Table 4.3 Material flow between collection centers and ADCs (X_{jk}) (continued)

Collection center	ADC			ADC
J3	K3		J9	K3
	A. -			A. -
	B. -			B. 2120
	C. -			C. 6860
	D. -			D. 9832
	E. -			E. 10000
	F. 2750			F. 10000
	G. 5431			G. 10000
J4	K5		J10	K3
	A. 4161			A. 3586
	B. 5295			B. 4564
	C. 7097			C. 5543
	D. 9880			D. 7548
	E. 10000			E. 9800
	F. 10000			F. 10000
	G. 10000			G. 10000
J5	K1	K5	J11	K3
	A. -			A. 8028
	B. -			B. 9918
	C. -			C. 10000
	D. -			D. 10000
	E. 7645			E. 10000
	F. 10000			F. 10000
	G. 10000			G. 10000
J6	K5		J12	K3
	A.			A. 7460
	B.			B. 9495
	C.			C. 10000
	D. 39			D. 10000
	E. 1474			E. 10000
	F. 9156			F. 10000
	G. 10000			G. 10000
J14	K3		J20	K5
	A. 6314			A. -
	B. 8037			B. -
	C. 9741			C. 1457
	D. 10000			D. 4992
	E. 10000			E. 5500
	F. 10000			F. 9860
	G. 10000			G. 2700
J15	K3		J21	K3
	A. 6059			A. 7380
	B. 7712			B. 10000
	C. 9364			C. 10000
	D. 9990			D. 10000
	E. 10000			E. 10000
	F. 10000			F. 10000
	G. 10000			G. 10000
J16	K1	K5	J22	K1
	A. -	A. 5054		A. -
	B. -	B. 6433		B. -
	C. -	C. 7812		C. -
	D. -	D. 9919		D. -
	E. 1170	E. 8829		E. -
	F. 10000	F. -		F. 1088
	G. 10000	G. -		G. 9733

Table 4.3 Material flow between collection centers and ADCs (X_{jk}) (continued)

Collection center	ADC			ADC	
J17	K1	K5	J23	K1	K5
	A. -	A. 5186		A. -	A. 10000
	B. -	B. 6600		B. -	B. 10000
	C. -	C. 8014		C. -	C. 10000
	D. -	D. 9429		D. -	D. 10000
	E. -	E. 9974		E. -	E. 10000
	F. -	F. 10000		F. 1769	F. 10000
	G. 642	G. 9357		G. 97	G. 10000
J18	K1	K5	J24	K3	K5
	A. -	A. 9971		A. 3431	A. 10000
	B. -	B. 10000		B. 4367	B. 10000
	C. -	C. 10000		C. 5303	C. 10000
	D. -	D. 10000		D. 6239	D. 10000
	E. -	E. 10000		E. 7175	E. 10000
	F. 9273	F. 726		F. 8111	F. 10000
	G. 10000	G. -		G. 7000	G. 2046
J19	K5		J25	K5	
	A. -			A. 10000	
	B. -			B. 10000	
	C. 1289			C. 10000	
	D. 3282			D. 10000	
	E. 5274			E. 10000	
	F. 552			F. 10000	
	G. -			G. 10000	
J26	K5		J32	K5	
	A. 7115			A. 3394	
	B. 9055			B. 4319	
	C. 9988			C. 5245	
	D. 10000			D. 6220	
	E. 10000			E. 7387	
	F. 10000			F. 10000	
	G. 10000			G. 10000	
J27	K3		J33	K5	
	A. 10000			A. 6872	
	B. 10000			B. 8747	
	C. 10000			C. 9954	
	D. 10000			D. 10000	
	E. 10000			E. 10000	
	F. 10000			F. 10000	
	G. 10000			G. 10000	
J28	K3		J34	K3	
	A. -			A. 3077	
	B. -			B. 3916	
	C. -			C. 7589	
	D. -			D. 9918	
	E. -			E. 10000	
	F. 411			F. 10000	
	G. 5544			G. 10000	
J29	K1	K5	J35	K3	
	A. -	A. 1820		A. -	
	B. -	B. 2947		B. 298	
	C. -	C. 7006		C. 2406	
	D. -	D. 7354		D. 4596	
	E. -	E. 9853		E. 6785	
	F. -	F. 10000		F. 9705	
	G. 8487	G. 1512		G. 10000	

Table 4.3 Material flow between collection centers and ADCs (X_{jk}) (continued)

Collection center	ADC		Collection center	ADC	
J30	K3		J36	K1	
	A. 10000			A. 10000	
	B. 10000			B. 10000	
	C. 10000			C. 10000	
	D. 10000			D. 10000	
	E. 10000			E. 10000	
	F. 10000			F. 10000	
	G. 10000			G. 10000	
J31	K5		J37	K5	
	A. 4501			A. 4003	
	B. 5729			B. 5095	
	C. 6956			C. 6187	
	D. 8184			D. 8096	
	E. 9841			E. 8956	
	F. 10000			F. 10000	
	G. 10000			G. 10000	
J40	K1	K5	J48	K3	
	A. -	A. -		A. -	
	B. -	B. -		B. -	
	C. -	C. -		C. 202	
	D. -	D. 1507		D. -	
	E. 13	E. 5148		E. 1161	
	F. 9000	F. 699		F. 1373	
	G. 10000	G. -		G. 4986	
J42	K3	K5	J49	K5	
	A. 2614	A. -		A. 6981	
	B. 3327	B. -		B. 8886	
	C. 4040	C. -		C. 9970	
	D. 4753	D. -		D. 10000	
	E. 7766	E. -		E. 10000	
	F. 6516	F. 2961		F. 10000	
	G. 669	G. 9315		G. 10000	
J43	K3		J50	K5	
	A. -			A. -	
	B. -			B. -	
	C. 17			C. 1007	
	D. 1481			D. 2936	
	E. 3203			E. 4876	
	F. 4926			F. 6828	
	G. 10000			G. 9595	
J44	K3		J51	K3	K5
	A. -			A. -	A. 833
	B. -			B. -	B. 3751
	C. 17			C. -	C. 6697
	D. 1481			D. -	D. 9595
	E. 3203			E. 2821	E. 7178
	F. 4926			F. 276	F. 9723
	G. 6648			G. -	G. 10000
J46	K5		J52	K3	K5
	A. -			A. 7305	A. -
	B. -			B. 9297	B. -
	C. -			C. 10000	C. -
	D. -			D. 10000	D. -
	E. -			E. 10000	E. -
	F. 262			F. 10000	F. 260
	G. 4340			G. -	G. -

Table 4.3 Material flow between collection centers and ADCs (X_{jk}) (continued)

Collection center	ADC
J47	K3
	A. -
	B. -
	C. -
	D. 2539
	E. 7695
	F. 9843
	G. 10000

Figure 4.4 depicts material flow between ADCs and shredder facilities. The result of the mathematical model shows that three ADCs and three shredder facilities must be opened and these facilities must stay open for 10 years continuously.

Figure 4.4 ADCs and shredder cacilities opened as result of mathematical model

Table 4.4 presents the material flow details between ADCs and shredder facilities for three scenarios.

Table 4.4 Material flow between ADCs and shredder centers (Y_{kl})

ADC	Shredder Facilities		Shredder Center
K1	L1	K5	L3
	A. 14240		A. 77546
	B. 15915		B. 100904
	C. 19590		C. 123307
	D. 23255		D. 152092
	E. 32749		E. 160130
	F. 76411		F. 160380
	G. 122238		G. 160380
K3	L4		
	A. 76247		
	B. 97041		
	C. 116791		
	D. 136999		
	E. 158463		
	F. 160380		
	G. 160380		

Table 4.5 presents material flow details between shredder facilities and landfilling centers.

Table 4.5 Material flow between shredder centers and landfilling center (Z_{lu})

Shredder center			
	L_1	L_3	L_4
Landfilling center (U1)	A. 2634	A. 14346	A. 14105
	B. 2944	B. 18667	B. 17952
	C. 3624	C. 22811	C. 21606
	D. 4302	D. 28137	D. 25344
	E. 6058	E. 29624	E. 29315
	F. 14136	F. 29670	F. 29670
	G. 22614	G. 29670	G. 29670

Table 4.6 – 4.8 present material flow details between ADCs and recycling facilities.

Table 4.6 Material flow between ADCs and recycling centers for fluids (V_{kp})

Dismantler facility	Fluid recycling facility (ton)	
K_1	P_2	P_3
	A. 210	A. -
	B. 235	B. -
	C. 290	C. -
	D. 344	D. -
	E. 485	E. -
	F. 1132	F. -
	G. 1810	G. -
K_3	A. -	A. 1129
	B. -	B. 1437
	C. -	C. 1730
	D. -	D. 2029
	E. -	E. 2347
	F. -	F. 2376
	G. -	G. 2376

Table 4.6 Material flow between ADCs and recycling centers for fluids (V_{kp}) (continued)

Dismantler facility	Fluid recycling facility (ton)	
K_5	A. 1148	A. -
	B. 1494	B. -
	C. 1826	C. -
	D. 2253	D. -
	E. 2372	E. -
	F. 2376	F. -
	G. 2376	G. -

Table 4.7 Material flow between ADCs and recycling centers for tyres (W_{kr})

Dismantler facility			
	K1	K3	K5
Recycling center (R1)	A. 527	A. 2823	A. 2872
	B. 589	B. 3594	B. 3737
	C. 725	C. 4325	C. 4566
	D. 861	D. 5074	D. 5633
	E. 1212	E. 5869	E. 5930
	F. 2830	F. 5940	F. 5940
	G. 4527	G. 5940	G. 5940

Table 4.8 Material flow between ADCs and recycling centers for batteries (U_{ks})

Dismantler facility			
	K_1	K_3	K_5
Recycling center (S1)	A. 210	A. 1129	A. 1148
	B. 235	B. 1437	B. 1494
	C. 290	C. 1730	C. 1826
	D. 344	D. 2029	D. 2253
	E. 485	E. 2347	E. 2372
	F. 1132	F. 2376	F. 2376
	G. 1810	G. 2376	G. 2376

Table 4.9 - 4.10 present material flow details between shredder facilities and recycling.

Table 4.9 Ferrous material flow between shredder centers and recycling centers ($P1_{ln}$)

Shredder facility	Recycling facility			Shredder facility	Recycling facility		
L_1	N_1	N_2	N_3	L_4	N_1	N_2	N_3
	A. 6516	A. 4377	A. -		A. 34906	A. 5876	A. 17545
	B. 6073	B. 3650	B. 2451		B. 44848	B. -	B. 29388
	C. 5861	C. 6091	C. 3033		C. 44951	C. 9008	C. 35385
	D. 10790	D. 5211	D. 1788		D. 72989	D. -	D. 31815
	E. 4444	E. 5272	E. 15336		E. 96686	E. 12269	E. 12269
	F. 24411	F. 16442	F. 17601		F. 98152	F. 12269	F. 12269
	G. 20087	G. 16338	G. 57086		G. 36807	G. 73614	G. 12269

Table 4.9 Ferrous material flow between shredder centers and recycling centers ($P1_{ln}$) (continued)

Shredder facility	Recycling facility		
L3	N1	N2	N3
	A. 29385	A. 18080	A. 11856
	B. 14947	B. 15536	B. 46707
	C. 47446	C. 37188	C. 9694
	D. 22182	D. 23483	D. 70684
	E. 61345	E. 61154	E. -
	F. 12269	F. 36807	F. 73614
	G. 73614	G. 36807	G. 12269

Table 4.10 Non-ferrous material flow between shredder centers and recycling centers ($P2_{ln}$)

Shredder facility	Recycling facility			Shredder facility	Recycling facility		
L1	N1	N2	N3	L4	N1	N2	N3
	A. 282	A. 213	A. 215		A. 1898	A. 384	A. 1528
	B. 239	B. 316	B. 239		B. 1418	B. 1976	B. 1457
	C. 295	C. 396	C. 287		C. 3468	C. 1191	C. 1179
	D. 235	D. 457	D. 469		D. 2069	D. 2681	D. 2099
	E. 544	E. 504	E. 588		E. 3913	E. 2405	E. 1603
	F. 1165	F. 1189	F. 1465		F. 3207	F. 2405	F. 2405
	G. 1754	G. 2475	G. 1881		G. 3207	G. 3207	G. 1603
L3	N1	N2	N3				
	A. 2313	A. 1172	A. 391				
	B. 1526	B. 1538	B. 1980				
	C. 1861	C. 3047	C. 1255				
	D. 6039	D. 1565	D. -				
	E. 1603	E. 2393	E. 4009				
	F. 4811	F. 2405	F. 801				
	G. 2405	G. 1603	G. 4009				

Apart from processed materials of ELV, reasonable amount of ELV components are transferred to second-hand markets. Approximately 44 % of these components are ferrous, 29 % are non-ferrous, 4 % are fluids, 1 % are battery and 22 % are other types of materials. Table 4.11 presents the material types of ELV components sold to second-hand markets.

Table 4.11 Type of materials sold to the second-hand markets

Material type	Total (ton)	Rate of Material
Ferrous	A. 12446	
	B. 15841	
	C. 19236	
	D. 23136	44 %
	E. 26025	
	F. 29420	
	G. 32814	
Non-ferrous	A. 8297	
	B. 10561	

Table 4.11 Type of materials sold to the second-hand markets (continued)

Material type	Total (ton)	Rate of Material
Non-ferrous	C. 12824	
	D. 15424	29 %
	E. 17350	
	F. 19613	
	G. 21876	
Fluids	A. 1037	
	B. 1320	
	C. 1603	
	D. 1928	4 %
	E. 2168	
	F. 2451	
	G. 2734	
Battery	A. 207	
	B. 264	
	C. 320	
	D. 385	1 %
	E. 433	
	F. 490	
	G. 546	
Others	A. 6223	
	B. 7920	
	C. 9618	
	D. 11568	22 %
	E. 13012	
	F. 14710	
	G. 16407	
Total	A. 28210	
	B. 35906	
	C. 43601	
	D. 52441	
	E. 58988	
	F. 66684	
	G. 74377	

4.2 Sensitivity Analysis

As it is covered in section 4.1. Computational Results, the proposed mathematical model is solved to optimality with seven scenarios (ω = A, B, C, D, E, F, G) and p_{ω}(occurrence probability for scenario ω) is assumed as 0.143 for each scenario. This means, our model is solved with the assumption of equal probability for each scenario. In this section, it is assumed that p_{ω} is an external parameter and it effects the amount of ELVs generated (R_{it}^{w}) for each scenario. The variation of R_{it}^{w} values and its effect on the items of objective function (costs and profit), as well as decision variables (binary variables for ADCs and shredder facilities) are reported. Table 4.13 presents the results of this sensitivity analyses for five different scenarios. Based

Case represents the results of the actual model covered in Chapter 4. According to the results of the sensitivity analyses, the same number of ADCs and shredder centers are opened, however different facilities are opened in the last scenarios (e_k = 2, 3, 4, 5 and e_l = 1, 3, 4 for Case 4). Figure 4.5 focuses on the objective variable value and cost items of five scenarios. Not surprisingly, fixed-cost values are the same for Case 1, Case 2, Case 3 and Case 4. Furthermore, cost and revenue items in the objective function do not change significantly with the change of ELVs' amount. The total cost reaches its minimum value in Case 2 and the revenue item reaches its maximum value in Case 4. Table 4.12 and Figure 4.5 reveal that changes in the amount of ELVs in optimistic and pessimistic scenarios cause more significant changes in the locations of the facilities opened.

Table 4.12 Results of the sensitivity analysis regarding to ELV amount in scenarios

Change in the Amount of ELV	Fixed- Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
Based Case $R_{it}^A = 0.55.R_{it}^D$ $R_{it}^B = 0.70.R_{it}^D$ $R_{it}^C = 0.85.R_{it}^D$ $R_{it}^E = 1.15.R_{it}^D$ $R_{it}^F = 1.30.R_{it}^D$ $R_{it}^G = 1.45.R_{it}^D$	10162500	7672609	436795500	454630609	269542700	185087909	1, 3, 5	1, 3, 4
Case 1 $R_{it}^A = 0.25.R_{it}^D$ $R_{it}^B = 0.50.R_{it}^D$ $R_{it}^C = 0.75.R_{it}^D$ $R_{it}^E = 1.25.R_{it}^D$ $R_{it}^F = 1.50.R_{it}^D$ $R_{it}^G = 1.75.R_{it}^D$	11050000	7627717	436795500	455473217	269542700	185930517	1, 3, 4, 5	2, 3, 4
Case 2 $R_{it}^A = 0.10.R_{it}^D$ $R_{it}^B = 0.40.R_{it}^D$ $R_{it}^C = 0.70.R_{it}^D$ $R_{it}^E = 1.30.R_{it}^D$ $R_{it}^F = 1.60.R_{it}^D$ $R_{it}^G = 1.90.R_{it}^D$	11050000	7714794	434449400	453214194	268095000	185119194	1, 3, 4, 5	2, 3, 4
Case 3 $R_{it}^A = 0.05.R_{it}^D$ $R_{it}^B = 0.35.R_{it}^D$ $R_{it}^C = 0.65.R_{it}^D$ $R_{it}^E = 1.35.R_{it}^D$ $R_{it}^F = 1.65.R_{it}^D$ $R_{it}^G = 1.95.R_{it}^D$	11050000	7814775	436795500	455660275	269542700	186117575	1, 3, 4, 5	2, 3, 4
Case 4 $R_{it}^A = 0.01.R_{it}^D$ $R_{it}^B = 0.20.R_{it}^D$ $R_{it}^C = 0.60.R_{it}^D$ $R_{it}^E = 1.40.R_{it}^D$ $R_{it}^F = 1.80.R_{it}^D$ $R_{it}^G = 2.00.R_{it}^D$	11050000	7930179	437451500	456431679	269947500	186484179	2, 3, 4, 5	1, 3, 4

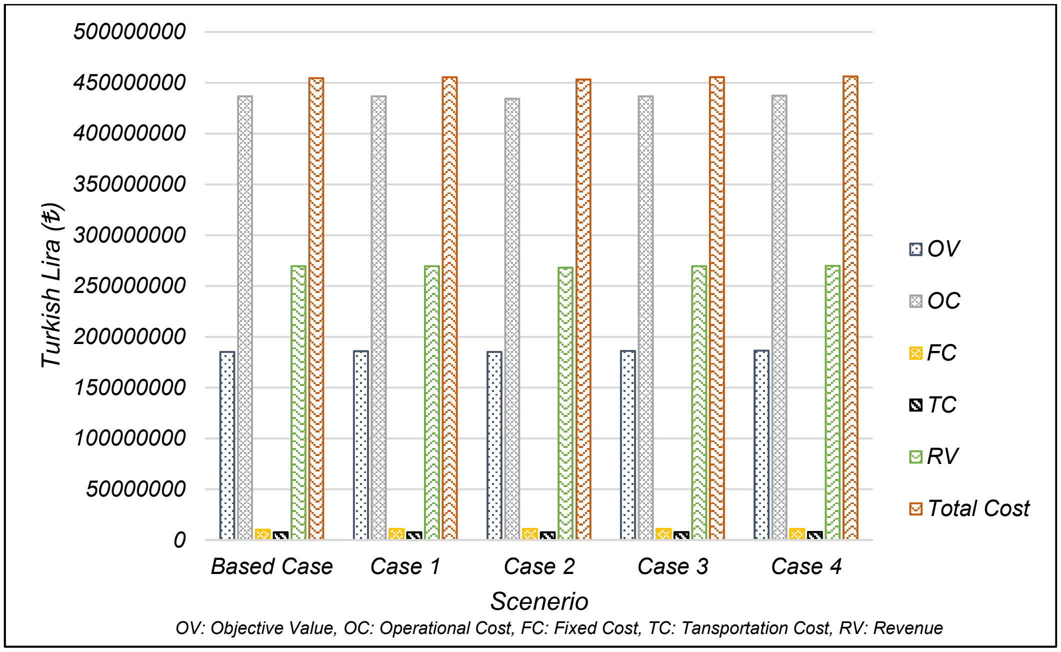


Figure 4.5 Change in the objective function items regarding to the sensitivity analysis on changes in the amount of ELV

Figure 4.1 demonstrates that operational cost has the highest rate in the cost items. On the other hand, the revenue has a significant impact on the objective value. For this reason, another sensitivity analysis is applied to see the impact of the changes in the operational costs and the selling prices of the components of ELVs to the objective value. In Case 5, the operational costs (dismantling cost, shredding cost, landfilling cost and recycling cost) are decreased 50%. In Case 6, the selling prices of the materials (ferrous, non-ferrous, fluids, batteries and others) are increased 100%. Table 4.13. and Figure 4.6 establish that the objective value attains negative values when operational costs increased or selling prices increased. For this reason, changes in the operational costs or the selling prices have crucial impact on profitability of the ELVs' recovery network.

Table 4.13 Results of the sensitivity analysis regarding to operational costs and selling prices

Change in the OC and RV	Fixed-Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
Based Case	10162500	7672609	436795500	454630609	269542700	185087909	1, 3, 5	1, 3, 4
Case 5 -50%. OC	10162500	7672609	218501200	236336309	269542700	-33206391	1, 3, 5	1, 3, 4
Case 6 +100%. RV	10162500	7672609	436795500	454630609	539085500	-84454891	1, 3, 5	1, 3, 4

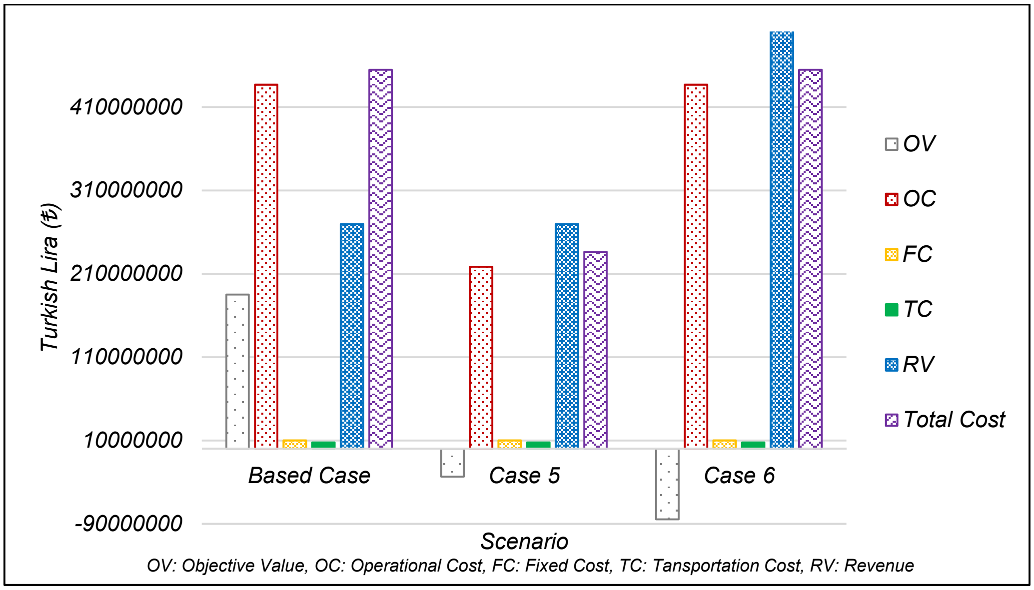


Figure 4.6 Change in the objective function items regarding to the sensitivity analysis on operational costs and selling prices

Table 4.13 and Figure 4.6 prove that material composition of the ELVs has crucial effect on the profitability of the supply chain network of ELVs' recovery. With this motivation, another sensitivity analysis regarding the change in material composition rates of the ELVs sold to the second hand markets and material suppliers is applied. In Cases 7 – 11, changes in the rates of materials sold from ADCs to the second hand markets (ferrous material: μ_1, non-ferrous material: μ_2, fluid: μ_3, battery: μ_4, other materials: μ_5) are analyzed. In Cases 12 – 14, changes in the rates of materials sold from ADCs to material suppliers (fluid: λ_1, tyre: λ_2, battery: λ_3) are analyzed. In Case 15 and Case 16, changes in the rates of materials sold from shredder centers to the material suppliers (ferrous material: γ_1, non-ferrous material: γ_2) are analyzed. Table 4.14 and Figure 4.7 represent the results of the sensitivity analysis regarding to the change in the rate of ELVs' components. The results establish that objective variable attains its minimum value and revenue attains its maximum value in Case 15. This depicts that rates of ferrous (γ_1) and non-ferrous (γ_2) materials sold from the shredder centers to the material suppliers have the most significant impact on the total revenue.

Table 4.14 Results of the sensitivity analysis regarding to material composition rates

Change in the Material Composition	Fixed- Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
Based Case μ_1= 0.060 μ_2= 0.040 μ_3= 0.005 μ_4= 0.001 μ_5= 0.030	10162500	7672609	436795500	454630609	269542700	185087909	1, 3, 5	1, 3, 4
Case 7 μ_1= 0.000 μ_2= 0.050 μ_3= 0.015 μ_4= 0.011 μ_5= 0.040	10162500	7672609	436795500	454630609	363570900	91059709	1, 3, 5	1, 3, 4
Case 8 μ_1= 0.070 μ_2= 0.000 μ_3= 0.015 μ_4= 0.011 μ_5= 0.040	10162500	7672609	436795500	454630609	241324800	213305809	1, 3, 5	1, 3, 4
Case 9 μ_1= 0.061 μ_2= 0.040 μ_3= 0.000 μ_4= 0.002 μ_5= 0.031	10162500	7672609	436795500	454630609	265423700	189206909	1, 3, 5	1, 3, 4
Case 10 μ_1= 0.060 μ_2= 0.040 μ_3= 0.005 μ_4= 0.000 μ_5= 0.030	10162500	7672609	436795500	454630609	270210300	184420309	1, 3, 5	1, 3, 4
Case 11 μ_1= 0.068 μ_2= 0.048 μ_3= 0.013 μ_4= 0.009 μ_5= 0.000	10162500	7672609	436795500	454630609	248379300	206251309	1, 3, 5	1, 3, 4

Table 4.14 Results of the sensitivity analysis regarding to material composition rates (continued)

Change in the Material Composition	Fixed-Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
Based Case λ_1= 0.012 λ_2= 0.030 λ_3= 0.012 γ_1= 0.765 γ_2= 0.05	10162500	7672609	436795500	454630609	269542700	185087909	1, 3, 5	1, 3, 4
Case 12 λ_1= 0.000 λ_2= 0.036 λ_3= 0.018	10162500	7616897	437022700	454802097	269542700	185259397	1, 3, 5	1, 3, 4
Case 13 λ_1= 0.027 λ_2= 0.000 λ_3= 0.027	10162500	7740554	436511400	454414454	269542700	184871754	1, 3, 5	1, 3, 4
Case 14 λ_1= 0.018 λ_2= 0.036 λ_3= 0.000	10162500	7700009	436681900	454544409	269542700	185001709	1, 3, 5	1, 3, 4
Case 15 γ_1= 0.000 γ_2= 0.815	10162500	7672609	436795500	454630609	386893300	67737309	1, 3, 5	1, 3, 4
Case 16 γ_1= 0.815 γ_2= 0.000	10162500	7672609	436795500	454630609	261872800	192757809	1, 3, 5	1, 3, 4

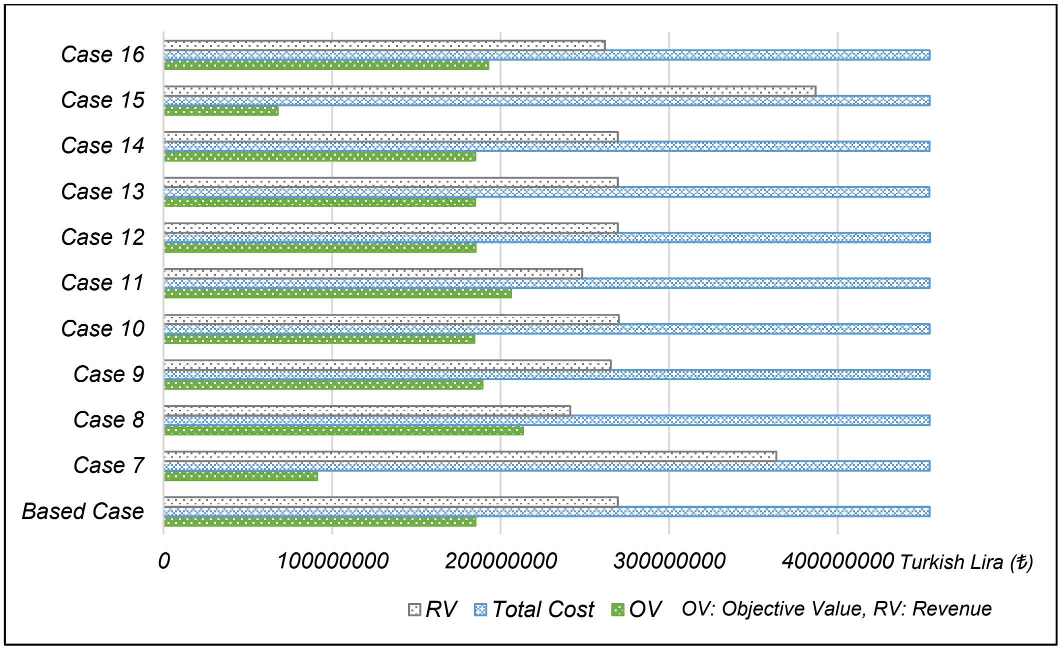


Figure 4.7 Change in the objective function items regarding to the sensitivity analysis on material rates

The capacities of the facilities play crucial role in the decision making process of supply chain management. In this section, another sensitivity analysis is applied by focusing on the changes in the capacities of ADCs and shredder centers. Table 4.15 and Figure 4.8 present the results of the sensitivity analysis regarding the capacities of the facilities. In Case 17 and Case 18, the capacities of the shredder centers are fixed and the capacities of ADCs are increased simultaneously. In Case 19 and Case 20, the capacities of ADCs are fixed and the capacities of shredder centers are increased partially. The results depict that the capacities of the facilities have direct effect on the number of opened facilities. Furthermore, changes in the capacities of the facilities have an impact on the locations of the facilities. The fixed-cost item and the objective variable attain their minimum values in Case 20, when the capacities of the shredder centers are increased. This result highlights that the changes in the capacities of the shredder centers have significant effect on the profitability of the supply chain network of ELVs.

Table 4.15 Results of the sensitivity analysis regarding to capacities of the facilities

Change in the Capacities of the Facilities	Fixed-Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
Based Case cap_k= 19800 cap_l= 22500	10162500	7672609	436795500	454630609	269542700	185087909	1, 3, 5	1, 3, 4
Case 17 cap_k= 35000 cap_l= 22500	9275000	7713078	436795500	453783578	269542700	184240878	3, 5	1, 3, 4
Case 18 cap_k= 50000 cap_l= 22500	9275000	7713078	436795500	453783578	269542700	184240878	3, 5	1, 3, 4
Case 19 cap_k= 19800 cap_l= 30000	7662500	7696318	436795500	452154318	269542700	182611618	2, 3, 5	3, 4
Case 20 cap_k= 19800 cap_l= 70000	5162500	8594381	436795500	450552381	269542700	181009681	2, 3, 5	3

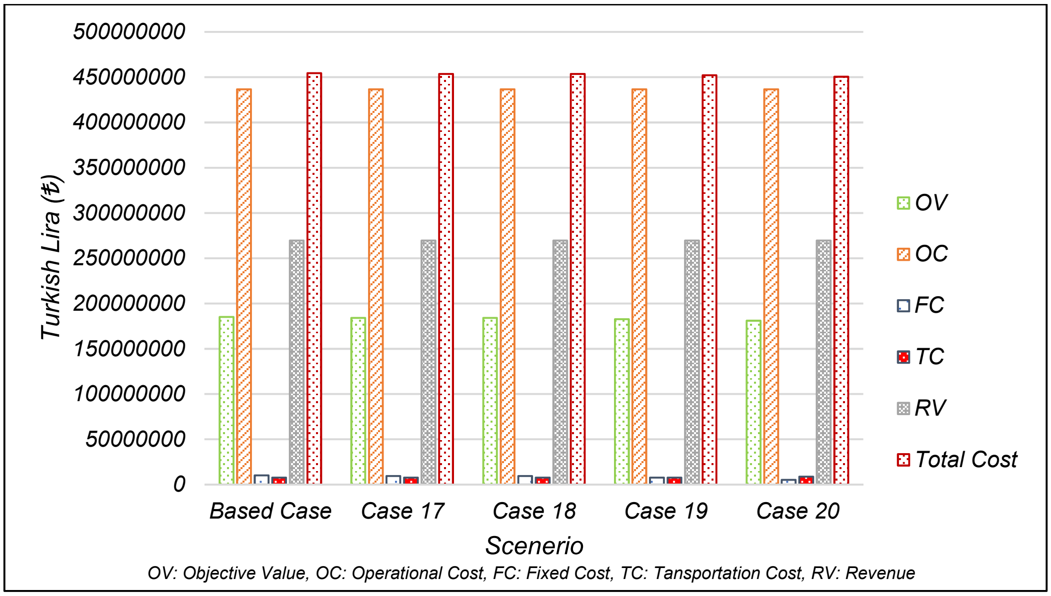


Figure 4.8 Change in the objective function items regarding to the sensitivity analysis on capacities of the facilities

4.3 Scenario Analysis

In S1, the proposed mathematical model is solved to optimality with seven scenarios (ω = A, B, C, D, E, F, G) and p_ω(occurrence probability for scenario ω) is assumed as 0.143 for each scenario. This means, our model was solved with the assumption of equal probability for each scenario. In this section, impacts of each scenario on the results are analyzed via scenario analysis. For this reason, the mathematical model is solved with assigning zero to each scenario and assigning 0.167 to other scenarios simultaneously. Table 4.16 and Figure 4.9 represent the results of seven scenarios.

Table 4.16 Results of the scenario analysis regarding to scenario weights

Scenarios	Fixed- Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
SCN1. p_A= 0.000 p_B= 0.167 p_C= 0.167 p_D= 0.167 p_E= 0.167 p_F= 0.167 p_G= 0.167	10162500	8289163	470151800	488603463	290126600	198476863	1, 3, 5	1, 3, 4
SCN2. p_A= 0.167 p_B= 0.000 p_C= 0.167 p_D= 0.167 p_E= 0.167 p_F= 0.167 p_G= 0.167	10162500	8102756	459255900	477521156	283402800	194118356	1, 3, 5	1, 3, 4
SCN3. p_A= 0.167 p_B= 0.167 p_C= 0.000 p_D= 0.167 p_E= 0.167 p_F= 0.167 p_G= 0.167	10162500	7912423	448359900	466434823	276679000	189755823	1, 3, 5	1, 3, 4
SCN4. p_A= 0.167 p_B= 0.167 p_C= 0.167 p_D= 0.000 p_E= 0.167 p_F= 0.167 p_G= 0.167	10162500	7691245	435839600	453693345	268952900	184740445	1, 3, 5	1, 3, 4
SCN5. p_A= 0.167 p_B= 0.167 p_C= 0.167 p_D= 0.167 p_E= 0.000 p_F= 0.167 p_G= 0.167	10162500	7510980	426567900	444241380	263231400	181009980	1, 3, 5	1, 3, 4

Table 4.16 Results of the scenario analysis regarding to scenario weights (continued)

Scenarios	Fixed- Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
SCN6. p_A= 0.167 p_B= 0.167 p_C= 0.167 p_D= 0.167 p_E= 0.167 p_F= 0.000 p_G= 0.167	10162500	7279862	415671900	433114262	256507500	176606762	1, 3, 5	1, 3, 4
SCN7. p_A= 0.167 p_B= 0.167 p_C= 0.167 p_D= 0.167 p_E= 0.167 p_F= 0.167 p_G= 0.000	10162500	6975487	404775900	421913887	249783700	172130187	1, 3, 5	1, 3, 4

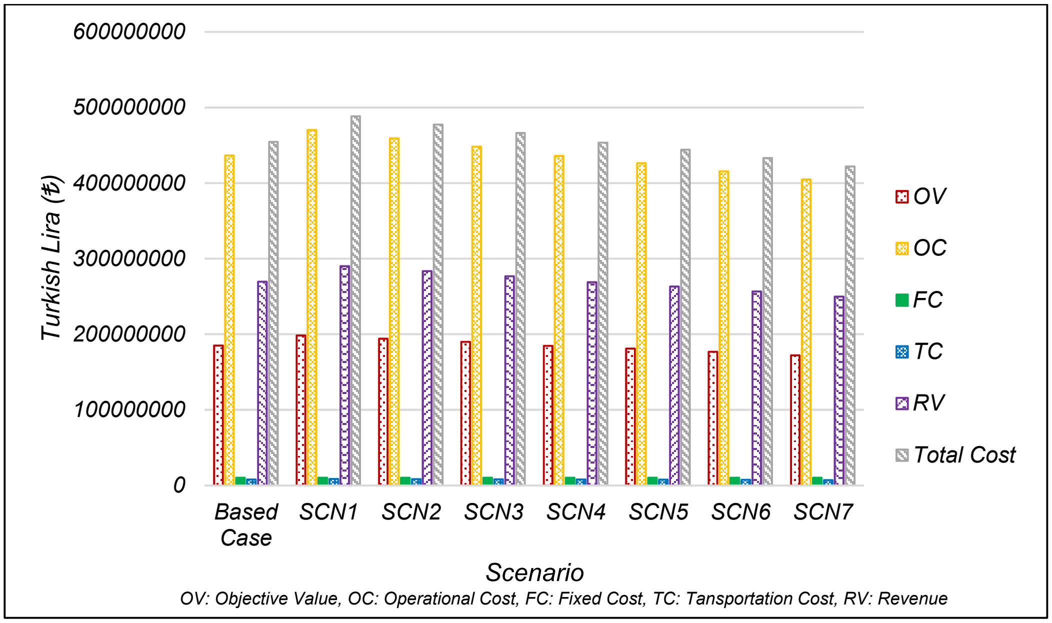


Figure 4.9 Change in the objective function items regarding to the scenario analysis

Table 4.16 and Figure 4.9 establish that the values of objective variable, operational cost, transportation cost and revenue decrease linearly in seven scenarios. The objective variable attains its minimum value in SCN7 and the revenue values attains its maximum value in SCN1. However, the fixed-cost value and opened facilities are the same for each scenario. This result highlights that scenario weights have a significant impact on the values of the objective variable items rather than the number and/or locations of the facilities.

Apart from the seven scenarios, another seven scenarios are analyzed. In this section, occurance probability of each scenario (p_{ω}) attains 1 and rest of the occurance probabilities attain zero for each scenario simultaneously. Table 4.17 and Figure 4.10 establish the results of the scenario analysis.

Table 4.17 Results of the scenario analysis regarding to occurance probabilities in the model

Scenarios	Fixed- Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
SCN8. p_A= 1.000 p_B= 0.000 p_C= 0.000 p_D= 0.000 p_E= 0.000 p_F= 0.000 p_G= 0.000	10162500	4018903	239233400	253414803	147628900	105785903	1, 3, 5	1, 3, 4
SCN9. p_A= 0.000 p_B= 1.000 p_C= 0.000 p_D= 0.000 p_E= 0.000 p_F= 0.000 p_G= 0.000	10162500	5135108	304478700	319776308	187891200	131885108	1, 3, 5	1, 3, 4
SCN10. p_A= 0.000 p_B= 0.000 p_C= 1.000 p_D= 0.000 p_E= 0.000 p_F= 0.000 p_G= 0.000	10162500	6274827	369724200	386161527	228153600	158007927	1, 3, 5	1, 3, 4
SCN11. p_A= 0.000 p_B= 0.000 p_C= 0.000 p_D= 1.000 p_E= 0.000 p_F= 0.000 p_G= 0.000	10162500	7599248	444695700	462457448	274417900	188039548	1, 3, 5	1, 3, 4
SCN12. p_A= 0.000 p_B= 0.000 p_C= 0.000 p_D= 0.000 p_E= 1.000 p_F= 0.000 p_G= 0.000	10162500	8678678	500215100	519056278	308678500	210377778	1, 3, 5	1, 3, 4

Table 4.17 Results of the scenario analysis regarding to occurance probabilities in the model (continued)

Scenarios	Fixed- Cost	Transportation Cost	Operational Cost	Total Cost	Revenue (₺)	Objective Variable (₺)	Opened ADCs (e_k)	Opened Shredder Facilities (e_l)
SCN13 p_A= 0.000 p_B= 0.000 p_C= 0.000 p_D= 0.000 p_E= 0.000 p_F= 1.000 p_G= 0.000	10162500	10062620	565460700	585685820	348940900	236744920	1, 3, 5	1, 3, 4
SCN14. p_A= 0.000 p_B= 0.000 p_C= 0.000 p_D= 0.000 p_E= 0.000 p_F= 0.000 p_G= 1.000	10162500	11504660	630706100	652373260	389203300	263169960	1, 3, 5	1, 3, 4

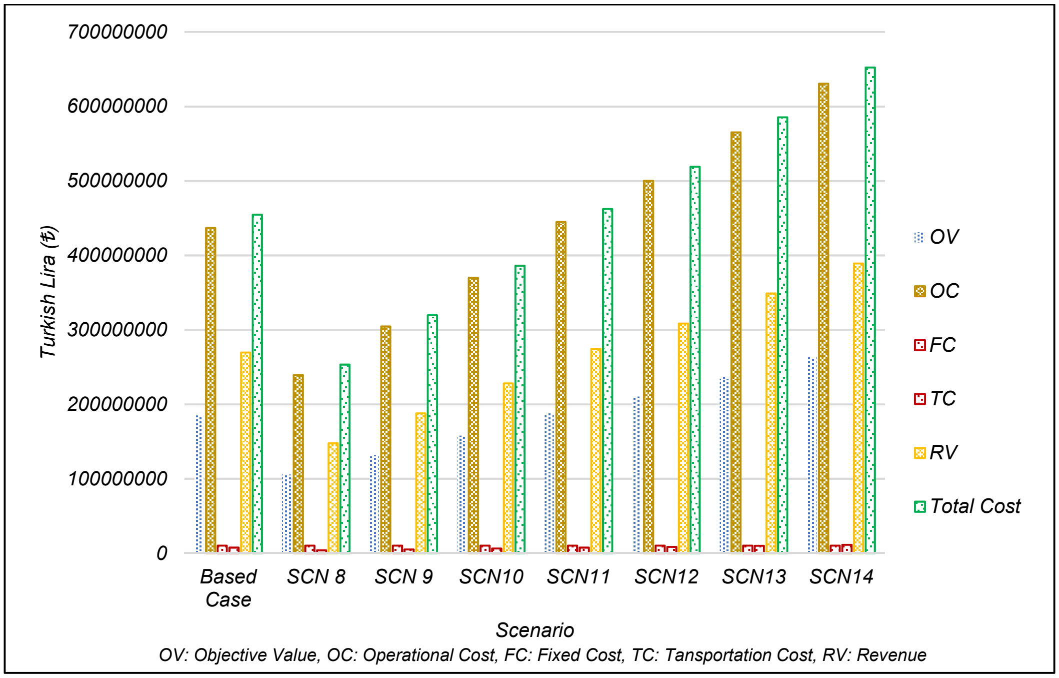


Figure 4.10 Change in the objective function items regarding to the second scenario analysis

Table 4.17 and Figure 4.10 establish that the values of objective variable, operational cost, transportation cost and revenue increase linearly in seven scenarios. The objective variable attains its minimum value in SCN8 and the revenue values attains its maximum value in SCN14. However, the fixed-cost value and opened facilities are the same for each scenario. This result highlights that pessimistic scenarios tend to provide higher revenue and total cost. Scenario weights have a significant impact on the values of the objective variable items. However, they do not have a significant impact on the number and/or locations of the facilities.

4.4 Facilitiy Utilization

Based on the results of the mathematical model (Based Case), Figure 4.11 represents the capacity utilization rates of ADCs and the shredder centers. The facility utilization rates establish that both shredder centers and ADCs are used most effectively in pessimistic scenarios. On the other hand, ADCs are operated more effectively than the shredder centers.

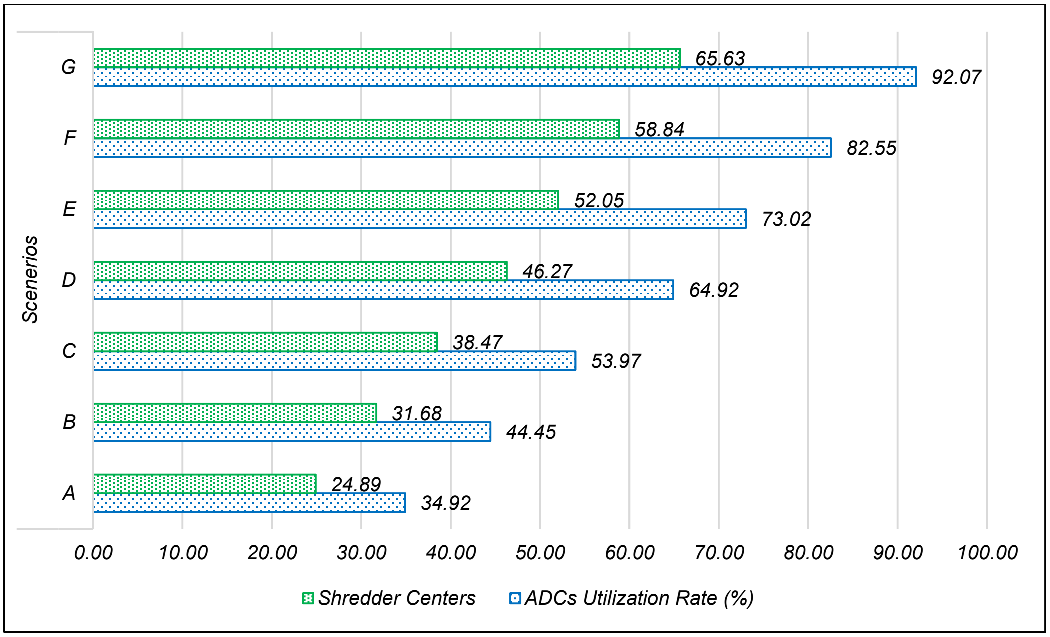


Figure 4.11 Capacity utilization rates of the facilities

5
RESULTS AND DISCUSSION

The ELV management is recently being paid more attention by the researchers from both academic and industrial backgrounds. Latest environmental challenges triggered policy makers to take action, and new legislations are promulgated by both local and global authorities. Multiple players like users, producers, treatment facilities, municipalities etc. require a cooperative engagement and they are being conferred new responsibilities in ELV management due to new legislations. Due to legislative improvements, it is becoming even more important both environmentally and economically. Furthermore, the ELV recovery and management problem is not only an operational process, it is also a strategic and tactical level processes for decision-makers. Participations of multiple actors in the recycling process of ELV causes various uncertainties to management of ELV recycling network. For this reason, it is aimed to propose a scenario based real life stochastic optimization model for the management of supply chain network of ELV recycling process in Istanbul. Consequently, various sensitivity analyses are applied to question the consistency of the study and to review the results with different scenario.

Results of the literature review indicate that available review papers are focused only on a limited scope of the ELV management, such as reverse logistics, recovery infrastructure, treatment processes. In addition, a review of state–of–the–art mathematical models for the ELVs' management are not studied by the researchers.

The previous studies, related to recycling processes and analyses of materials, mostly focused on solutions for local problems. More global approaches and solutions are highly needed. Furthermore, material concepts and perceptions of the vehicles tend to change. For this reason, more studies regarding this issue are needed in the future studies. Thus, majority of the studies, considering the managerial perspective, are suggesting solution approaches for economic and/or material issues. However, there are not enough studies that focusing on social aspect. The participation of the public has a crucial impact for an effective ELV management. Owners need to be encouraged to withdraw their vehicles from the traffic. For this reason, social awareness and acceptance also have crucial impact on an effective ELV management. Apart from these, there are not enough studies comparing the designing and planning systems as before and after. Impacts of recycling friendly product design and production planning could be monitored via customer feedbacks, financial analyses, etc.

Due to new ELV regulations, researchers need to focus on producers' responsibilities. Decision makers are expected to make their designs and revise their production plans according to legislation. On the other hand, there are a few types of studies published by the researchers.

Available publications cope with supply chain issues of the ELV management are mostly performed with deterministic data. Real life ELV management systems have many uncertain components. Furthermore, there are various uncertainties with economic and technical parameters, amount of supplied ELV, etc. An extension of the reviewed modeling frameworks to address uncertainties can provide more realistic representation of ELV management systems.

It depicts that most of the studies in the scope of regulation review are considering local issues related to ELV management. However, regulations have global affects in the world simultaneously.

As it is covered in the fourth chapter, the operational cost has the highest rate in the cost items of ELVs' recycling process. Furthermore, dismantling cost has the highest rate in the operational cost item. This fact shows that the cost items can be decreased with improvements of dismantling processes. Furthermore, rates of material components of ELVs have significant effect on the objective variable. This result highlights that improvements in the operational costs and the material components are able to improve the profitability of the recovery supply chain of ELVs.

It is obvious that capacities of the facilities are not used effectively. It can be as consequence of lower return rates of ELVs or ill-planned facility operational capacity and location management. At this point, policy makers may need to revise legislations to put more pressure on various players of ELV recycling process in Istanbul.

Further research should examine the effectiveness of ELV recycling management in Istanbul since Istanbul represent whole Turkey with its economic and cultural characteristics. The proposed model can be applied to larger regions such as the whole country.

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